Network Enabled Capability of Remote Operation: Systems Engineering and Human Factors

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by
John Kenneth Davis

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Abstract

Air-to-surface weapons, and the platforms that deliver them, are becoming increasingly automated and remote from operators. The benefits of remotely operated systems have been widely agreed, yet the question of accountability remains an issue – both from a legal standpoint and with regard to public opinion. The current focus of the military and industry is to develop weapons with more autonomy and an increased range. This motivation is part of a wider aim for Network Enabled Capability across all military forces.

This thesis focuses on one aspect of Network Enabled Capability, the remote re-tasking of air-to-surface weapons in flight, the aim being to explore the potential capabilities of the human operator that may use such a system. Further, this thesis sets out to investigate the differences between using an automated system for re-tasking air-to-surface missiles in flight as opposed to assigning the task to a human operator.

A simulation test-bed facility was established to investigate these research aims. The development of this system first required a complete simulation of two air to surface weapon systems, a generic guided bomb, and an extended range missile. These simulation models were integrated into the test-bed facility to allow real-time targeting and firing of the weapon systems in a 3D simulation environment.

Two participant trials were carried out to test firstly, the operator terminal designed for re-tasking air-to-surface weapons in flight, and secondly, the operator capacity limits when re-tasking multiple air-to-surface weapons against multiple defended targets. These trials found that the system developed was suitable for the task, with interesting results that prove counter to the expectation that operator capacity would severely limit their capability to complete the task. Instead, operator capacity was found to be sufficient to perform well in a demanding scenario in which 32 concurrent air-to-surface missiles must be re-tasked amongst 8 targets. Their performance was comparable with an ideal automatic system developed for the same role.

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Acronyms

3D	Three Dimensional
6DoF	Six Degrees of Freedom
AAA	Anti-Air Artillery
AAAW	Autonomous Anti Armour Weapon
ACS	Automated Control System
ANOVA	Analysis of Variance
APN	Augmented Proportional Navigation
ASM	Air-to-Surface Missile
ATC	Air Traffic Control
ATF	Avionics Testbed Facility
BCE	Before Common Era
BDA	Battle Damage Assessment
BFT	Blue Force Tracker
C2	Command and Control
Cap3	Capability 3
CAS	Close Air Support
CLoS	Command Line-of-Sight
CNR	Combat Net Radio
DCCP	Datagram Congestion Control Protocol
DG	Differential Geometry
DP	Deviated-Pursuit
DSS	Decision Support Systems
ePWII	Enhanced Paveway II
FAC	Forward Air Controller
FAD	Functional Area Designators
FPI	Field Presence Indicator
FRI	Field Recurrence Indicator
GBU	Guided Bomb Unit
GPI	Group Presence Indicator
GPS	Global Positioning System
GRI	Group Recurrence Indicator
GUI	Graphical User Interface
IDM	Improved Data Modem
INS	Inertial Navigation System
IP	Internet Protocol
ISE/S2E	Integrated Sensor to Effect
JDAM	Joint Direct Attack Munition
LAN	Local Area Network

LAR	Launch Acceptability Region
LGAAW	Laser-Guided Anti Armour Weapon
LGB	Laser-Guided Bomb
LLA	Latitude, Longitude, Altitude
LoS	Line-of-Sight
LPD	Landing Point Designation
LRAGM	Long Range Air-to-Ground Missile
M	Mean
M-WU	Mann-Whitney U
MIL-STD	Military Standard
MoD	Ministry of Defence
MSFSX	Microsoft Flight Simulator X
NATO	North Atlantic Treaty Organisation
NCW	Network-Centric Warfare
NEC	Network Enabled Capability
NED	North East Down
NEW	Network Enabled Weapon
OCT	Optimal Control Theory
OODA	Observe Orient Decide Act
OSM	Open Street Map
p	Significance Value p
PC	Personal Computer
PN	Proportional Navigation
PoI	Point of Interest
PP	Pure-Pursuit
RAF	Royal Air Force
RAR	Re-task Availability Region
RED	Risk Estimated Distance
RF	Radio Frequency
RoE	Rules of Engagement
RS	Reachable Set
SA	Situational Awareness
SAGAT	Situational Awareness Global Assessment Technique
SAM	Surface-to-Air Missile
SCTP	Stream Control Transmission Protocol
SD	Standard Deviation
SDK	Software Development Kit
SEAD	Suppression of Enemy Air Defence
SPEAR	Selective Precision Effects at Range
TAT	Task Allocation Table
TCP/IP	Transmission Control Protocol/Internet Protocol
TDL	Tactical Data Link
TDS	Tactical Data System
TLAM	Tomahawk Land Attack Missile
TLAR	Transporter Launcher and Radar
TLX	Task Load Index
TST	Time Sensitive Targeting
TTG	Time to Go
U	U-Statistic

UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Air Vehicle
UDP	User Datagram Protocol
UK	United Kingdom
UN	United Nations
UNITAF	United Task Force
UNOSOM I	United Nations Operation in Somalia
US	United States of America
UWS	Unmanned Weapon System
VMF	Variable Message Format
WAN	Wide Area Network
WO	Weapons Officer
Z	Z-Statistic

Notation

α	Angle of Attack (*deg* or *rad*)
α^2	Angle of Attack Squared – sign is maintained
$\dot{\alpha}$	Rate of Change of α (rad/sec)
β	Angle of Sideslip (*deg* or *rad*)
β^2	Angle of Sideslip Squared – sign is maintained
$\dot{\beta}$	Rate of Change of β (rad/sec)
δp	Deflection Angle of the Control Surfaces used to Roll the Airframe (*deg* or *rad*)
δp^2	δp Squared – sign is maintained
δq	Deflection Angle of the Control Surfaces used to Pitch the Airframe (*deg* or *rad*)
δq^2	δq Squared – sign is maintained
δr	Deflection Angle of the Control Surfaces used to Yaw the Airframe (*deg* or *rad*)
δr^2	δr Squared – sign is maintained
ΔT	Model Time-Step (s)
δx	Deflection Angle of the Control Surfaces used to Slow the Airframe (*deg* or *rad*)
δx^2	δx Squared – sign is maintained
ϕ	Euler Roll Angle (*deg* or *rad*)
ψ	Euler Heading Angle (*deg* or *rad*)
ρ	Density of Air (kg/m^3)
θ	Euler Pitch Angle (*deg* or *rad*)
C_A	Drag (Axial) Force Coefficient
C_D	Drag Force Coefficient
C_L	Lift Force Coefficient
C_l	Rolling Moment Coefficient
C_m	Pitching Moment Coefficient
C_N	Normal (Lift) Force Coefficient
C_n	Yawing Moment Coefficient
C_Y	Side Force Coefficient
g	Acceleration due to Gravity ($9.81m/s^2$)
I_{xx}	Moment of Inertia about x-x axis (kg/m^2)
I_{yy}	Moment of Inertia about y-y axis (kg/m^2)
I_{zz}	Moment of Inertia about z-z axis (kg/m^2)
l	Length of Moment Arm (m)
M	Mass (kg)
P	Roll Rate about Body Axis (rad/s)
Q	Pitch Rate about Body Axis (rad/s)

q_n	Quaternion for the nth element $n = 1 - 4$
R	Yaw Rate about Body Axis (rad/s)
S	Reference Area (m^2)
u	Velocity along X body axis (m/s)
V	Airspeed (m/s^2)
v	Velocity along Y body axis (m/s)
V_D	Velocity in Down Direction (m/s)
V_E	Velocity in East Direction (m/s)
V_N	Velocity in North Direction (m/s)
w	Velocity along Z body axis (m/s)
X	Position in X (m)
Y	Position in Y (m)
Z	Position in Z (m)

Chapter 1

Introduction

1.1 Significance and Motivation

The development of Network Enabled Capability (NEC) in military systems is allowing greater connectivity between individual military personnel and the wider distributed Command and Control (C2) structure. Such techniques have already been used widely in civilian industry with positive effect. For example, Amazon's internal data network, used for live monitoring of stock and dispatching, allows for increased efficiency within the company as well as improving the end user's experience by providing them with useful information that facilitates decision making. This network-driven revolution, made possible by the internet, has changed the current state of affairs such that timeliness of information and increased data transfer between platforms allows for new capabilities to be generated where they were not possible before.

In the commercial sector the increase in applications for network driven products has quickly surpassed the military in terms of use. In particular, multi-player gaming is continuously adding new features, with the requirement for more network dependency. Large numbers of players can simultaneously play in a single game world – requiring significant overheads in terms of networking. Military systems have been slow on the uptake of networked solutions to support the way in which wars are fought for several reasons. One of the primary reasons is safety – any network used in the military must be robust, as it will inherently involve information relating to military actions. Failures of the network could result in potential loss of life. Networked gaming and other commercial outlets for networking have far less risk to the users or others when the system fails. Moreover, the commercial sector have far more opportunities to roll out patches and updates to fix problems as and when they need to. This continuous development is more difficult in military systems, where the product life cycle of any system may be decades, and when platforms are required to be compatible with both legacy and future systems. It is for these reasons that the military must have clear, long lasting, doctrine outlining the intended use of networked systems and architecture. In the United Kingdom this exists in the form of NEC Joint Service Doctrine 777 [1]. First published in 2005, Joint Service Publication 777 aimed to set out the British Armed Forces' use of networked systems.

Through collaborative efforts between the government, industry and academia, military commanders are reaching the point of being able to use a wide range of NEC features in battles. These range from enhanced air-to-surface weapon aiming – through to stores management and logistics. Whilst some of the capabilities such as logistics clearly benefit the military, other areas such as remotely piloted air systems or remote re-tasking, re-targeting or refining of weapons in flight require in-depth knowledge of the limits placed on such systems – not so much by the limitations in hardware or software, but by the human operator.

One key element within NEC is the improved air-to-surface weapon aiming that can be achieved through the ability to remotely update information on the weapon whilst it is in flight. The main advantage of such a capability is the extended 'stand-off' range of a platform. Stand-off range is the ability to attack targets/launch weapons against targets from outside of the range of their defensive capabilities. However, extending the stand-off range of a weapon system increases the time of flight of the weapon. This increases the chance the target has to attempt to evade the incoming attack through evasive manoeuvring or by moving into cover, and allows time for the situation on the ground to change significantly. Furthermore, civilians or non-combatants may have come within the effect of the weapon. These uncertainties require increased tactical command of these weapons during their flight, so that appropriate target position updates or abort commands can be transmitted to the weapon should the situation change.

The UK Ministry of Defence (MoD) Selective Precision Effects at Range (SPEAR) Capability 3 (Cap3) is a 100kg class air-launched precision-guided air-to-surface weapon program [2, 3]. A weapon developed by MBDA to meet this capability includes a two-way data link that allows for in-flight updates, re-targeting and abort functions [4]. This NEC opens up the roles for which a SPEAR type weapon could be used. For example, a SPEAR type weapon could be sent updated targeting information over a network that can either re-task, re-target or refine targeting information, in a similar way to loitering munitions such as the Fire Shadow missile [5]. These actions are related to three distinct levels of updating target information relating to the overall objective, strategic benefits and updating the specific location of targets. Re-tasking is the act of changing the main task, for example, switching from target A to target B. Re-targeting is the act of changing the aim point of a weapon for specific effect – for example, targeting the stern of a ship to disable rudder control. Refining is the act of providing refined target coordinates to ensure that the weapon hits the target as intended – this is particularly relevant for moving targets.

Re-tasking an air-to-surface weapon remotely to different targets is not only a significant technical challenge but also a human factors challenge. The way in which specific information relating to a weapon's capability to be re-tasked is displayed to a remote operator to support their decision making is critically important. Further, an understanding of the boundaries and limitations that exist within the domain of remote operation of Network Enabled Weapon (NEW) are needed to allow commanders to configure military engagements in a way that is not too demanding of operators. This thesis describes an investigation into the way in which re-tasking information is displayed to operators of remote weapon systems, and the limits that the operator has when using these systems.

Firstly, a simulation test-bed facility was developed to represent air-to-surface engagements in a safe, controlled research environment. This simulation test-bed facility exists in a distributed network of aircraft simulators at the University of Liverpool, and has been extended as part of this research to include two real-time air-to-surface weapon simulations and a simulated remote operator terminal.

This test-bed facility enabled the human factors research to be conducted into the best display methods of re-tasking information and the workload factors associated with them. The first human factors trial sought to find the best way of visualising the Re-task Availability Region (RAR) of an in-flight air-to-surface weapon. The RAR is the area on the ground (for air-to-surface weapons) to which the weapon can be safely re-tasked and is affected by the weapon's proximity to the target and by the physical limitations of the weapon such as its aerodynamic and propulsion properties. Two methods of displaying the information were used. A RAR polygon overlaid on a map display, and a numeric representation of the RAR capability adapted from the RAR values made up the two different formats. A participant group was presented with these two different display formats and tested for decision making accuracy and reaction time for a set of scenarios.

Following the first human factors trial, a follow-up trial was conducted to evaluate the workload related performance issued when operators used a more complex display that was developed to allow for multiple weapons to be re-tasked amongst a number of targets simultaneously. Again, a group of participants were presented a series of scenarios to test their ability to perform the task. The scenarios presented were of different levels of difficulty rather than display type, so that findings of operator workload capacity could be found.

The results of these human factors trials and recommendations for practitioners when developing future remote operator terminal displays are presented and discussed in this thesis. The findings of this research aim to lay out a baseline standard for the development and use of remote re-tasking systems for military applications.

1.2 Structure of Thesis

This thesis is divided into 6 further chapters:

- Chapter 2 is an overview of the relevant research in the fields of weapon simulation, air-to-surface weapon developments, ecological and other methods of designing graphical user interfaces, as well as the psychology disciplines of decision making and cognition.

- Chapter 3 details the necessary computational steps needed for simulation of both the weapon systems and the network protocol used to communicate information between different 'players' in the simulation.

- Chapter 4 describes an overall picture of a battle-space where there are multiple targets, target types and multiple delivery aircraft (platforms) each with different sets of weapons. It goes on to offer several solutions to the task allocation problem, where the platforms and their weapons need to be tasked to the targets in order to achieve a stated military objective.

- Chapter 5 discusses the first of two participant studies carried out as part of this research. The study involved participants, acting as a remote weapons operator, re-tasking a single weapon to a emergent target of opportunity.

- Chapter 6 is the second of the two participant studies. This study involved participants freely re-tasking multiple weapons amongst multiple targets given a set of objectives in a Suppression of Enemy Air Defence scenario.

- Chapter 7 concludes the thesis, detailing specific contributions made and the impact that these have in the field of air-to-surface weapon use. It also makes recommendations for further investigations.

1.3 Publications

1.3.1 Conference Papers

Davis, J. K., Griffith, E. J. and Ralph, J. F. *Real-Time Task Allocation for Remote Weapon Operators*, In Proceedings, ISIF FUSION, Istanbul, 2013.

1.3.2 Conference Presentations

Davis, J. K., Power, N., Davies, J., Ralph, J. F., Alison, L. *Simulation of Network Enabled Weapons and SPEAR Strike Capabilities* at "Hitting the Target?" How New Capabilities are Shaping Contemporary International Intervention, Centre for International Intervention, University of Surrey, 2012.

Davis, J.K., Mehta, M., Ralph, J.F., Power, N., Alison, L. *Remote Operator Terminal Design for use in a Real-Time Distributed Simulation Environment* at RAeS Simulation and Mission Training Conference, RAeS, London, 2013.

Davis, J.K., Griffith, E.J., Mehta, M., Ralph, J.F. *Distributed Simulation of Supervised UAV* at RAeS Flight Simulation Seminar, University of Liverpool, 2014.

Davis, J.K., Ralph, J.F., Power, N., Alison, L. *Suppression of Enemy Air Defence – A New Targeting Capability* at RAeS Delivering Weapon System Effects: The Contrast Between Piloted and Remotely-Piloted Platforms, QinetiQ, Malvern, 2015.

1.4 Novel Contributions

This thesis covers the Systems Engineering and Human Factors of re-tasking NEW, specifically focussing on the design and use of remote operator terminals for the first time in open literature. Two main sets of novel findings are presented herein.

Firstly – the study of the difference between display types for initial re-tasking of a remotely operated weapon system found that the graphical RAR (the native format of the information) display effectively reduces the decision making time for operators by approximately 0.5 seconds, compared to using a digital numeric display for the same task. However, those using the numerical display format showed increased decision accuracy compared to those using the graphical RAR. This research also found that during borderline cases there is a large difference in accurate decision making between groups – those using the graphical format of the RAR making a significant number of mistakes, whereas those using the numerical display format maintaining 100% accuracy in their decisions. These findings are important to those who might seek to develop these capabilities in the near future.

Secondly – investigations into the effects of simultaneous multiple re-tasking on operator performance revealed that whilst there are real identifiable limits on the number and frequency of simultaneous weapon engagements that can be handled by an operator, performance is sufficient to manage the task at a reasonable pace. An automated re-tasking system was used to establish a baseline ideal performance across scenarios where acknowledged communication and weapon system limitations were built into the system. Performance of human operators was compared to the automated process with some interesting comparable results. Human operators are able to maintain sufficient performance until a point where the additional workload, caused by having a large number of weapons to re-task in a short period of time, causes a drop off in performance. It is necessary to credit MBDA Systems for their input when designing a potential future scenario of particular interest to both the military and industry.

This thesis provides an in depth analysis into the potential future of the use of NEC for the purpose of re-tasking NEW and provides the outcomes of two studies for the military, industry and academia to use as a basis for developing remote operator terminals for future systems.

Chapter 2

Literature Review

This thesis encompasses several fields of academic and industrial research. These are Aerospace, Systems & Networking (Engineering) and Human Factors, Ergonomics & Human Computer Interfaces (Psychology). It is necessary to draw from these fields of research in order to fully place and understand the research embodied herein. For the purpose of this literature review several main areas will be discussed as related to their fields, but firstly the relevant background behind the overall project will be discussed.

2.1 The History of Data and Communication Networks

Data communication networks are not something recent. Carrier pigeons were used from 2900 Before Common Era (BCE) [6] and records from as early as 2000BCE indicate the use of complex communication relay systems using messengers on horseback and relay posts [6]. The Byzantine Navy had a well established method of communicating command intent between ships in naval battles by raising different flags, dating back to 800BCE [6]. For longer distance communication fire beacons as warnings signals were used and can be dated back to 650BCE [6]. Whilst they are fairly simple, the beacon signal can be considered as one bit of binary data that travels as fast as the speed of light. Ranged communications could now travel almost instantly between relay points and no longer took days to travel by horseback or pigeon.

In 1793 a novel method of communicating more complex coded messages was developed in France by Claude Chappe. Chappe's Semaphore Telegraph was a mechanical signalling system made up of a central pivoting beam that had additional rotating beams extending from each end of the main central beam. The whole system was built into tower structures that contained the control systems within the buildings. In total 196 positions were available to be used to represent different characters for coded messages. Chains of towers were placed roughly 15km apart and allowed messages to be sent very quickly from one part of France to another. A set of codes and codebooks were agreed upon which prevented 'eavesdropping' on the messages as they were sent down the communication network. Only 'Superintendents' at each end of a chain – or based in strategically important locations – were able to decode the messages. A complex set of control signals existed to communicate the priority of messages, handshakes and potential breakdown issues of the network.

The invention of the Electrical Telegraph, and then the rapid development of communication technologies from the mid 19th Century, provided the foundations for the complex telecommunications networks of today. Many lessons have been learned about the importance of such communications infrastructure in the military environment from the strategic and tactical failures and successes during the First and Second World Wars. The benefits of the rapid development of portable electronic equipment across a very wide range of uses has shaped the outlook for future uses of such technology. Now, in the 21st Century, technology such as digital radio communications has matured to the level that it can and is being exploited by the more advanced militaries to increase their capabilities beyond simple voice radio communications.

One such development is NEC, the use of electronic, radio and information technology to create a network of networks to distribute command intent, share sensor data and intelligence, as well as provide communication channels for units within the British Armed Forces and North Atlantic Treaty Organisation (NATO) Allies [1]. First announced in 2005, the United Kingdom (UK)'s NEC is more recent, compared to the United States of America (US)'s Network-Centric Warfare (NCW) concept proposed in 1998 [7]. NEC integrates several programmes with an aim to synchronise all operations from the tactical up to the strategic level and share relevant information between both commanders and units in order to mount seamless joint service missions. In theory, this will allow the military as a whole to use the correct force and tactics where needed. For example, providing Close Air Support (CAS) to the front line, whilst keeping track of ground force positions, or monitoring the remaining ammunition levels of forces deployed across the globe. However, in practice the adoption of new technologies often throws up more unforeseen challenges, particularly surrounding the utility of systems that present information for an operator. How long these teething problems last can be dramatically reduced through insightful research into these areas.

Although NEC was not announced as a coherent aim in the UK until 2005, some development-related work was already under-way. In 2001, third party targeting information was successfully transmitted from ground units to an air platform [8]. In this work, a NATO standard "9-Line Brief" CAS message was drafted using targeting information gathered from range finding binoculars and a Global Positioning System (GPS) receiver. The 9-Line Brief was then transmitted to, and received by, a Royal

Air Force (RAF) Jaguar, whose pilot then digitally transferred the target information to the aircraft's weapon system. The work, named 'Project Extendor', ran from 2001 through to 2006 [9–11]. The modernisation of CAS and remote targeting has been influenced somewhat by the changing environment in which countries carry out military campaigns; as coalition forces, rather than as individual nation states. In this instance, Project Extendor was carried out to show the UK's Time Sensitive Targeting (TST) system for the NATO requirement on the coalition forces to produce TST systems [12]. Providing friendly force location allows the aircraft systems to check that no friendly forces are at risk of fratricide from the weapon. The individual responsible for managing the weapon systems on-board the aircraft – be it the Pilot in a single seat aircraft or a Weapons Officer (WO)/Navigator in a two or more seat aircraft – can also choose a different weapon so as to minimise the risk of collateral damage [13].

2.2 Technology Context

The focus of this thesis surrounds the potential use of NEC for improving the capabilities for air-to-surface weapon aiming and target assignment management. Although there has already been some development work in the area of networking weapons and extending the targeting capabilities of weapon systems, the impact this will have in complex time-critical situations has not yet been investigated in open literature. Whilst this technology advance will help to increase the utility of weapon systems after the point of launch from the delivery aircraft, the risks of collateral damage will increase as the flight ranges of modern weapons are extended. Presently there are limited number of weapons that have been demonstrated which include an Improved Data Modem (IDM) for the purpose of allowing remote operation of the weapon [4, 14]. However, the next generation of weapons will have this network capability [15]. It is therefore imperative that research is carried out to establish some form of guidelines as to how such weapons might be used and how best to present information to operators whom are responsible for them.

2.2.1 Networked Close Air Support and Sensor To Shooter Capabilities

As mentioned previously, NEC can be used to enhance CAS missions by enabling the sensing equipment used for marking targets to be remote from the shooter of the weapon itself. Take an example with a unit that has become pinned down by enemy fire, and knows the location of the aggressor. Using radio systems, the ground unit's Forward Air Controller (FAC) would need to use a GPS device (or be very good at reading a map), a set of range-finding binoculars, and a laser range-finder to fix the target's position [9]. Then, he or she would need to request CAS from a friendly aircraft. In order to transfer the target information the FAC needs to read out the '9-Line Brief', a standardised NATO briefing tool for CAS [16]. A typical example would be:

- Initial Point: Charlie 12345.
- Target Bearing: 100 True.
- Target Distance from IP: 10 Nautical Miles.
- Target Position: North 12.345678 Degrees, East 12.345678 Degrees.
- Target Elevation: 12345 Feet.
- Target Description: Infantry Unit in cover...
- Mandatory Attack Heading: 123 True.
- Friendly Distance: SW 10 Nautical Miles.
- Time on Target: 12Hrs 34Mins.

This message would need to be read over the secure radio network to the Pilot or WO/Navigator (if the aircraft was a multi-seat aircraft), who would then need to physically write it down [8]. If the target is being lased (the act of shining laser energy onto the target with a laser designator) the FAC would also need to communicate the laser designator's code. Once the message has been received, the Pilot or WO would then need to enter this data into the weapon targeting system for the specific weapon, and read back the information to the FAC for confirmation, before being able to attack the target. This process is clearly time consuming and has many opportunities for errors to occur such as the misinterpretation of information.

2.2.2 Risks in Air-Strikes and Sources of Error

One of the biggest concerns with calling in an air-strike is the risk of fratricide. This occurs when a weapon falls sufficiently close enough to friendly ground troops to cause fatalities. Several case studies have been carried out on the causes of fratricide in both the UK [17] and the US [18]. UK data shows that the majority of fratricide incidents occur due to communications or information errors, 21% of cases. The joint second highest causes are procedural and C2 at 13.5%. Critically, the data shows that the equipment/technology itself was seldom a cause or contributory factor in fratricide with a frequency score of only 2.5%. Very similar data is presented from the US source with the equipment/technology causing fratricide with a slightly higher 3% of cases. Figure 2.1 shows the information collected from the UK [17] and US [18] data.

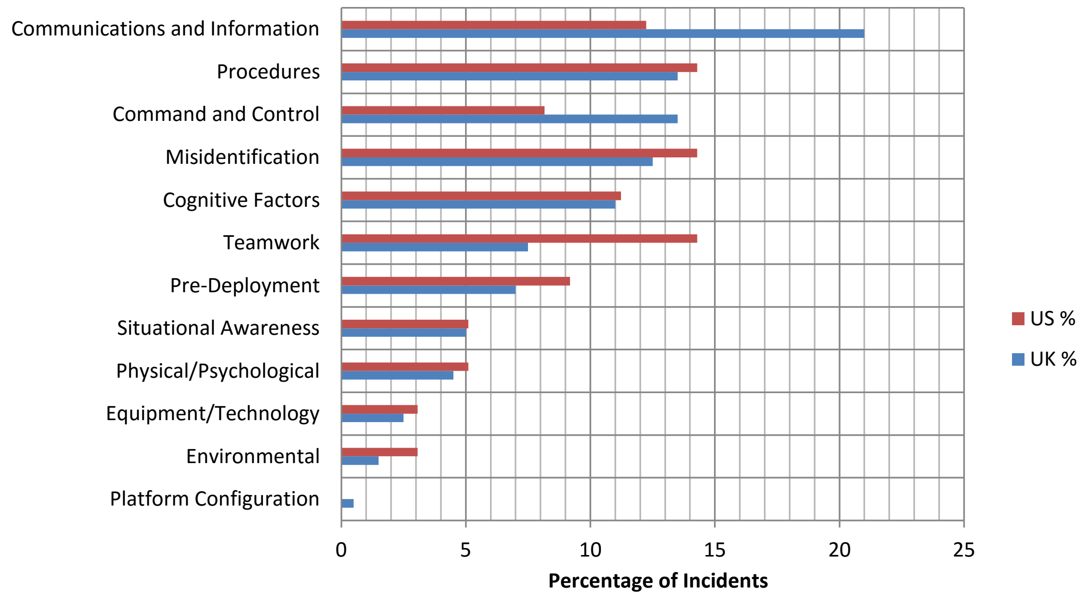

Figure 2.1: UK and US Causes of Fratricide

Whilst the above factors account for around 37% of errors, another error which can occur is the obtaining of an incorrect range from laser ranging equipment by improper use. This can happen when there is a slight misalignment between the sight and the target, and the laser energy reflects off an object closer to or further away from the FAC. A misalignment may not be apparent due to the fact that the laser spot on the target is often not visible in the view finder or other imaging equipment due to the difference between the waveband that the lasers operate in and the range of wavebands that make up the visible spectrum that a human can see. This means that the laser spot cannot always be visually verified to be in the correct place. If laser ranging is carried out incorrectly, and the target range is very short, there is a possibility that the target location could be so close to the FAC that he or she is in the Risk Estimated Distance (RED) of the weapon to be launched [19]. There is a need for techniques to remove risks from procedural, communication and information errors when using any weapon system, and although there has been some success, achieved through the digitisation of these elements, there is still more that can be done.

Within the scope of NEC is the need for a holistic approach to remote targeting and CAS that gives commanders more options when controlling key assets within a theatre of war. A Blue Force Tracker (BFT) is a system that uses GPS receivers and radio transmitters as part of equipment provided to vehicles and personnel so that a real-time situational picture can be seen by anyone with a receiving terminal. Friendly, neutral and known enemy locations are plotted on a real-time map displayed on a ruggedised laptop or console that is man portable or located within a larger platform. The term

BFT is given as the colour blue is the standard colour for friendly troops (red being hostile/enemy) in NATO countries [20]. The FBCB2 is one such a system developed by the US between 1995-2004 to increase Situational Awareness (SA) and real-time representation of the battlefield situation to commanders [21].

CAS missions and targeting are now at a stage where a FAC can fix the location of a target using GPS-equipped binoculars and range finding equipment. This target position can then be correlated with information on the network, for example the radar track of an identified hostile vehicle. The FAC can then locate an available CAS aircraft using a BFT system. The FAC can then contact the attack aircraft directly to request CAS. Upon confirmation of a task, the FAC can send a data packet containing the target and friendly force (own location) information directly to the aircraft's weapon computer – to be used by the Pilot or WO/Navigator – removing the risk for verbal communication misinterpretations and decreasing the time it takes for the information required to be transmitted.

One issue with this practice – and in general the overall practice of CAS missions – is the way in which they tie in with the overall tactical air picture. Militaries may provide CAS through a number of different aircraft types – each with their own levels of anti-surface capability. For example, Apache Helicopters are equipped with guns, rockets and Hellfire missiles for short range anti-personnel and anti-armour roles. When operating in Afghanistan their role was to provide 'top cover' to ground troops during missions [22]. Harrier (before their retirement) and Tornado attack aircraft were also operational in the same airspace and predominantly used for pre-planned air-strikes. However, Harriers and Tornados were both tasked to CAS missions at points in their deployment [23, 24]. In a complex and often cluttered airspace above any land battle there may be tens of operational aircraft from surveillance, re-fuelling, transport and attack roles. When a FAC orders a CAS air strike on a position, it will be of great importance that the assignment is appropriate and of measurable effects in accordance with Rules of Engagement (RoE), and that the tasking does not impact adversely upon other strategic requirements. The task allocation problem is still one that must be investigated so that a FAC or ground operator can optimise aircraft assignments, and more importantly specific weapon assignments, quickly in this complex dynamic environment.

In 2002, Northrop Grumman successfully engaged moving surface targets with the JSOW and two JDAMs using Link-16 Data Links as part of the Air Force Research Laboratory's Affordable Moving Surface Target Engagement (AMSTE) contract sponsored by the Defence Advanced Research Projects Agency (DARPA). The weapons were sent targeting updates from an airborne BAC 1-11 test bed aircraft [25]. The UK company QinetiQ then developed a capability to communicate with a weapon in-flight under the Integrated Sensor to Effect (ISE/S2E) program. The initial proof of concept was completed in December 2005 [26], with its first successful demonstration in 2007 [27]. In this demonstration, an Enhanced Paveway II (ePWII) GPS guided weapon was redirected in flight against a moving target. This demonstrated the ability to use an IDM to transmit targeting updates to a weapon in-flight. The US Navy demonstrated their first use of a NEW in use against a mobile maritime target [28] in late 2011. During the US Navy's test, the weapon (a JSOW C-1) was launched by an F/A-18 E/F and was able to receive in-flight target position updates via a Link-16 network from a third-party. In this case the third party was an on shore naval ground station who's data was relayed via aircraft. These weapon trials were proofs of concept for the transfer of control authority of a weapon system after launch to a remote location, and the foreseeable future of modern air launched weapons. The development of this capability now raises the question of how well a weapon can be controlled, or rather have its targeting information updated, by a remote operator and how to display this information in order to make best use of the weapon's full capability.

One method of visualising how a 'third-party' may control a NEW can be adapted from the widely used Launch Acceptability Region (LAR). LARs define the area in space from which a weapon may be released against a target [29–33]. These areas can be small or large, depending on both the position and flight conditions of the carrying aircraft as well as on the physical characteristics of the weapon, for example, whether it is powered or unpowered. Research into improving the working environment and user interfaces for WOs on-board B-1B bombers releasing the GPS guided Joint Direct Attack Munition (JDAM) was carried out by the US Air Force Engineering Directorate of Aeronautical Systems Center [34,35]. This research incorporated the use of static LAR overlaid onto a 2D map view of a set of targets. These static LARs were pre-calculated based upon mission requirements and uploaded to the aircraft's weapon computer before flight. The static LAR display was integrated into the weapon operator station as a decision aid for the WO to assign and launch weapons against the target set efficiently through being able to see and predict the scheduling of weapon launch events. It was greeted with strong enthusiasm by the participating flight crews [35] (pg.32).

The algorithms and data used to generate the LAR display for the B-1B WO terminal could be sent using NEC to a remote operator to process. This would allow the WO to do their job from a base of operations rather than in the aircraft, and allow the WO to be placed closer to the commander responsible for the mission he/she is carrying out [36]. In addition to a pre-calculated LAR, a Reachable Set (RS) could be provided to the WO. A RS is the area on the surface that is within the weapon's capability at that point in time given the release aircraft's current position and flight conditions [37]. The RS can be utilised far more than the LAR in the sense that an operator could use the information to assess whether a weapon can hit other targets from its point of release, rather than retrospectively looking for the correct drop point for a weapon to hit a single specific target. If the RS can be calculated in real-time based upon the current position, velocity and attitude of the aircraft, then it should be straightforward for a network enabled weapon to have its own RS, which could be generated and updated continuously in real-time and presented to a remote operator live.

Both LAR and RS are terms that are static and are concerned with the ability of the weapon whilst still being carried by an aircraft. Once the weapon is launched, a new term is needed to describe the ability of the weapon to hit alternative targets or to abort if the situation changes whilst it is en-route to the intended target. The term Re-task Acceptability Region will be used herein to define a RS that is calculated and updated in real-time whilst a weapon is in flight. It defines the area on the surface to which a NEW can be re-tasked to when in flight and still prosecute the target successfully. The aim is for this to be both generated and presented in real-time, with minimum latency.

A significant difference between the use of LARs by WOs on the B-1B compared to the use of RARs by remote weapons operators is the way in which the information presented changes dynamically over time. For the B-1B WOs the static LARs exist in a fixed position in space, and the B-1B aircraft must pass through these areas to satisfy release conditions for prosecuting particular targets. Dynamically the LARs remain the same, and it is the aircraft icon that moves through the top down 2D map scene. By contrast, the RAR changes dramatically over time, with several distinct phases. Generally these relate to the three phases of flight of air-to-surface guided weapons; Launch (or fly-out), Mid-Course/Cruise, and Terminal Intercept [38]. The launch phase is used to separate the weapon safely from the launch aircraft. In Mid-Course Guidance, the weapon attempts to use the minimal control necessary to cruise/glide towards the target and to shape the trajectory to improve the likelihood of engaging the target or improving the efficacy of the weapon. Finally, the Terminal Intercept phase is the final phase of flight when the weapon fixes its target and flies an intercept path. Figure 2.2 shows the normal phases of flight for an air-to-surface bomb, whilst Figure 2.3 shows the normal phases of flight for an air-to-surface missile that has been equipped with range extending wings. In this case the glide and cruise (mid) phases of flight are independent. Both Figures have an example RAR superimposed onto the ground plane, note that neither image is to scale.

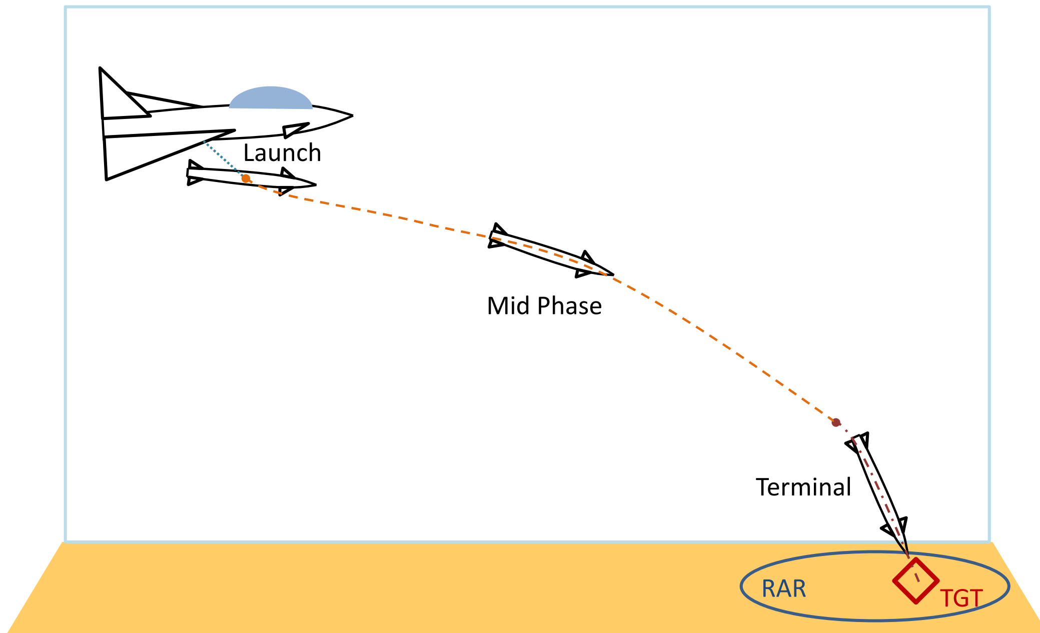

Figure 2.2: Phases of Flight for Air-to-Surface Bombs

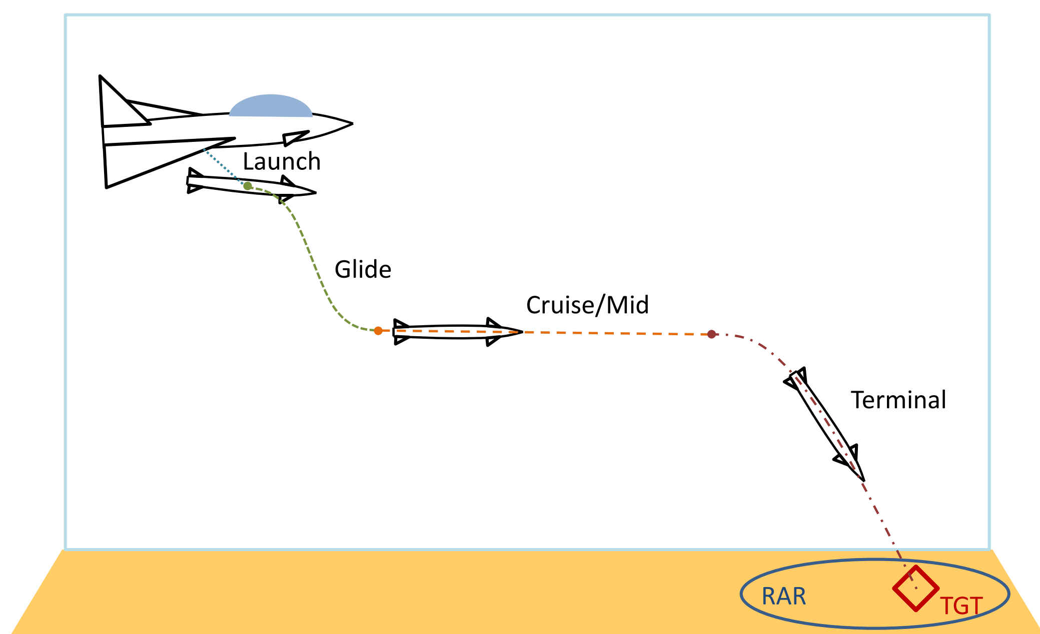

Figure 2.3: Phases of Flight for Air-to-Surface Missiles

In Launch or fly out, the RAR remains fairly constant in size and shape, as typically this phase of flight is only a matter of seconds. During the Mid-Course phase the RAR begins to reduce in size slowly and at a constant rate. Then, as the weapon approaches and enters the Terminal Phase of flight, the RAR starts to decrease significantly, collapsing in as the weapon falls closer to the surface. Weapons would not normally be re-tasked during their Terminal Phase because the weapon is locked on to the target and has very limited alternatives during the short time immediately before target intercept. Instead, it would be sensible to only consider re-tasking a weapon during the Mid-Course phase of flight. However, this is a novel situation which needs research into this cut-off point and sets of guidelines for system developers. These have not yet been fully explored or been documented in the public domain.

For an operator, who is in control of the weapon via NEC, the collapse of the RAR poses a problem. At what point does the weapon become committed to the target? Although the RAR decreases in size, it may be necessary to be able to re-task a weapon that has already been committed to a target in order to hit a more immediate-risk, a high-value target, or even to abort the attack. Two such scenarios exist where the RAR would be utilised to great effect. These are the re-tasking of weapons aimed at non-time-sensitive targets to emergent threats or for CAS tasks, or the use of re-tasking to manage the allocation of weapons aimed at targets in a scenario where weapons may be lost in flight due to enemy fire.

2.2.3 Rules of Engagement Considerations

RoE are the guidelines set out at a national command level which are used by all forces, to define when and in what manner force can be used justifiably against an enemy. The RoE in modern conflicts are a great deal stricter than in previous 'Total' wars such as World War II. The main differences arise from the role that the UK and Coalition forces are playing in current operations and the threats to our forces and nationals. Under the United Nations (UN) Charter and international law the use of force or threat of use of force are prohibited except for self defence or when authorised by the UN Security Council to maintain or restore international peace and security, such as the United Nations Operation in Somalia (UNOSOM I) 1992 [39, 40], which allowed a US led United Task Force (UNITAF) to operate in Somalia to enforce peace.

RoE during peacetime operations are based upon the principles and rights of self defence against an act of violence or the threat of violence. However, they change if there is "War" or "Armed Conflict". In war, it is customary that enemy forces have been declared to be hostile by national command. From this point on, the RoE are used to limit the methods of warfare allowed by placing restrictions on the weapons that can be used against different enemy unit types, as well as limiting the risk of collateral damage and risk to friendly forces. The RoE are used to ensure that the force applied is justified and that the minimum force necessary is used to achieve the desired effect on the battlefield.

For RoE to be satisfied when prosecuting targets there is a need for someone in the 'kill-chain' to have 'eyes on target' – verified through visuals of Electro-Optical sensors, and a calculation of the expected Battle Damage Estimates [41]. Given the capabilities that NEC provides, an operator could be located remotely from the real world environment in which an engagement may be happening. This is made possible by the wealth of information and high integrity communication channels available to assist them in making a firm judgement on the appropriate method of prosecuting a target, which will include the RoE in effect at that time for that particular operation.

Furthermore, there is a need for remote operators to have an up-to-date assessment of the significance of a target and the value of attacking it [11]. If there is a choice of methods, the commander should select those which minimise collateral damage and civilian casualties. The commander is entitled to take into account other factors such as stock levels, future demands, the timeliness of the attack and the risk to his own forces, however, there may be RoE which require a commander to accept a higher level of risk to his own forces in order to reduce or avoid collateral damage and civilian casualties.

2.2.4 Dynamic and High Fidelity Modelling of Network Enabled Capabilities

In order to successfully test the impact of NEC on the way in which air-to-surface target engagements can be managed remotely, the system itself needs to be simulated. This simulation needs to be real-time, realistic, and holistic in its approach so that the breadth of both technical and psychological challenges can be tackled. A variety of algorithms and simulations have been generated from within the Autonomous Systems and Big Data research group at the University of Liverpool's Department of Electrical Engineering & Electronics including the following: targeting systems [42, 43], sensors and imaging [44, 45], navigation via visual scene matching [46], feature recognition and tracking [47], weapon guidance [48], and task allocation algorithms [13, 49].

There are several different key areas of simulation that must be carried out to establish a test-bed for human factors testing. These are as follows:

- Weapon: Six Degrees of Freedom Simulation
- Weapon: Launch System Interface Simulation
- Network Protocol & Communications Infrastructure

- Remote Operator Station
- Distributed Interactive Simulation Networking
- Target Simulation

These elements can be considered parts of an overall holistic simulation environment. Chapter 3 covers the methods of simulation in more detail.

2.3 The Human Side of Complex Systems

Given the new features that NEC and NEW provide the military, the Human Factors issues that surround the use of future remote operator systems must be investigated to ensure that any interface system developed is fit for purpose. Whilst studies in Human Factors for network enabled systems may be conducted by manufacturers and other defence organisations, it is also important for the academic community to engage with this topic. Such engagement allows advances from academic research to be fed into the design and development of new military systems. Known methodologies from related human factors research can be applied to existing or future military systems such that improvements can be made, from increasing the SA of the operator, to expanding their potential job role through effective ecological interface design – a framework used to avoid interfaces contributing to the difficulty of a task [50]. Relevant information in this research area should be visible to and comprehensible by the general public to avoid misinformation being propagated in the absence of valid research. From the coverage of recent conflicts in the Western media, it is clear that confidence in remotely controlled military operations is at a low ebb [51], and although a recent YouGov poll suggests that the public are becoming more accepting of Unmanned Aerial Vehicle (UAV) for civilian use in principle, opinion is still divided as to the foreign policy determining their use by the military [52]. More openness and clarity can be found through collaborative academic-military research.

Historically, the responsibility for a weapon fell with the person who fired it. However, the capabilities provided by NEC allow for the handover of control authority to a third party. The person that fires the weapon is responsible for it when it is fired, but then has to transfer responsibility to a remote operator. At all points in time someone has control authority of the weapon (on the weapon pylon and in the air) and someone has eyes on target. The effect of NEC is that where these roles were once managed by a single crew on an aircraft, they can now be distributed and/or transferred off platform. Responsibility is monitored, recorded and assessed such that the chain of accountability can be traced. This is all too important for systems such as the MBDA Fire Shadow – a loitering munition that remains circling above a battlefield for a number of hours until needed [5]. However, the Loitering Munition element of the UK MoD's Complex Weapon program has not conducted a capability demonstration in Afghanistan 'due to system maturity' [53] (pg. 17).

For any remote operator terminal system there needs to be a robust networking protocol and a usable interface to provide decision making cues to an operator. There are several areas to draw knowledge from regarding how best to present re-tasking information to an operator. Once such area is the research into Decision Support Systems (DSS). These are systems that facilitate human decision making when information may be difficult to process in its raw form – or needs to be relayed through electronic communication channels before being reconstituted on a display. The following sections introduce the areas of psychology that must be considered when developing the necessary human computer interfaces to support decision making when using NEC systems.

2.3.1 Situational Awareness and Decision Making

NEC is primarily concerned with effecting major improvements in the military through increasing the amount of information available to commanders and operators of remote systems, and providing them new capabilities using new network connections. However, having large amounts of information, or data, does not necessarily translate into having good SA or improving the decision making of personnel. SA is defined in three levels as: "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [54]. The three levels of SA are split therefore as follows [55]:

- SA Level 1: Perception – The perception of cues and elements in the current situation.
- SA Level 2: Comprehension – The integration of multiple pieces of information and a determination of their relevance to the person's goals.
- SA Level 3: Projection – The ability to forecast future situation evens and dynamics.

These three levels increase from basic **perception** of the situation – seeing that there is a blip marked on a radar screen, to **comprehension** – that blip is an enemy aircraft, to **projection** – the positioning and path of the enemy aircraft indicates it is probably going to attack. What SA provides therefore is a basis upon which an individual can make a decision.

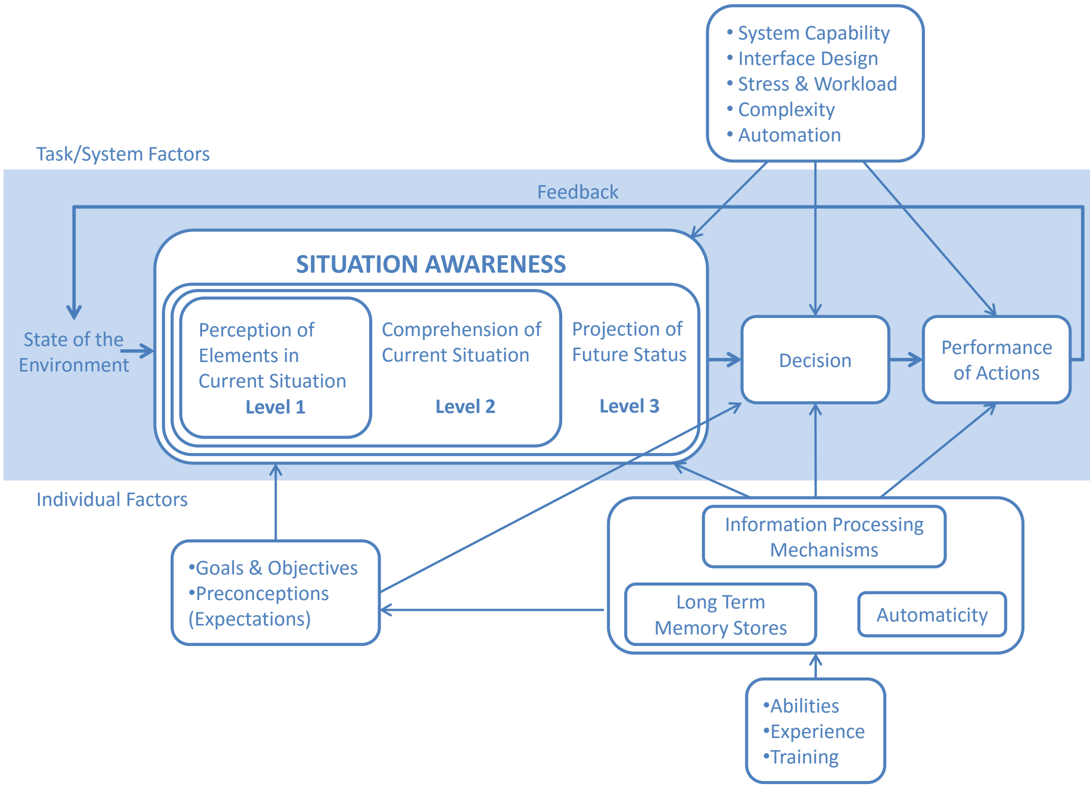

Figure 2.4: Model of SA in Dynamic Decision Making

Figure 2.4 shows Endsley's SA model in Dynamic Decision Making [56]. It includes in the centre, the model of SA, including decision making. It also expands into Task/System factors and Individual factors relating to SA. Of the Task/System factors, issues such as interface design and stress/workload are identified. Further, Endsley states "The highlighted emphasis on SA in current system design has occurred because (a) we can now do more to help provide good SA through decision aids and system interfaces, and (b) we are far more able to actually hinder SA through these same efforts if, as designers, we fail in adequately addressing the SA needs of the operator." [55] (pg. 6).

SA is built up by an individual processing information from a number of different sources. Endsley presents a model for these different sources in Figure 2.5 [57]. Information cues are interpreted through senses but are based upon either direct observation, indirect observation through a system interface, or from SA attained by others and communicated to the individual (for example rally drivers using cues from their co-driver). Endsley's models [54–58] are typically applied to pilots of aircraft, however, they are still relevant for many complex systems that require information from many sensors to be interpreted by an operator.

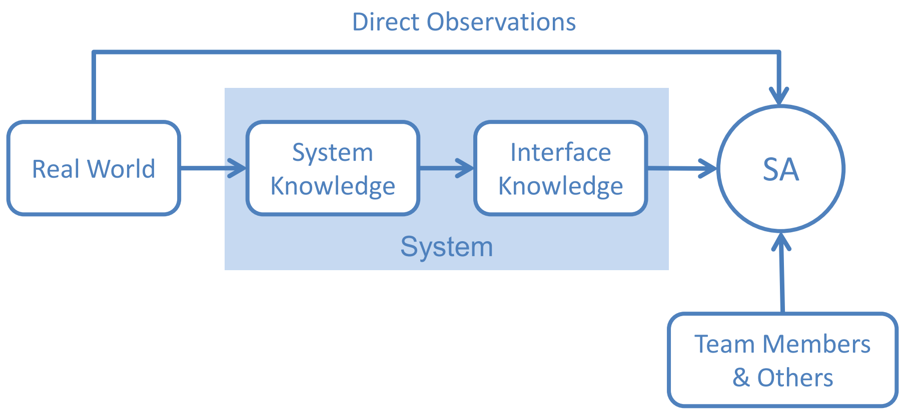

Figure 2.5: Sources of SA Information

The move towards remote systems – particularly with regard to NEW – involves the removal of the operator from the direct environment in which the actions of entities are taking place. Lots of subtle cues exist in the real world environment that are lost through remoteness and the effects of these are yet to be fully rationalised. In the environment where remote operators of NEWs will carry out their jobs, the user interface will be burdened with providing operators almost all of their environmental cues to facilitate operators' ability to build SA. It is therefore imperative that SA design principles are taken into consideration when investigating the user interface.

Endsley published a set of thirteen SA design principles as part of her work on the Situational Awareness Global Assessment Technique (SAGAT) [54, 58]. The six main principles that are salient to the research and investigations developed in this thesis are:

- Minimise divided attention requirements, information should be grouped in terms of spatial proximity and multiple pieces of information embedded within objects. Attention shifts should be minimised and the number of display sources reduced (Req. 1).
- Information grouping should be used to attach multiple attributes to each object, whilst minimising the total number of objects shown. "The entire display should be viewable in a single glance" and pictorial coding of information used where possible (Req. 2).

- It is unnecessary to display systems functioning normally and instead only deviations from normal system states should be presented when they occur (Req. 5).

- Information that contains information about trends or rates, or that allows the trends or rates to be determined should be available (Req. 6).

- "The most important information should be the most salient perceptually to insure focussed attention after pre-attentive processing" (Req. 7).

- "Verbal information requirements on short term memory should be minimised, particularly for spatial information" (Req. 9).

Memory in its entirety is used in a variety of ways when relating to SA and the process of decision making. There are currently three widely accepted forms of memory:

- Long-Term Memory is the store of knowledge and experiences that have been acquired by a person over their lifetimes [59].

- Short-Term Memory is the part that "can hold a limited amount of information in a very accessible state temporarily" [59].

- Working Memory is a multi component system that holds and manipulates information in Short-Term Memory; it is used to plan and carry out behaviour [59,60]. It is also described as the attention-related aspect of Short-Term Memory [61].

The attention of individuals (and thus working memory) must be drawn to important elements displayed on interfaces to maintain SA. A study by Jones and Endsley found that failure to attend to information that was available to individuals was the most frequent factor associated with errors in SA despite the research being carried out on fully trained and experienced aviators [62].

Where long term memory impacts on SA is when additional SA is gained through applying previous experiences to a current situation. Typically these experiences will enhance the third level of SA - Projection. Experienced individuals apply pattern matching to the information they are presented to form a mental model of the current situation and then use this to guide their decision making. The Recognition Primed Decision model describes this process in depth – and discusses the benefits and misgivings of this experience based decision making [63]. The use of previous experience to enhance SA and make decisions reduces the cognitive load on Working Memory capacity of individuals as they do not rely on Working Memory to evaluate and compare multiple options before making a decision. However, this approach has risks as the decision making process can be biased and the interpretation of important information presented may be disregarded in order to maintain the current schema (mental model) being applied to the situation resulting in errors in SA [64]. Poor application of mental models to situations was found to represent 18% of SA errors in Jones and Endsley's study [62].

However, it has been found that experienced decision makers using mental models generally outperform novices when making decisions in time critical, high stake situations [65]. It has also been shown that in these high stake, time-limited scenarios, where there are few quantitative cues, that experienced decision makers rely on heuristic, simple problem solving strategies [66–70]. These mental models applied by experts are often useful in practice. Nonetheless, novices can still provide useful insight when carrying out principle testing of DSS usability. The use of novices mitigates against the potential of unknown mental models being applied to the task – which is beyond the scope of the research presented herein.

Decision making cannot be duly covered without mention of Boyd's Observe Orient Decide Act (OODA) loop [71]. The loop, shown in Figure 2.6, is a decision cycle posited in four main levels. Observe, Orient, Decide and Act. Decision making is argued to occur in this cycle whether in military uses or in other areas such as business. It is argued that the speed at which this process can be repeated indicates the individual's ability to make effective decisions. The OODA loop relates to the studies presented herein in that individuals must be able to process information quickly and then act on the information. Network Enabled Weapon interface systems must allow for quick acquisition of the information available to assist in decision making.

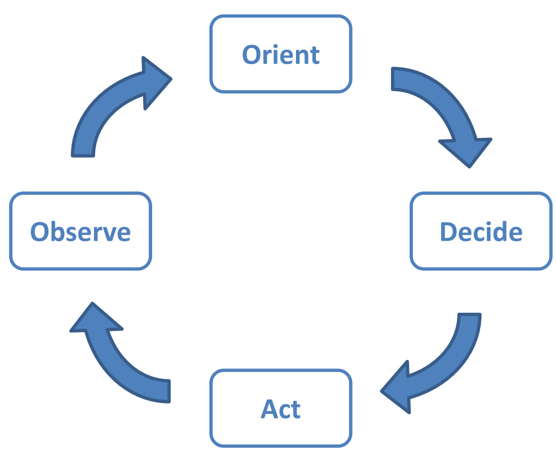

Figure 2.6: Boyd's OODA Loop

The problem that designers face is the disconnect between data and information. The information that is needed in order to support effective decision making may not, and often does not, correspond directly to the data that is produced. Data must be sorted and processed by the human to find and integrate the information needed for good SA before making an effective decision. More data, does not mean more information, nor does it mean good SA or a better Decision Making process [55]. Therefore it is of great importance to establish the benefit of different methods of displaying data and information so that decision making is facilitated rather than hindered.

2.3.2 Graphical vs. Numerical Display Format

The study of graphical vs. numerical displays for DSS is a well covered area of Human Factors research that stems from perceptual based reasoning and the ecological approach to visual perception and interface design [72, 73]. However, little of this research has been applied to the area of Network Enabled Weapon systems outside of the security-limited commercial world of the defence industry. This thesis aims to bridge this gap.

It is widely accepted that there are two main types of information processing that occur within the brain, Analytical and Perceptual processing.

- Analytical processing: "focussing on a salient object independently of its context" (page 467) [74]
- Perceptual processing: "attending to the relationship between the object and the context in which the object is located" (page 467) [74]

Unsurprisingly, it has been shown that spatial or geo-spatial information is associated with perceptual processing and that specific data extraction, or obtaining direct values, are associated with analytical processing [75]. The Theory of Cognitive Fit suggests that to achieve effective and efficient decision making, the DSS format should 'fit' (i.e. match) the context of the task [75]. Failure to do so will increase the level of cognitive effort required to respond and complete the task and lower the accuracy of decision making. Therefore, for spatial tasks, graphs are more useful than tables in facilitating timely decision making, but do not improve decision accuracy. Similarly for symbolic tasks, tables/symbolic representations outperform graphical representations in decision making speed, but both have equivalent performance in accuracy [75].

As with all developing theories, there have been some opposing findings within the Theory of Cognitive Fit as to which display method induces better performance from participants. Speier [76] showed that increased decision accuracy and faster decision making can be achieved using spatial representation for all tasks, except those that were complex-symbolic tasks (those tasks which require participants to establish the relationships between words). In the complex-symbolic tasks both graph and table representation drew similar decision making times from participants. Cao [77] found that cognitive load is reduced when using image/graphical presentation for a geo-spatial resource allocation task. It has also been found that for dynamic situations, decision making performance in terms of reaction time and accuracy between graphical and numerical representation was similar, with only a difference in attention levels [78]. In Gonzalez & Golenbock [78] participants were tasked to distribute water amongst tanks using a simulated water purification plant control terminal. By measuring eye movement it was determined that throughout the trials participants attention within the graphical condition remained constant over time, whereas participants in the numerical condition had increased attention in the same period. This suggests that more effort is required when the information representation is numeric. Studies have shown that there is a solid link between attention and effort, and that spare capacity – the indication of the amount of effort being exerted by a subject [79] – can be inferred from the level of attention given to a task [80–85].

More recently, individual differences have been quantified when using different display methods to communicate heath risk and treatment risk to patients [86]. They found that graphical literacy (one's ability to interpret data represented graphically) was a good indicator of an individual's ability to interpret graphical and numerical forms of data. High graphical literacy translates to higher performance when using graphical displays and low performance when using numerical displays. The opposite is found of those with low graphical literacy. However, numeric literacy (one's ability to understand and use mathematics) only affected participants' ability to use numerical displays and has no effect on ability to use graphical displays.

Weapon re-tasking is a geo-spatial task, i.e. the operator is in control of an object located within physical space. Further, the RAR is a conceptual boundary to the capability of the weapon system that also exists in a physical space. Therefore, according to the Theory of Cognitive Fit, the design of a DSS to be used for aiding re-tasking decisions should represent key information graphically, rather than numerically, to aid quicker decision making from participants. Further, it should be expected that decision accuracy would be similar with either representation. These theories provided are interesting for the purpose of guiding initial development into the displays to be used. It has been already highlighted that there are still differences in opinion as to how to best represent types of information across the board, therefore investigation into how this applies to the direct context of Re-tasking for Network Enabled Weapon systems is needed.

2.3.3 Decision Priming and Approach-Avoid Conditions

Another influential role of individual performance at tasks is the priming a participant receives in the lead-up to an experiment. Priming is when an exposure to an object, event or condition then influences the response to another object, event or condition. Early research into priming found implications that words are more quickly recognised when following associated words [87]. This type of priming has been expanded into the area of approach-avoid motivations. Humans, as organisms, will approach favourable conditions and avoid those that might be dangerous or disadvantageous [88].

The conditioning of participants to what is an advantageous outcome is a construct that needs to be explicitly stated to an individual. This is particularly important for participants in a trial using a new or modified form of abstract interface such as a DSS. Without cause or justification an individual will not be motivated to take any actions. Further, using pre-emptive force (in a military scenario) as a positive motivator may be difficult based upon the implications of what using force might involve (pain, stress, fear). Negative stimuli can be used to invoke an approach condition to solve a goal, for example lashing out in defence. However, a behavioural inhibition system is known to generate the emotion of anxiety when seeking to resolve such cases and it is therefore favourable to set goals in a positive context [89,90]. When using a DSS, operators may have no feelings of approach/avoidance based upon the stimuli presented (graphical objects on a sterile screen, remote from any danger) without being provided a clear and distinct goal. It is hence necessary to establish such a goal for participants to complete by presenting them with a proposition: "[Goal] in order to [underlying reason]" [91,92].

Moreover, with the potential for numerous types of scenarios that might occur in the environment, the goal proposition must be holistic so that all possible scenarios are accounted for. Care must be taken when stating the goal in the form of an avoidance motivation. Avoidance motivation is used as the main reason for some activities. For Example, Air Traffic Control (ATC) is associated with monitoring negative possibilities (collisions) and acting to avoid them. This is known to be draining for controllers [93,94], who as a result have very strict work patterns with increased breaks at specific times to alleviate stress. It is therefore important to provide a clear goal and use it as an approach motivation, rather than an avoid motivation, to invoke the participant to perform actions 'correctly' based upon stimuli presented to them.

In the trials presented in this thesis, the participants were prompted to perform the task through developing a scenario context of providing CAS to friendly troops in the first trial (Chapter 5) and then in a Suppression of Enemy Air Defence (SEAD) scenario to remove the threat of friendly transport aircraft being shot down by enemy SAM sites (Chapter 6). In both trials the participants were also told that accuracy and speed were being measured to encourage their motivation to perform well.

2.3.4 Applications for Decision Support Systems

DSS are widely used for a range of purposes. One of the more investigated areas of the use of DSS is in aviation, where cockpit displays for instruments and ATC systems are continuously investigated to help increase SA and support decision making. This may be due to the problem of 'Pilot Error' that still exists within aviation despite the increase in DSS technology. In the decade from 2000-2010 57% of fatal air accidents were caused by Pilot Error [95]. Other areas that are heavily reliant on DSS are Space, ATC and Military Systems. This section will highlight relevant studies into DSS.

Chua's [96] work on Landing Point Designation (LPD) is similar to re-tasking a weapon in flight. In LPD, pilots use an interface with graphical overlays to safely designate a landing point for a lunar module moving towards the lunar surface, within a time-limited decision window. A fuel contour is overlaid onto a map of the lunar surface and used to bound the edge of the landing zone. Its secondary purpose is to imply fuel usage through proximity of the landing point to the centre of the fuel contour, with points further away from the centre incurring extra fuel usage.

Rather than comparing graphical vs. numerical displays, Chua's [96] work is focussed on automation and the differences between human participants (experienced pilots) and an automated LPD algorithm. It was found that pilots only performed better than, or equal to, the automated LPD algorithm in 18% of cases based on the scoring system used. The scoring system took into account fuel consumption, proximity to a designated Point of Interest (PoI) and the safety rating of the landing site chosen. Pilots incurred a heavy cost associated with the fuel wasted during the time it took them to make a decision. Pilots took from 12-28 seconds to process the information available and make their decisions. However, pilots performed better in terms of the safety of the landing site selected and closeness of the landing point to the desired PoI on the lunar surface than the automated process [97]. Moreover, the automated process carried no fuel cost penalty due to the near instantaneous computation of a LPD.

Clearly, in the above case, pilots prioritised the safety of the lander over the cost of fuel, whilst the automated process weighed each of the three factors equally and thus was not capable of making the same judgement. The model used for automation and the behaviour of human operators was not the same and therefore cannot be directly compared. It could be argued, therefore, that pilot performance is better than the automated system when the fuel cost is removed and the proximity and safety of the lander are prioritised such that their weighting is significantly higher than that of fuel. This is indicative of the behaviour summarised by Weiner & Curry [98] when discussing automation of aircraft flight decks. Pilots have the ability to be creative and adapt when given a task to solve. Weiner & Curry [98] also discuss the role automation plays in pilot engagement with their tasks. Too much automation causes pilots to be disengaged and bored, whereas too little causes pilots to be overworked [99]. The investigation of Human Factors issues with regard to the complex area of NEW is therefore vital if interface designs are to be utilised in a way that allows for operators to adapt to novel situations and facilitate confident decision making. Automated processes that do not match an operator's method of devising a solution to a complex problem can be both confusing and cause disengagement. Therefore, any automation process should be properly scoped, with high levels of input from subject matter experts, before being included in a DSS. Taking note that human oversight is always needed and that an operator should understand how the automated process is making its decisions.

Another cause of overworked operators is providing them with too many options to choose between when making a decision [100]. Cummings carried out a number of research trials investigating possible interfaces for use with the Tomahawk Land Attack Missile (TLAM) [36]. These investigations sought to find operator capacity limits on the re-tasking of TLAMs in a naval context. One study investigated the maximum number of TLAMs that could be simultaneously controlled by an operator. It found that the maximum limit on the number of entities that can be supervised by an operator was 12 [36]. Three difficulty levels were investigated – 8, 12 and 16 simultaneous missiles. When supervising 16 TLAMs there was significant degradation in three separate performance metrics; Decision Time, Accuracy of Decision and Percentage Busy Time (workload measurement).

Similar capacity limits were observed amongst ATC staff who were capable of handling 10 aircraft, but when that number increased to 17, the operators were unable to perform their tasks accurately [101]. Objective and subjective workload measures were taken (Pupil Diameter and Rating Scale for Mental Effort [102]) as they are suitably sensitive and reliable in simulated ATC tasks [103] as well as direct performance measures of the ability of controllers to accurately predict conflicts in the scenes.

Both studies state the reason for the drop off in performance is the lack of sufficient cognitive workload capacity of the participants. Operator workload capacity is the finite limit of the number of mental actions or tasks that can be achieved in a given time frame. If there is too much information presented, or too many tasks to be completed within a given time frame, the operators' workload capacity can be exceeded and the operator may become either ineffective by way of partial task completion, or become so overwhelmed that they cannot carry out any of the remaining tasks. With operator workload capacity in mind, it has been found that 70% utilisation (percentage busy time) is a good indicator of the maximum utilisation achievable in a system before seeing a drop off in operator performance [36].

The number of TLAMs being supervised by one operator in Cummings [36] is facilitated through the use of a decision matrix which matches weapons with appropriate tasks, and makes it clear to operators which assignments are possible with the weapons available [104]. Essentially the interface system presents the operator with clear instructions on procedure that bounds their decision making process. Further, the time-scales for their decision making is the minutes range rather than seconds. This is clearly different from the re-tasking scenarios proposed in this thesis – where decisions need to be made in very short time periods.

In the ATC task [101], aircraft were already established on predefined flight paths and controllers were only instructed to intervene to prevent collision. It would be far more interesting to see investigations into the maximum number of aircraft that can be handled during approach control at a busy airport. This role requires more direct control of aircraft heading and speed to manage their safe landing at airports.

When automation is reduced, and more direct control is required such as physical use of a flight control stick, it has been found that the maximum number of simultaneously controlled objects falls to four [105]. Clearly the level of autonomy within the system also influences the drop off point of performance and SA. Further, if the tandem between automation and the DSS is designed effectively, operator limits could in theory be increased.

Ruff further hypothesised three key levels of autonomy in remotely operated systems [105]; Manual (non-autonomous), Management-by-consent, and Management-by-exception [106]. Management-by-consent is used to describe a system that does not carry out its next task until the operator gives express permission. Conversely, Management-by-exception describes a system that acts independently but can be overridden at any point by the operator. An important finding by Ruff [105] was the inherent trade-off between workload and trust in the system when dealing with autonomous systems. Manual control of several UAVs increases workload but also increases the operators' trust in the system. Conversely, whilst Management-by-exception lowers the operator workload it also lowers the operators' trust in the system – almost to a level half that of when in full control of the UAVs. This would suggest that Management-by-exception autonomy does not provide operators with sufficient trust in the system, and given the potentially catastrophic consequences of failure, it should be avoided. For example, should a management-by-exception system decide to prosecute a target – which could ultimately result in death – and an operator misses the cue to opt out, rather than opt in, the decision has effectively been removed from the operator. Management-by-consent, however, provides a safety barrier of inaction, rather than action, should an operator miss a cue or need more time for deliberation.

It has been found that for time limited decisions, increasing the time allowed for decision making does not increase performance, and participants will often attempt more complex solutions, resulting in them failing to complete the task [107]. Chua [70] confirmed this finding in analysis of participant data from the LPD task. Across the pilot group, those who took significantly longer to complete the LPD task achieved worse scores than those who made their decisions quickly. Deliberating on an action can be costly. For DSS that are designed for use in time pressured weapon re-tasking scenarios, it is important to impart on the operator the time pressure that exists due to the often short duration and inevitability of air-to-surface weapon flights.

The TLAM and ATC scenarios, whilst similar in subject matter, resemble little in relation to the procedures likely to be used by military operators when coordinating dynamic and real-time reconnaissance or targeting missions. The TLAM scenarios used in the Cummings study only tested one aspect of an operator's role – the decision of which of the missiles should hit a specific set of non-time-sensitive targets. Hence this study could represent an underestimation of an operator's workload when faced with the need to make a snap decision on emerging threats.

2.4 Summary

The position of this body of work within the wider literature has been discussed, and the areas where information has been drawn highlighted. The remaining chapters of this thesis will include further exploration of the literature with specific relation to weapon system and network simulations, as well as more detail on the design of user interfaces and the experimental methodologies used when conducting participant trials.

The main takeaways from this chapter are that in principle re-tasking air-to-surface weapons is achievable within industry. This raises problematic questions as to how this capability might be integrated into some coherent role for an operator. The networking infrastructure is to be discussed in detail in Chapter 3, but the issue surrounding how such a capability might be developed with regard to a human operator has been discussed here.

If Re-tasking Network Enabled Weapons is to be achieved, there are a number of psychological issues that must be addressed. Firstly, an interface must provide a high level of SA to a physically remote operator of a complex system. The interfaces should facilitate good decision making by reflecting the decision making processes that operators will use when performing their tasks. This can be achieved by applying the theory of cognitive fit during the design stage. Moreover, caution should be taken when enhancing either SA or decision making through the use of automation to avoid disengagement and confusion of participants when automation either takes over too many tasks, or performs tasks in an unintelligible way.

Chapter 3

Simulation Facility Development

NEC provides operators with a new way in which to interact and control remote weapon systems. One of the main areas is re-tasking weapons to different targets once launched. A representative simulation of both the DSS that aid an operators decision making, and the objects that may appear in test scenarios are needed for meaningful participant trials. There are several independent systems that will make up a complete system of systems that can then be tailored to fit the specific aims of the automated task allocation solution and the two participant studies discussed later in this thesis.

The decisions made by operators in air-to-surface re-tasking scenarios require knowledge of the weapon system in flight and its behaviour in different phases of flight. As air-to-surface weapons are widely varied in role and capability, a mission requirement must be developed which will require a dedicated weapon type. Once this mission requirement is fully realised, a simulation of the required weapon can then be modelled and used in a trial. The development of two weapon systems and the necessary targets will be discussed.

For the Remote Operator System to represent information from the simulation, data messages must be relayed from the simulation to the operator terminal, which may be operating on separate Personal Computer (PC)s in a distributed facility. Similarly, in order for an operator to re-task a weapon remotely, command intent must be logged by the remote operator system and then transmitted to the weapon system. The development of a simulated communication channel between the two independent systems will be discussed.

Lastly, different simulated entities such as release aircraft, weapons, and targets must all be present in the same simulated interactive environment. The development of a bespoke shared simulation environment will be discussed.

3.1 Simulation Models

Modern computing provides many useful resources and capabilities for engineers. One such capability is simulation – the ability to replicate a real world object or process in the digital environment. Simulation can be used for a number of reasons, from prototype testing – where it may take too long or be too costly to manufacture a real object, to training – where the systems developed are detailed enough to allow personnel to be trained with simulations before using the system in the real world.

Simulations require different levels of fidelity dependent on the requirements of the system being modelled. Fidelity is a term used to describe the level of detail used in the simulation formula, and the quality of the visualisation environment and other sensory stimulation presented to a user – particularly audio, tactile and motion simulation. The main levels of simulation are termed High-Fidelity, Medium-Fidelity and Low-Fidelity. A High-Fidelity model may represent a large number of degrees of freedom, where a Medium-Fidelity model may only model a few, and a Low-Fidelity model may only represent the object as a point mass. The simulation formula is based upon basic equations of motion, which are then adapted to include specific properties of the object or system that is to be simulated. The time step is a term used to describe the length of time that elapses for each loop around a simulation. For example, a simulation of a simple point mass object might have a 1 dimensional velocity of 5 metres per second, and a time step of one second. This means that for each time step, the point mass object will move 5 metres. If the time step were only 0.1 second, each time step the point mass would move 0.5 metres. The term resolution can be used when referencing the time step of the model. A fine resolution may be a high frequency of around 200Hz – a time step of 0.005 seconds, and a low resolution may be a low frequency of 1Hz.

There are two main areas in which simulation was necessary for the research to be conducted in this thesis. These are Weapon Systems and Target Systems. The weapon systems are bombs and missiles that are used to prosecute targets, and the targets are objects of significance that need to be destroyed.

3.1.1 Weapon Systems

This section will detail the development of two Six Degrees of Freedom (6DoF) air-to-surface weapon system simulations for the two participant trials. A low fidelity surface-to-air missile model will also be discussed.

3.1.1.1 Types of Weapons

There are four main types of weapons that can be used to effect damage on ground targets; these are guns, rockets, bombs and missiles. Guns and rockets are unguided, bombs can be either unguided or guided, and missiles are guided systems. The different weapon types are used for different effects that match the types of targets being prosecuted. These effects are generated by the different warheads on the weapon. Conventional types of warhead include Blast – detonation produces a strong shock wave, Fragmentation – detonation causes metal fragments to be projected at high velocity, Shaped Charge – the explosive charge is shaped to focus energy and project a hypervelocity jet of metal that perforates heavy armour, or High Energy (Kinetic) Penetrator – there is no explosive charge but the kinetic energy is high enough to cause damage localised to the impact area. Table 3.1 shows a list of typical warheads and their target types (reproduced from Rigby [108] pg. 8).

Table 3.1: List of Typical Warhead for Target Type

	Warhead Type		
Target Type	Blast/frag	Shaped charge	HE penetrator
Troops	X		
Block wall buildings	X		X
Hardened buildings			X
Soft-skinned vehicles	X		
Missile launchers	X		
Armoured vehicles		X	
Aircraft	X		
Radar installations	X		
Ships			X
Airfields			X

Further, the stand-off range and the mobility of the target dictates the type of weapon and guidance that needs to be used. Stand-off ranges on air-to-surface weapons relate to the maximum range that a weapon can be launched at a target. This is crucial when needing to avoid enemy air defences, and so weapons have been developed that incorporate lifting wing surfaces, and motors, to extend their range. The expected target motion contributes to what type of guidance capability is required. If the target is highly mobile and dynamic, such as a road vehicle, then lateral accelerations might be needed from the weapon to intercept the target. If the target is static, such as a building or fortification, then reduced lateral acceleration will be needed, and unguided free fall bombs could be used instead of complex guided missiles.

The scope of this thesis is to determine the ability for human operators to extend the capability of re-tasking weapons in flight by using NEC and Tactical Data Link (TDL)s between operator stations and the weapons themselves. A guided short-range free fall bomb and a long range guided missile were chosen as candidates for the testing of operator ability to re-task weapons in flight. These two types of air-to-surface weapon are greatly different in guidance method and range. A re-tasking system for each application (weapon system) must be developed and tested before commenting on the applicability of re-tasking scenarios for each weapon type. Before a system can be developed, information on how the weapon systems behave during flight is vital. As this information for specific weapon systems is highly classified it was necessary to develop generic models to represent these systems.

3.1.1.2 Generic Airframe/Bomb/Missile Simulation

As mentioned previously, the motion of a point mass can be described with simple equations. First the object must have a set of properties or states that tell us information about the behaviour of the object. In a three dimensional coordinate system such as North East Down (NED) the states may be position and velocity. This system has only three degrees of freedom, i.e. the model handles only translational motion in three axes. However, aerodynamic bodies such as aircraft, bombs, rockets or missiles require further degrees of freedom to account for the orientation of the object. This is because aerodynamic bodies are affected by the direction of travel through air, and can affect motion (either translation or rotation) by changing the shape and orientation of its aerodynamic surfaces.

The number of degrees of freedom that a simulation model of a rigid body airframe requires is based upon the requirements set out by the designer. For simple planar engagements, three degrees of freedom can be modelled, for example, translation in two axes and a single rotation [109]. However, for three dimensional simulation there are three translational axes and hence three rotational degrees of freedom, more commonly known as a 6DoF model [110].

A generic airframe has three axes in which both translation and rotation can occur. These axes are as shown in figure 3.1; the longitudinal axis runs through the nose to tail of the airframe (front to back). The lateral axis runs through the wing tips, perpendicular to the longitudinal axis and parallel to the horizon (when not banked). The normal/vertical axis is perpendicular to both other axes. Rotation about these axes are, Roll – rotation around the longitudinal axis, Pitch – rotation around the lateral axis, and Yaw – rotation around the normal/vertical axis. The origin of the three axes is located at the airframe's centre of gravity.

Orientation allows for the object to be given an attitude in a three-dimensional environment, but a common set of coordinates are needed to position it. Due to the earth being spherical, the Latitude, Longitude, Altitude (LLA) system allows for a position to be identified relative to the earth. However, often in simulation environments, the small distances travelled allow for a Cartesian coordinate system to be used such as NED. In the NED system the three axes (x, y, z) are aligned with the North direction, East direction and Down direction as shown in figure 3.2.

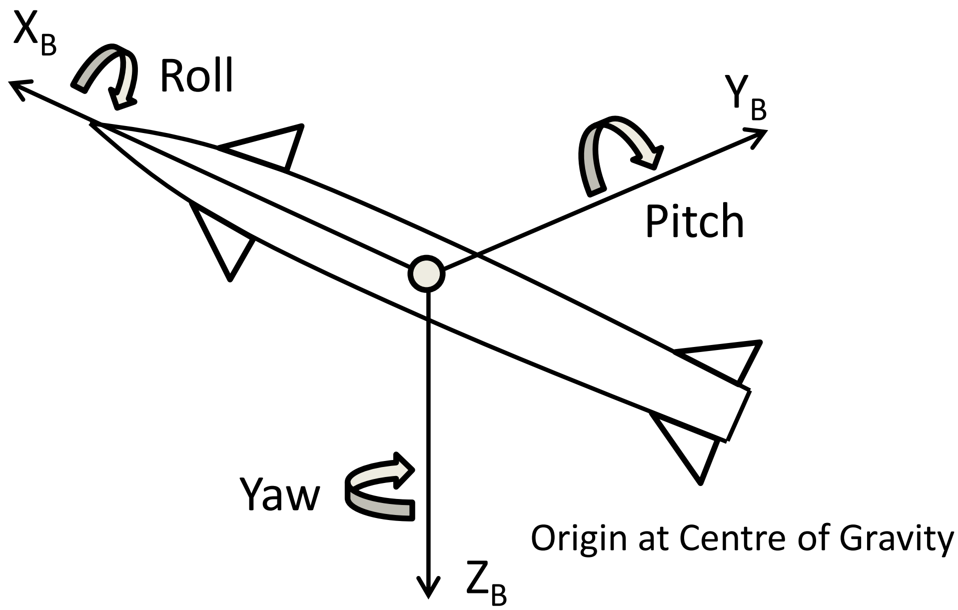

Figure 3.1: Translational and Rotational Degrees of Freedom of a Generic Airframe

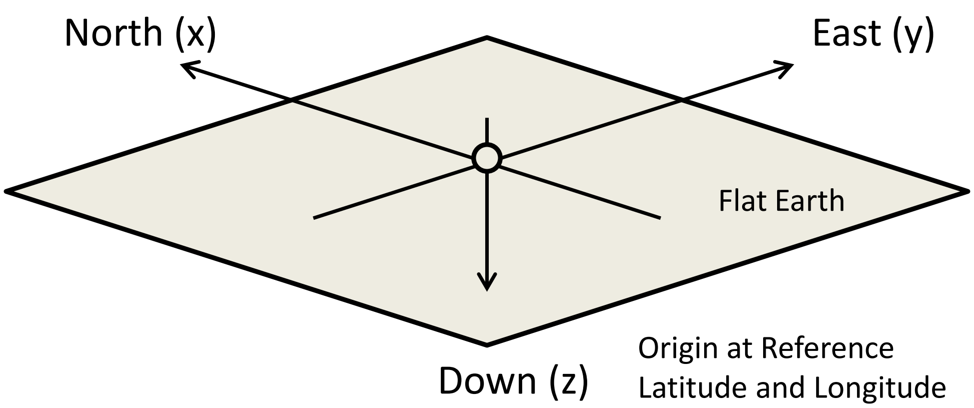

Figure 3.2: North East Down Coordinate Reference System

A general set of equations can be used to represent a 6DoF model of an airframe/ bomb/missile for the purpose of simulation. These equations are standardised in a number of technical documents from the US's NASA Ames Research Centre [111] to the Australian DSTO [110]. A brief overview of the simulation equation set will be discussed, in reference to figure 3.3 – a flow diagram of the 6DoF equations of motion.

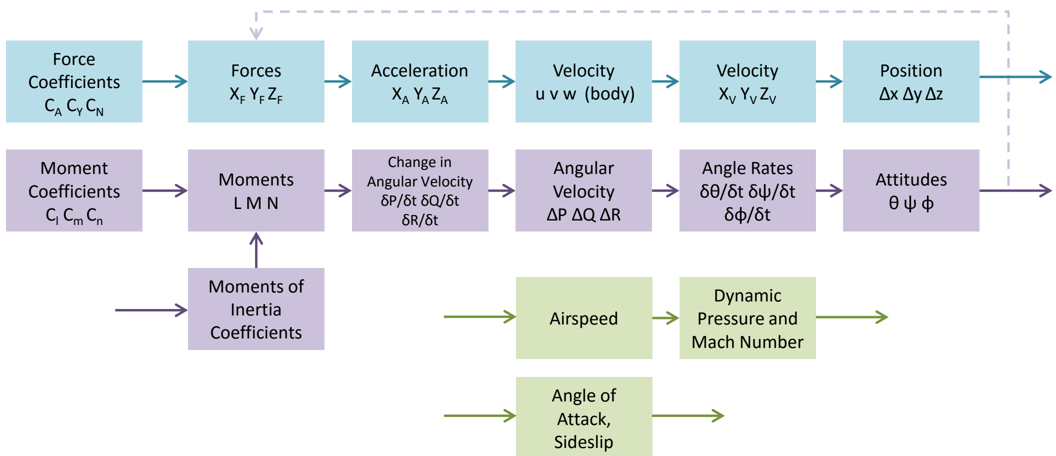

Figure 3.3: 6DoF Equations of Motion Flow Diagram

There are six aerodynamic coefficients that correspond to the 6DoF of the model. The coefficients are as follows:

- Drag (Axial) Force Coefficient (C_A also known as C_D)
- Side Force Coefficient (C_Y)
- Lift (Normal) Force Coefficient (C_N also known as C_L)
- Rolling Moment Coefficient (C_l)
- Pitching Moment Coefficient (C_m)
- Yawing Moment Coefficient (C_n)

These terms are generated by taking into account the various shapes of the parts of an airframe, and then summing the effect of each part on the overall behaviour of the airframe in its current position and attitude. There are several components that make up the 6 coefficients needed for the 6DoF Equations of Motion to be calculated. The following equations list the terms that contribute to the coefficients:

$$C_A = C_{A_0} + C_{A_\alpha}\alpha + C_{A_\beta}\beta + C_{A_{\delta p}}\delta p + C_{A_{\delta q}}\delta q + C_{A_{\delta r}}\delta r + C_{A_{\delta x}}\delta x + C_{A_{\alpha^2}}\alpha^2 + C_{A_{\beta^2}}\beta^2 ...$$
$$+ C_{A_{\delta p^2}}\delta p^2 + C_{A_{\delta q^2}}\delta q^2 + C_{A_{\delta r^2}}\delta r^2 + C_{A_{\delta x^2}}\delta x^2 + \frac{S}{2V}(C_{A_{\dot\alpha}}\dot\alpha + C_{A_{\dot\beta}}\dot\beta + C_{A_P}P ...$$
$$+ C_{A_Q}Q + C_{A_R}R) \tag{3.1}$$

$$C_Y = C_{Y_0} + C_{Y_\alpha}\alpha + C_{Y_\beta}\beta + C_{Y_{\delta p}}\delta p + C_{Y_{\delta q}}\delta q + C_{Y_{\delta r}}\delta r + C_{Y_{\delta x}}\delta x + C_{Y_{\alpha^2}}\alpha^2 + C_{Y_{\beta^2}}\beta^2 ...$$
$$+ C_{Y_{\delta p^2}}\delta p^2 + C_{Y_{\delta q^2}}\delta q^2 + C_{Y_{\delta r^2}}\delta r^2 + C_{Y_{\delta x^2}}\delta x^2 + \frac{S}{2V}(C_{Y_{\dot\alpha}}\dot\alpha + C_{Y_{\dot\beta}}\dot\beta + C_{Y_P}P ...$$
$$+ C_{Y_Q}Q + C_{Y_R}R) \tag{3.2}$$

$$C_N = C_{N_0} + C_{N_\alpha}\alpha + C_{N_\beta}\beta + C_{N_{\delta p}}\delta p + C_{N_{\delta q}}\delta q + C_{N_{\delta r}}\delta r + C_{N_{\delta x}}\delta x + C_{N_{\alpha^2}}\alpha^2 + C_{N_{\beta^2}}\beta^2 ...$$
$$+ C_{N_{\delta p^2}}\delta p^2 + C_{N_{\delta q^2}}\delta q^2 + C_{N_{\delta r^2}}\delta r^2 + C_{N_{\delta x^2}}\delta x^2 + \frac{S}{2V}(C_{N_{\dot\alpha}}\dot\alpha + C_{N_{\dot\beta}}\dot\beta + C_{N_P}P ...$$
$$+ C_{N_Q}Q + C_{N_R}R) \tag{3.3}$$

$$C_l = C_{l_0} + C_{L_\alpha}\alpha + C_{l_\beta}\beta + C_{l_{\delta p}}\delta p + C_{l_{\delta q}}\delta q + C_{l_{\delta r}}\delta r + C_{l_{\delta x}}\delta x + C_{l_{\alpha^2}}\alpha^2 + C_{l_{\beta^2}}\beta^2 ...$$
$$+ C_{l_{\delta p^2}}\delta p^2 + C_{l_{\delta q^2}}\delta q^2 + C_{l_{\delta r^2}}\delta r^2 + C_{l_{\delta x^2}}\delta x^2 + \frac{S}{2V}(C_{l_{\dot\alpha}}\dot\alpha + C_{l_{\dot\beta}}\dot\beta + C_{l_P}P ...$$
$$+ C_{l_Q}Q + C_{l_R}R) \tag{3.4}$$

$$C_m = C_{m_0} + C_{L_\alpha}\alpha + C_{m_\beta}\beta + C_{m_{\delta p}}\delta p + C_{m_{\delta q}}\delta q + C_{m_{\delta r}}\delta r + C_{m_{\delta x}}\delta x + C_{m_{\alpha^2}}\alpha^2 + C_{m_{\beta^2}}\beta^2 ...$$
$$+ C_{m_{\delta p^2}}\delta p^2 + C_{m_{\delta q^2}}\delta q^2 + C_{m_{\delta r^2}}\delta r^2 + C_{m_{\delta x^2}}\delta x^2 + \frac{S}{2V}(C_{m_{\dot\alpha}}\dot\alpha + C_{m_{\dot\beta}}\dot\beta + C_{m_P}P ...$$
$$+ C_{m_Q}Q + C_{m_R}R) \tag{3.5}$$

$$C_n = C_{n_0} + C_{L_\alpha}\alpha + C_{n_\beta}\beta + C_{n_{\delta p}}\delta p + C_{n_{\delta q}}\delta q + C_{n_{\delta r}}\delta r + C_{n_{\delta x}}\delta x + C_{n_{\alpha^2}}\alpha^2 + C_{n_{\beta^2}}\beta^2 ...$$
$$+ C_{n_{\delta p^2}}\delta p^2 + C_{n_{\delta q^2}}\delta q^2 + C_{n_{\delta r^2}}\delta r^2 + C_{n_{\delta x^2}}\delta x^2 + \frac{S}{2V}(C_{n_{\dot\alpha}}\dot\alpha + C_{n_{\dot\beta}}\dot\beta + C_{n_P}P ...$$
$$+ C_{n_Q}Q + C_{n_R}R) \tag{3.6}$$

where:
α is with respect to angle of attack
β is with respect to angle of sideslip
δp is with respect to deflection angle of the control surfaces used to roll the airframe
δq is with respect to deflection angle of the control surfaces used to pitch the airframe
δr is with respect to deflection angle of the control surfaces used to yaw the airframe
δx is with respect to deflection angle of the control surfaces used to slow the airframe
α^2 is as above squared – sign is maintained
β^2 is as above squared – sign is maintained

δp^2 is as above squared – sign is maintained
δq^2 is as above squared – sign is maintained
δr^2 is as above squared – sign is maintained
δx^2 is as above squared – sign is maintained
$\dot{\alpha}$ is with respect to the rate of change of alpha
$\dot{\beta}$ is with respect to the rate of change of beta
P is with respect to Roll rate
Q is with respect to Pitch rate
R is with respect to Yaw rate

The components of the six coefficients can be summed and used in the dynamic 6DoF equations of motion model shown in figure 3.3. Firstly, the forces are calculated using the coefficients and multiplying them by their reference areas and dynamic pressure, as well as terms to represent the effect of gravity:

$$F_X = -Mg\sin\theta - 0.5\rho V^2 S C_A \tag{3.7}$$

$$F_Y = Mg\cos\theta\sin\phi - 0.5\rho V^2 S C_Y \tag{3.8}$$

$$F_Z = Mg\cos\theta\cos\phi - 0.5\rho V^2 S C_N \tag{3.9}$$

where:
M = mass
g = acceleration due to gravity ($9.81 m/s^2$)
ρ = density of air
V = airspeed
S = reference area
C_A = Axial Force Coefficient
C_Y = Side Force Coefficient
C_N = Normal Force Coefficient

Then accelerations can be calculated based upon the forces currently being exerted on the airframe:

$$A_X = -wQ + vR + (F_X)/M \tag{3.10}$$

$$A_Y = -uR + wP + (F_Y)/M \tag{3.11}$$

$$A_Z = -vP + uQ + (F_Z)/M \tag{3.12}$$

u = Velocity along X axis (body)
v = Velocity along Y axis (body)
w = Velocity along Z axis (body)

P = Roll Rate about X axis (body)
Q = Pitch Rate about Y axis (body)
R = Yaw Rate about Z axis (body)

The small change in body axes velocities can be calculated based upon integrating the acceleration over the model's time-step:

$$\delta u = A_X \Delta T \tag{3.13}$$

$$\delta v = A_Y \Delta T \tag{3.14}$$

$$\delta w = A_Z \Delta T \tag{3.15}$$

ΔT = model time step in seconds

The small change in body axes velocities can then be summed with the initial velocity to find the new velocity after the model time-step has elapsed:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} + \begin{pmatrix} \delta u \\ \delta v \\ \delta w \end{pmatrix} \tag{3.16}$$

It is also necessary to convert the body velocity into earth axes so that motion can be represented in Three Dimensional (3D) space. This is done though rotating the body velocity vector through the three rotational axes in the order; heading, pitch, roll:

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} \tag{3.17}$$

$$\begin{pmatrix} X'' \\ Y'' \\ Z'' \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} \tag{3.18}$$

$$\begin{pmatrix} V_N \\ V_E \\ V_D \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} X'' \\ Y'' \\ Z'' \end{pmatrix} \tag{3.19}$$

X = Position in X ($'$ first transform, $''$ second transform)
Y = Position in Y
Z = Position in Z
V_N = Velocity in North Direction
V_E = Velocity in East Direction
V_D = Velocity in Down Direction

The change in position in Earth axes can then be calculated:

$$\delta N = V_N \Delta T \tag{3.20}$$

$$\delta E = V_E \Delta T \tag{3.21}$$

$$\delta D = V_D \Delta T \tag{3.22}$$

A similar process, as described above for the forces, is carried out for the moments. First the moment coefficients are converted into moments using the reference area, dynamic pressure and their moment arm:

$$L = 0.5 \rho V^2 S l C_l \tag{3.23}$$

$$M = 0.5 \rho V^2 S l C_m \tag{3.24}$$

$$N = 0.5 \rho V^2 S l C_n \tag{3.25}$$

l = length of moment arm

Then the change in the angular velocities are calculated based upon these moments, the airframe's current rotation rates, and its moments of inertia (axially symmetric airframe):

$$\frac{\delta P}{\delta t} = (-RQ(I_{zz} - I_{yy}) + L)/I_{xx} \tag{3.26}$$

$$\frac{\delta Q}{\delta t} = (-PR(I_{xx} - I_{zz}) + M)/I_{yy} \tag{3.27}$$

$$\frac{\delta R}{\delta t} = (-PQ(I_{yy} - I_{xx}) + N)/I_{zz} \tag{3.28}$$

I_{xx} = moment of inertia (xx)
I_{yy} = moment of inertia (yy)
I_{zz} = moment of inertia (zz)

The change in angular velocity can be calculated for the model's time-step as follows:

$$\delta P = \frac{\delta P}{\delta t} \Delta T \tag{3.29}$$

$$\delta Q = \frac{\delta Q}{\delta t} \Delta T \tag{3.30}$$

$$\delta R = \frac{\delta R}{\delta t} \Delta T \tag{3.31}$$

Then the Euler angle rates can be calculated:

$$\frac{\delta \theta}{\delta t} = (Q + \delta Q) \cos \phi - (R + \delta R) \sin \phi \tag{3.32}$$

$$\frac{\delta \psi}{\delta t} = (Q + \delta Q) \sin \phi / \cos \theta + (R + \delta R) \cos \phi / \cos \theta \tag{3.33}$$

$$\frac{\delta \phi}{\delta t} = (P + \delta P) + \frac{\delta \psi}{\delta t} \sin \theta \tag{3.34}$$

ψ = Heading
θ = Pitch
ϕ = Roll

Lastly, the change in Euler angles can be calculated for the model's time-step:

$$\delta \psi = \frac{\delta \psi}{\delta t} \Delta T \tag{3.35}$$

$$\delta \theta = \frac{\delta \theta}{\delta t} \Delta T \tag{3.36}$$

$$\delta \phi = \frac{\delta \phi}{\delta t} \Delta T \tag{3.37}$$

The above equations have found the expected changes in the Position, Velocity, Attitude and Angle Rates of the model, which are then summed with the model's initial state and the final values are output. This process is then repeated each time step:

$$\textit{Position:} \begin{bmatrix} N \\ E \\ D \end{bmatrix} = \begin{bmatrix} N \\ E \\ D \end{bmatrix} + \begin{bmatrix} \delta N \\ \delta E \\ \delta D \end{bmatrix} \tag{3.38}$$

$$\textit{Velocity:} \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} + \begin{bmatrix} \delta u \\ \delta v \\ \delta w \end{bmatrix} \tag{3.39}$$

$$\textit{Attitude:} \begin{bmatrix} \psi \\ \theta \\ \phi \end{bmatrix} = \begin{bmatrix} \psi \\ \theta \\ \phi \end{bmatrix} + \begin{bmatrix} \delta \psi \\ \delta \theta \\ \delta \phi \end{bmatrix} \tag{3.40}$$

$$\textit{Angle Rates:} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} P \\ Q \\ R \end{bmatrix} + \begin{bmatrix} \delta P \\ \delta Q \\ \delta R \end{bmatrix} \tag{3.41}$$

Not only do the aerodynamics of the airframe need to be simulated, but the whole guidance and flight control system, and propulsion systems too. The guidance and flight control systems are critical for identifying the target using a seeker, establishing a set of guidance errors, and then displacing aerodynamic control surfaces to prosecute a target successfully. The propulsion system needs to be simulated and managed such that the weapon either maintains a specific air speed or Mach number, or that a rocket motor is sufficiently modelled to output various thrust levels based upon the burn profile of the motor and so that the change in mass from burning fuel is accounted for. Figure 3.4 shows the time step flow chart for a generic simulation model. The above formula is part of the Missile Dynamics block within the overall weapon simulation time step.

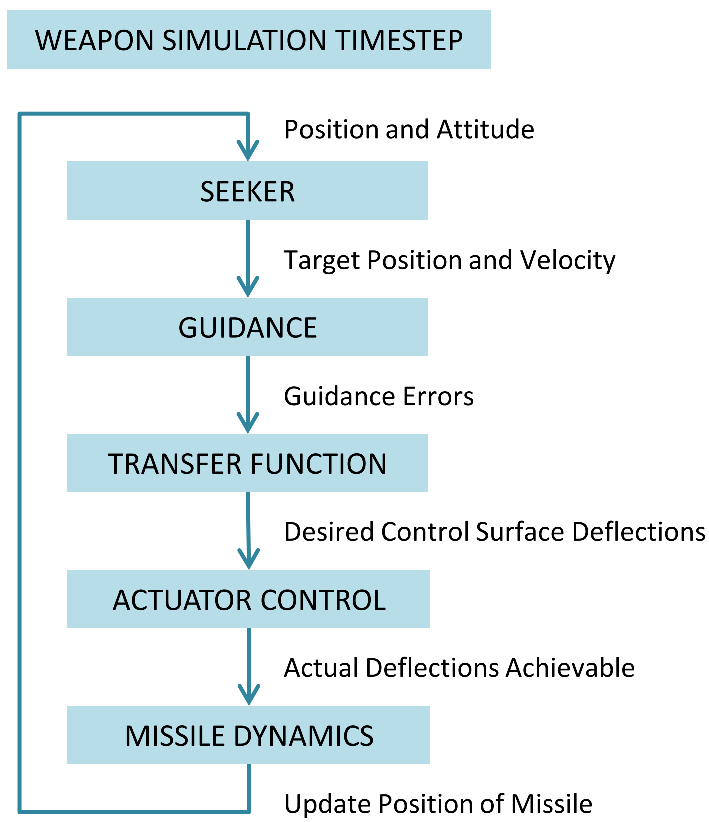

Figure 3.4: Generic Weapon Simulation Functions in Single Time Step

The other processes that occur in the main simulation time step are as follows:

3.1.1.2.1 Seeker

The seekers used in air-to-surface weapons range from Synthetic Aperture Radars, to mm Wave Radars, and Electro-Optical sensors that use Visual and/or Infra Red band light. The sensors then use various methods to turn the received signal into an angular offset from the weapon. In simple cases, such as for laser guided weapons, the seeker searches for a coded laser spot on a target provided by an third-party laser. In complex cases, an air-to-surface weapon may have a search radar to initially find and fix a target and then switch to a tracking mode where the radar scans a smaller area around the target at a higher resolution. Further filtering will take place, particularly for moving targets, so that the seeker can provide a state estimate of the target to the guidance system. For the purpose of this thesis the position and velocity states were generated from the seeker function by idealised GPS and Inertial Navigation System (INS) systems to provide the weapon's location. A standard Kalman Filter [112] was implemented to maintain estimates of position and velocity for the target from GPS based target position updates in-flight. The velocity estimations from the Kalman Filter allow for the target position at impact time to be estimated. Whilst not necessary for stationary targets, it is an important feature for mobile targets. The function outputs the estimated state of the target for the guidance system, specifically position and velocity in the North East Down coordinate reference system. The complexities of the end-game seeker (Find-Fix-Track-Target) have been omitted as it is beyond the scope of the modelling required to support the research in this thesis.

3.1.1.2.2 Guidance

Guidance systems used in air-to-surface weapons range from simple Line-of-Sight (LoS) guidance, typically used in beam riding systems, to complex Optimal Control Theory (OCT) which strives for efficient and optimal engagements using complex sets of algorithms and target manoeuvre estimation. The main set of guidance laws are as follows:

- Line-of-Sight Guidance
  - Command Line-of-Sight (CLoS) – The command system requires that the weapon fly along the aim-point of a fire control radar or other sensor. The weapons deviation from the desired course is sent via a data uplink.
  - Beam Riding – The command system requires that the weapon fly along the aim-point of a fire control beam - usually a laser. The weapon has an Electro-Optical sensor to measure deviation away from the commanded path.
- Pursuit Guidance
  - Pure-Pursuit (PP) – The weapon aims to position either its velocity vector or longitudinal axis such that it points directly at the target.
  - Deviated-Pursuit (DP) – The weapon aims to position either its velocity vector or longitudinal axis such that it points at a point ahead of the target's motion.
- Proportional Navigation (PN) – The weapon aims to impact the target based on a proportional constant by keeping the target LoS angle constant and closing on the target in range [113].
  - Augmented Proportional Navigation (APN) – The weapon aims to impact the target based on a proportional constant by keeping the target LoS angle constant and closing on the target in range with an additional term to account for a manoeuvring target [38, 114].
  - Differential Geometry (DG) – The weapon aims to impact the target based upon curvature control commands [115, 116].
- Optimal Control Theory – The weapon uses advanced algorithms to classify target motion and predict performance as well as optimise the weapon's own intercept trajectory [117, 118].

In this thesis the air-to-surface weapons used the DP guidance law, with the LRAGM using an additional way-point autopilot for early stages of flight.

3.1.1.2.3 Transfer Function

The transfer function is used to take the desired guidance accelerations that are needed to maintain the guidance of the air-to-surface weapon and turn them into control surface deflections needed to effect those accelerations. In order to calculate the control surface deflections needed, the transfer function first calculates the weapon's stability based upon its current attitude and flight conditions with neutral control deflections.

Next the transfer function estimates the effect of small control surface deflections in the roll, pitch, yaw rotational axes and the accelerations that these produce. Then, by subtracting the steady state accelerations from the output from the small perturbations in each axis the overall control surface deflections needed to achieve the guidance accelerations commanded can be calculated using linear extrapolation. The extrapolation assumption is based upon the linearity of the lift curve slope for a symmetrical thin aerofoil [119]. The region of interest for both weapons developed in this thesis is control surface deflections of ± 10 degrees.

3.1.1.2.4 Actuator Control

The actuator control system uses the desired deflections generated by the transfer function to drive the actuators that demand a control surface deflection. This hardware can be servo motors or gas driven solenoids amongst others. For the Guided Bomb Unit (GBU) the control surface deflections are governed by bang-bang control, compressed gas is used to extend the control surface to maximum deflection, and a spring is used to return the control surface to neutral. The control surfaces can only be fully deflected or neutral. The LRAGM uses an electrically driven servo motor that allows for precise deflection angles to be achieved and held without further use of power. Both systems have a maximum deflection limit of 10 degrees, and a first order delay of 0.03 seconds is applied to the commanded deflection of the control surfaces.

3.1.1.2.5 Dynamics

The dynamics function calculates the dynamic response of the airframe given its current state and the updated control surface deflections (and any change in thrust from the motor). The dynamics function first calculates any change in the weapon's moments of inertia due to fuel use, any change in the centre of gravity, and the forces experienced from the thrust. Then the airframe aerodynamic coefficients are generated, based upon the Mach number, altitude, airspeed, thrust and constant properties of the airframe such as canard/fin dimensions, body shape etc. The aerodynamic coefficients are then passed to the 6DoF function to calculate the updated states of the airframe for the time step. These final states are then output as the last step of the time step loop, and the process starts again at the seeker function.

3.1.1.3 Weapon Configurations

Two main air-to-surface weapon configurations were used in the operator trials presented later in this thesis. As mentioned these were a generic guided free fall bomb, and a generic small diameter, long range air-launched cruise missile. These will be termed GBU and LRAGM herein. These two systems are both able to fulfil the same targeting role. The target type being anything from troops, buildings, to both soft and armoured vehicles (depending on the fitted warhead). Their guidance systems are to be designed such that they are able to intercept ground vehicles in motion. Their main difference is that the GBU is unpowered with only canards and fins, whereas the LRAGM has both a motor, and a main lifting wing to extend range.

3.1.1.3.1 GBU - The Guided Bomb Unit

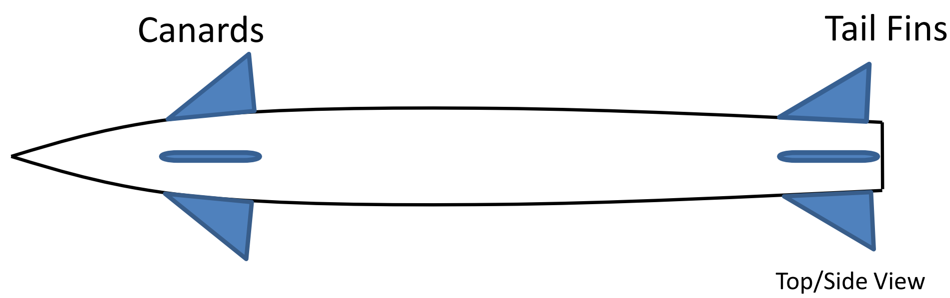

Figure 3.5: Control Surface Configuration for an Air-to-Surface GBU

The GBU is a guided free-fall bomb that uses GPS/INS or Laser guidance to home in on ground targets – stationary or moving. The main aerodynamic features are shown in figure 3.5. The weapon has four fins and four canards to stabilise flight. Controlled manoeuvres to reduce guidance errors are effected by displacing the canards. The control system uses simple bang-bang control to reduce the guidance errors to zero. Bang-bang control is where the actuators for changing the angle of a control surface do not have proportional travel in the mechanism and therefore can only vary between neutral or fully deflected. A spring system is used to return the control surfaces to their neutral positions, hence the name bang-bang control. The system is mechanically simpler and cheaper than a proportional control system, however, it means that the airframe is prone to wobble. A compressed gas system is used to drive the control surfaces during flight. The amount of compressed gas places a limit on overall duration that the control surfaces can be deflected for. The bang-bang system is mechanically and computationally simple, but inefficient in its use of the finite compressed gas available. The compressed gas is quickly expended by the system which must continuously correct itself during flight.

3.1.1.3.2 LRAGM - The Long Range Air-to-Ground Missile

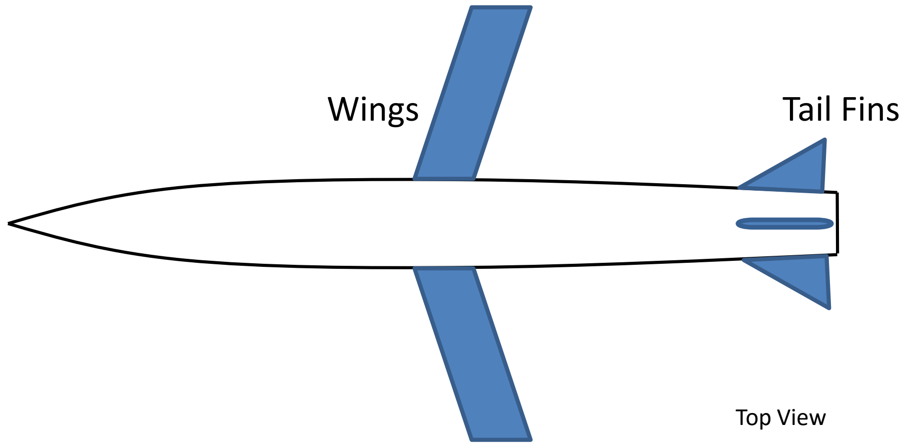

Figure 3.6: Control Surface Configuration for an Air-to-Surface LRAGM

The LRAGM is a medium to long range glide missile with range extending wings and is controlled by three fins. It uses GPS/INS and mm Wave Radar for guidance with a proportional control system for navigation. The missile is designed for stand-off ranges around 100km. This allows the launch platform to deliver the payload whilst remaining safely away from enemy air defences.

The LRAGM has three main phases of flight/guidance. First the weapon glides, un-powered, to a predefined cruise altitude. When launched from high altitude (around 25'000ft) this extends the range of the weapon by approximately 30km. Once at a cruise altitude of 1500m the missile then levels out and maintains altitude, and ignites the motor to maintain airspeed. During the glide and cruise phases, the missile will bank-to-turn in order to fly a straight intercept to the target. The intercept angle or attack heading can be specified. The missile will automatically plan a route to the target from launch point that includes up to three way-points, and two turns, to line itself up appropriately with the target. Finally in terminal phase – when the slant range left to the target corresponds with the last 5 seconds of flight, the altitude hold is switched off and the missile flies a direct path to the predicted target intercept point.

3.1.1.4 Generating Re-Targeting Capability Information

Re-tasking any bomb or missile in the air requires knowledge of the airframe's current flight parameters, and of its ability to hit other targets. The RS is the term used to describe the area on the ground that a weapon can be safely targeted at point of launch. A computer on-board the launch aircraft will calculate the possible trajectories and create a bounding polygon of the valid area before launch.

3.1.1.4.1 GBU RAR Estimation

For the GBU the RAR calculation starts with the predicted ballistic impact point of the weapon. This is the impact point if no further control deflections were to occur in flight. Then, from this point, false targets are generated at large distances along a number of bearings that are defined by the desired resolution passed to the function. For example 4 points would generate a rectangular RS for the weapon, although this would not be sufficient for generating an accurate RAR due to the general crescent shape of the GBU RS. The weapon simulation is propagated forward until impact towards these false target positions which require the maximum possible control deflection to achieve. The impact points are then used to generate a RAR polygon. Figure 3.7 shows the output set of the basic open-loop solution of the RS depicting the change in shape over time. The navy blue outer polygon indicates the RAR at launch, and the red inner polygon indicates the last RAR generated before impact. Note that there may be a section of time between the last perceivable RAR and impact.

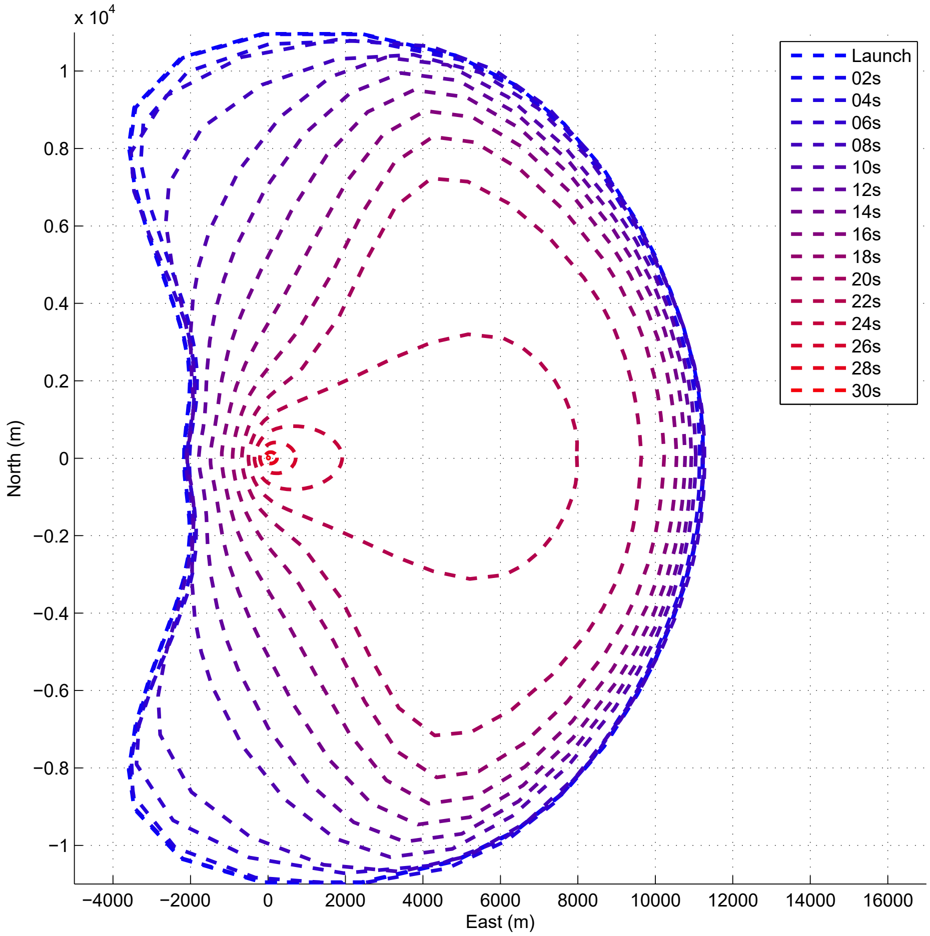

Figure 3.7: Change in RAR Size for Basic Algorithm (Full Output Set)

The solution shown in Figure 3.7 is the open-loop RAR solution, however, as the weapon is re-tasked to the limits of its physical manoeuvrability the time of flight is increased as is the demand on the finite level of compressed gas. If the time of flight is longer than the battery life available and/or the cumulative control deflection needed to achieve a particular intercept is exceeded, then clearly the weapon will be unable to reach the targets. The open-loop basic calculation includes these limits but allows the weapon to continue unguided and without power until impact, meaning that the weapon has no capability to attack moving targets at such extreme distances away from the ballistic flight path. To inhibit this, a limit is placed on the system that the weapon must not exceed battery life or the compressed gas available. This simple limit, called the Valid Set, constrains the RS. The limit is in the form of a maximum range limit from the ballistic flight path, and only restricts those areas ahead of the flight path of the GBU. A simple line intersection was used to stitch the Valid Set with the open-loop RS for the overall RAR shown in Figure 3.8. The Valid Set produced is course in comparison to the main RS calculated, and as such the shape can change in a way that produces the jagged shapes seen in Figure 3.8.

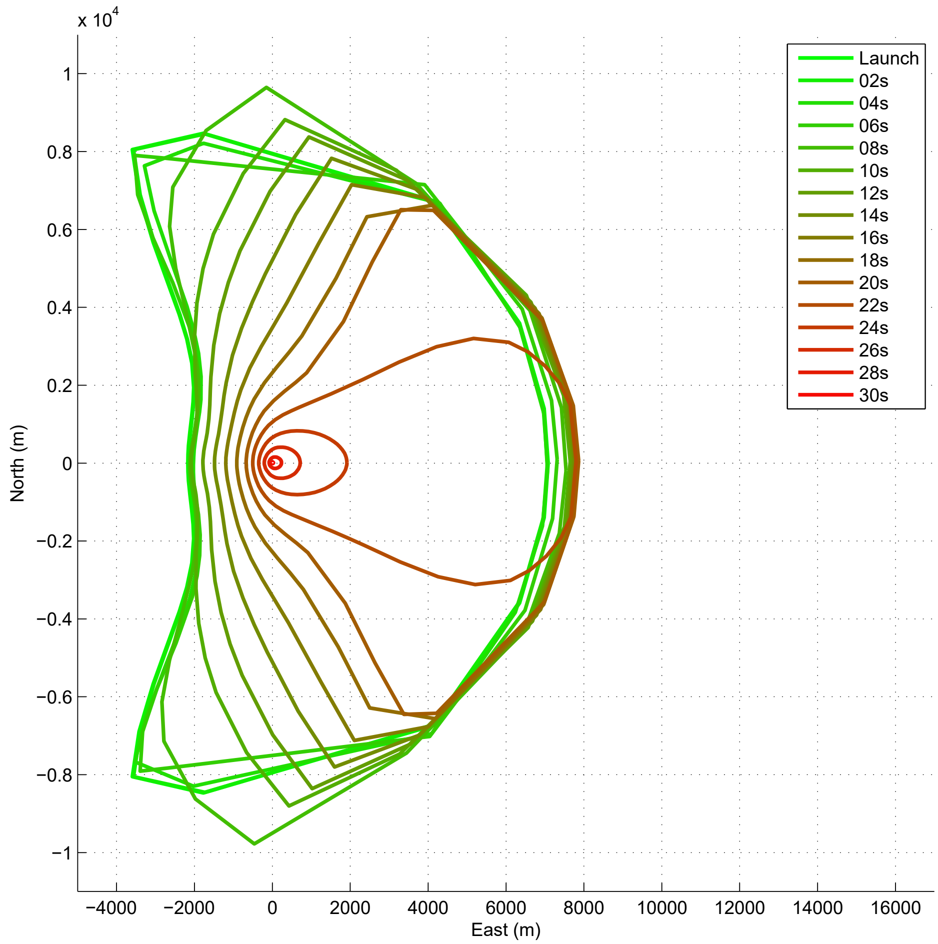

Figure 3.8: Change in RAR Size for Basic Algorithm (Valid Set)

Should a more complete estimation of the RS of the weapon be needed, there is the option of calculating a full closed-loop solution which is based upon the maximum time of guided flight (battery and compressed gas limits). It is more reliable than the basic solution, however, takes significantly longer to calculate as it maintains the same resolution of the RAR. To do this it must iterate along each bearing from the ballistic trajectory to find the point at which the GBU exceeds either the battery life or the compressed gas available. Figure 3.9 shows the closed loop solution. The size of the RS is larger than that calculated by the basic valid set calculations, meaning that the Valid Set is a significantly limited under estimation of capability.

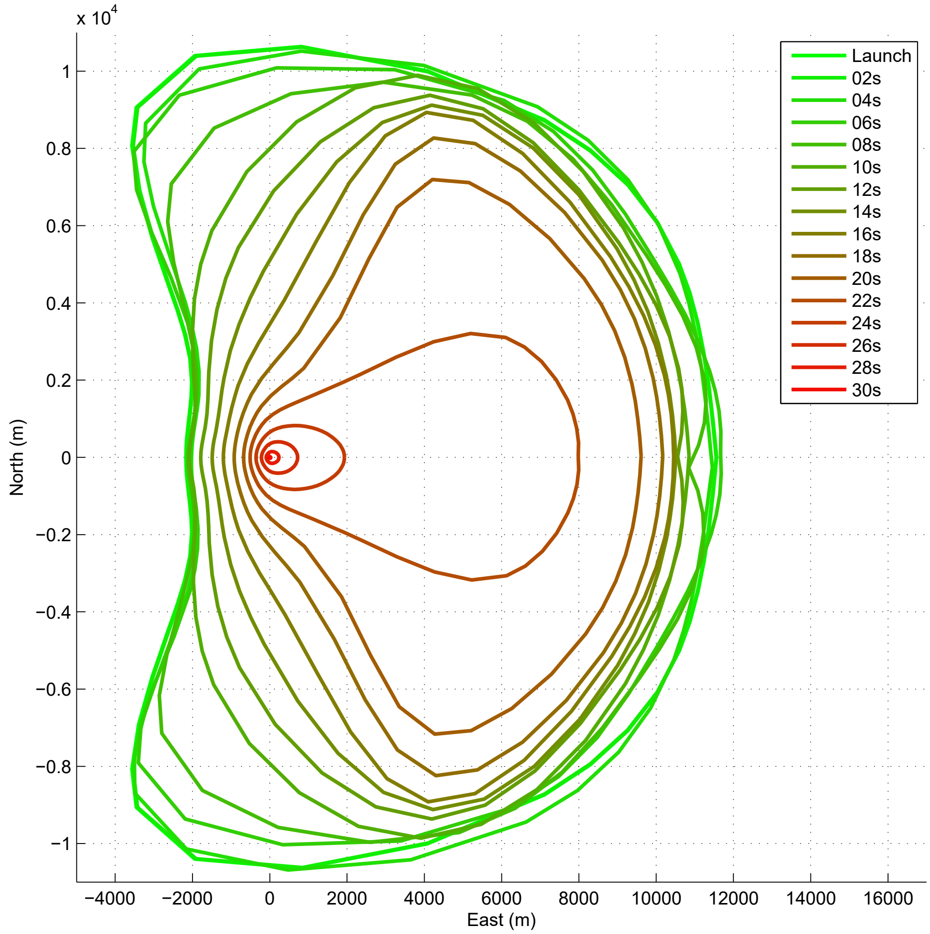

Figure 3.9: Change in RAR Size for Closed-Loop Algorithm (Output Set)

The time taken to run the GBU RAR calculation is directly proportional to the height of the system and the number of points to be generated. If the weapon is required to hit mobile targets, then guidance commands are needed throughout the flight. This requires the use of either the closed-loop RAR or the Valid Set output from the basic RAR algorithms. These solutions factor in the battery life and amount of gas available for control deflections and can be used to ensure that guidance will be available to the weapon until point of impact if needed. The closed-loop solution adds considerable time to the basic RAR computations. This is because the closed-loop function assesses whether the initial open-loop positions were achievable using the available battery time and compressed gas for control surface deflections. If the positions are unachievable, the function reduces the distance of the aim point from the neutral free fall position iteratively until the overall flight time of the weapon does not exceed the battery time available and the total control deflections needed do not exceed the limit placed by the amount of compressed gas available.

Figure 3.10 shows the time taken to run one iteration of the RAR calculation for the GBU through a typical ballistic flight from 15000ft in both the open-loop and closed loop solutions. The additional time that the closed-loop solution takes is due to the iterative process used to find the maximum capability of the GBU and the number of iterations needed is the source of the variance seen in figure 3.10.

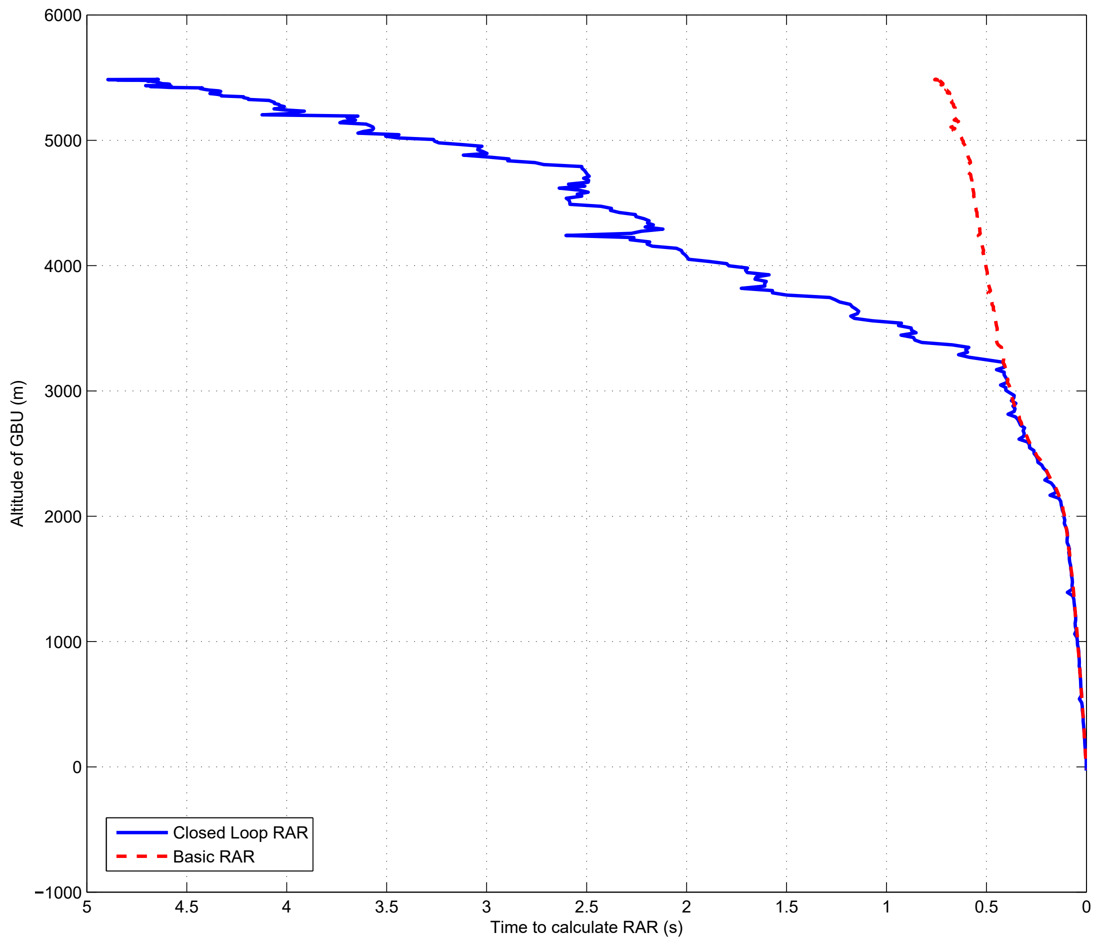

Figure 3.10: Time to Complete RAR Algorithm vs. Altitude of Weapon at Time of Calculation (Closed-Loop and Basic RAR Algorithms) – note: the x-axis is inverted such that from left to right is representative of decreasing TTG of the weapon

Considering the amount of time needed to run the simulation model each time step, and a requirement for use in a real-time environment, the closed-loop algorithm takes too much time to execute at higher altitudes. The Valid Set produced by the basic algorithm provides a somewhat cautious RS, however, it calculates sufficiently fast, that the output can be updated at least at 1Hz if not more (depending on PC specifications).

3.1.1.4.2 LRAGM RAR Estimation

As the LRAGM was a new model developed for the second of the two participant trials presented later in this thesis, an investigation into the capability of the weapon system was needed to find the expected RS of the weapon and then a data set and algorithms that could be used to generate a real time RAR. Due to the LRAGM being powered, having range extending wings, and having a proportional feedback control system that requires significantly fewer cumulative control deflections to reach a target, the way in which the RS and RAR are calculated is quite different than that of the unpowered, ballistic GBU (where battery life and compressed gas used for control deflection are the main limitations).

The LRAGM has three specific phases of flight. These are a glide phase, a cruise phase and a terminal phase. After launch the weapon glides, unpowered, down to pre-set cruise altitude. Then its motor starts and the weapon cruises towards the target – making turns if necessary to intercept moving targets. A prediction is made for moving targets that places the aim point up to 30 seconds ahead of where the target is, based upon an estimation of the target velocity. This reduces the amount of terminal guidance needed to intercept the target, albeit slightly reducing the RS.

In order to generate the RS of the LRAGM, two sets of Monte Carlo simulations were run. In these Monte Carlo analyses the off bore-sight angle and the range of the target were varied. Two conditions were analysed; model initialised with target in varying locations, and model initialised with target directly ahead then updating the target off bore-sight angle after the glide phase has been completed. These two cases were chosen as they expose the two main sections of flight where turns will impact on the flight capability of the weapon. Unlike the GBU, and other missiles with no main lifting wing surface, when the LRAGM performs turns it has a limited impact on the range and capability of the weapon. Instead, the turn radius and range of powered flight have the dominant effect on the RS of the weapon.

The following figures show the results of the Monte Carlo analysis for the two different test conditions. The control deflection for each phase of flight will be presented, along with the total deflection required and the accuracy of the weapon in each test case. The plots show range along the x-axis, with the off bore-sight angle shown on the y-axis.

Figure 3.11 shows the cumulative control surface deflections for Phase 1 (glide phase) of an engagement against a stationary target, where the turn against an off bore-sight target occurs in the glide phase. As can be seen, for targets immediately ahead of the weapon, with no update to off bore-sight angle, there is a constant amount of control deflection needed in the glide phase. As the off bore-sight angle is increased, there is an increase in the amount of control deflection required. However, as there is an initial control needed to start a turn manoeuvre, and one to then continue straight flight, the smaller off bore-sight angles require slightly more control surface deflections than the larger off bore-sight angles, which are roughly the same. Figure 3.12 shows the cumulative control surface deflections for Phase 1 where the off bore-sight turn occurs in the cruise phase of flight. As expected there is no variation in the control deflections needed for the glide phase. There is one erroneous case where the control deflections shown is zero, this case was omitted from the RS due to the lack of sufficient accuracy when targeting that position (shown in figure 3.20).

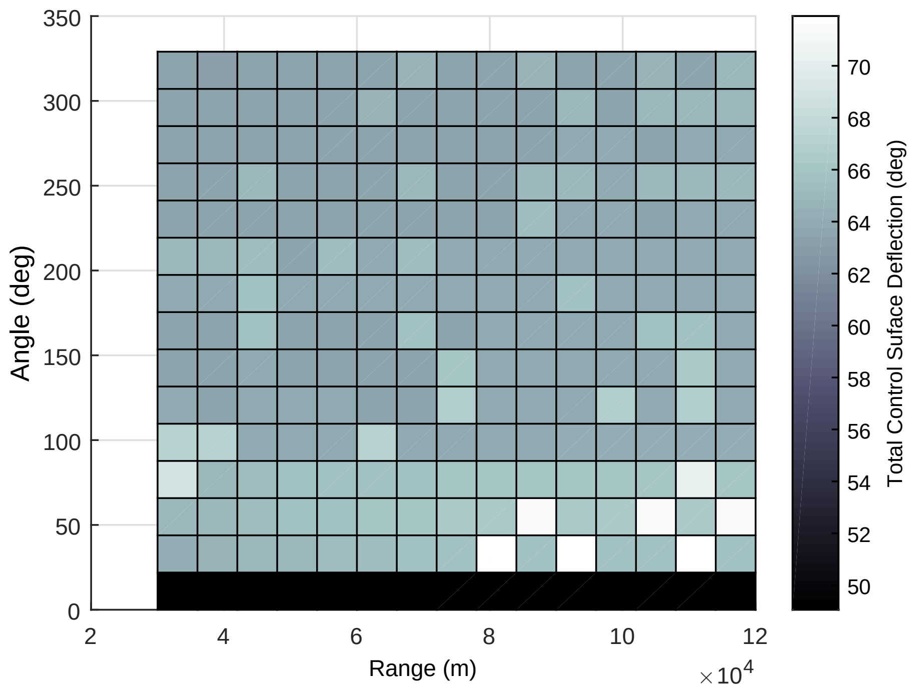

Figure 3.11: Turn in Glide - Phase 1 Cumulative Control Surface Deflection

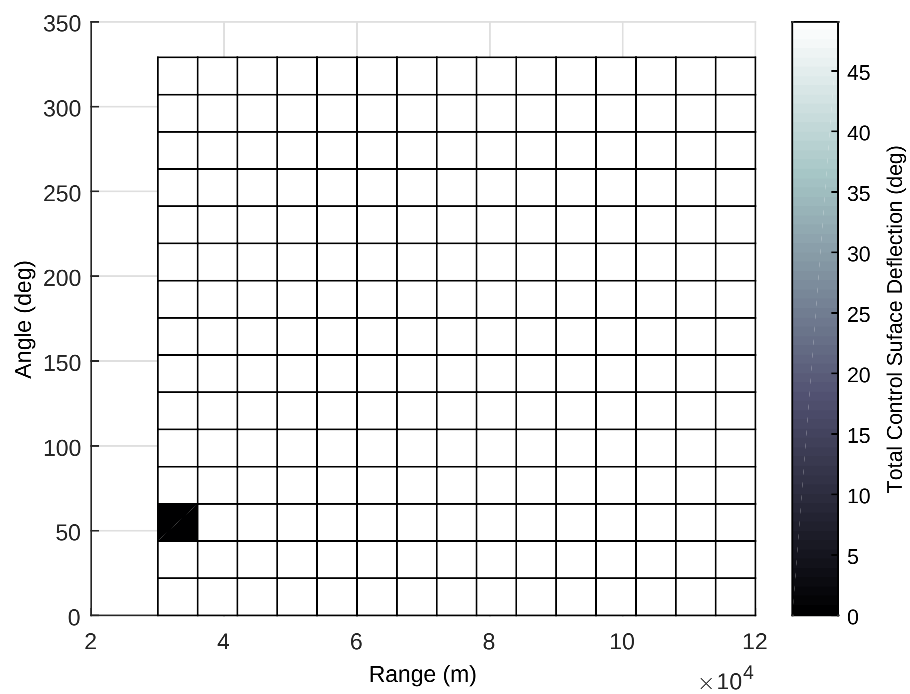

Figure 3.12: Turn in Cruise - Phase 1 Cumulative Control Surface Deflection

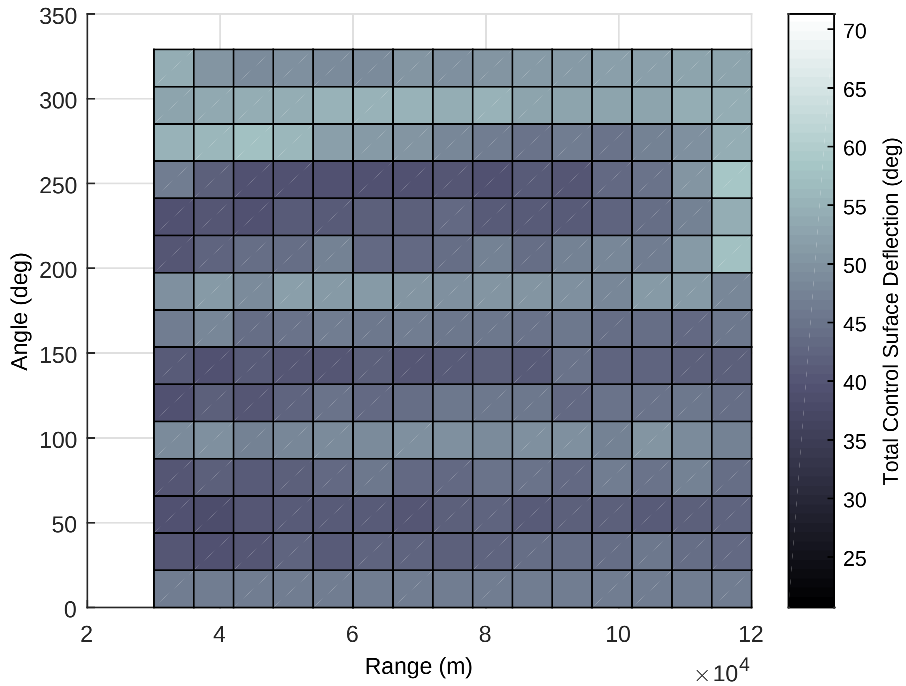

Figure 3.13: Turn in Glide - Phase 2 Cumulative Control Surface Deflection

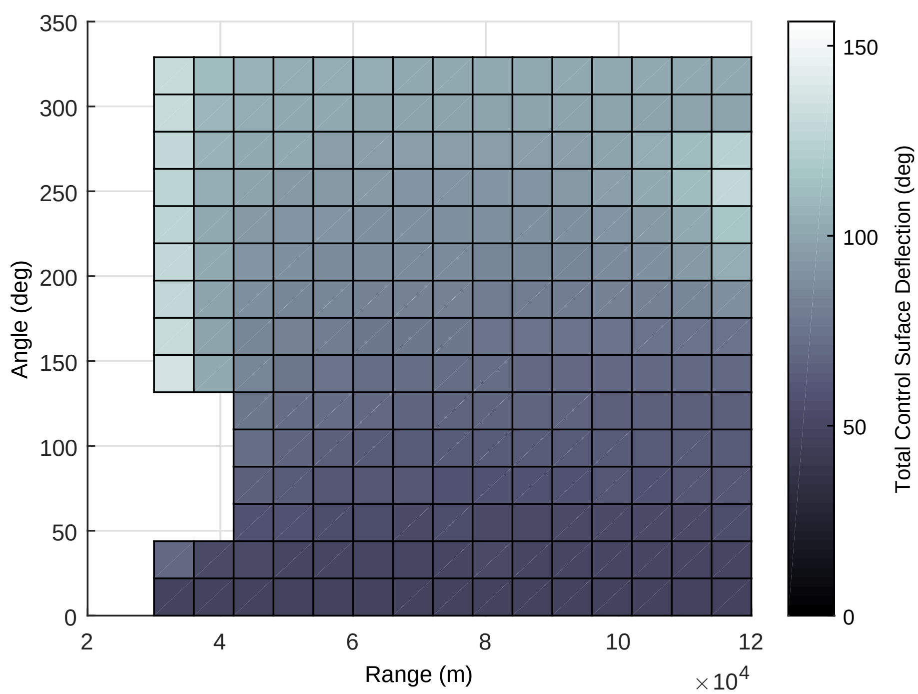

Figure 3.14: Turn in Cruise - Phase 2 Cumulative Control Surface Deflection

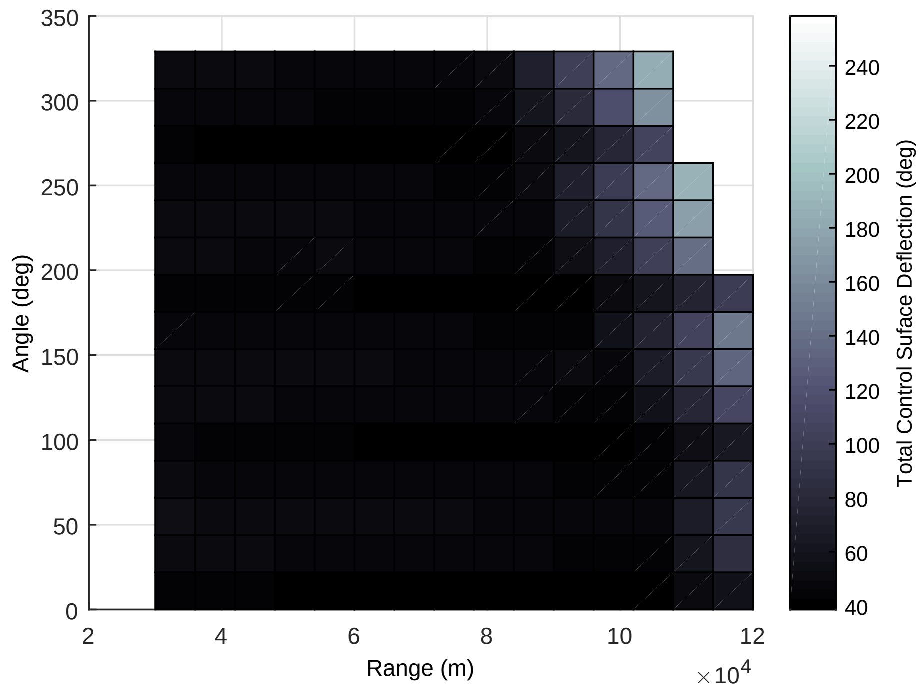

Figure 3.15: Turn in Glide - Phase 3 Cumulative Control Surface Deflection

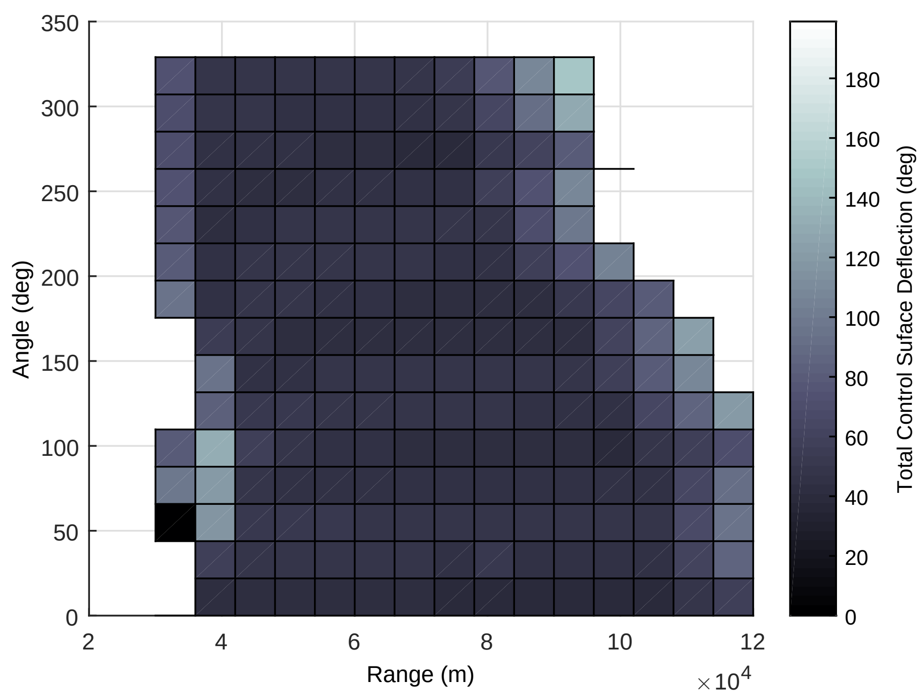

Figure 3.16: Turn in Cruise - Phase 3 Cumulative Control Surface Deflection

Figure 3.13 shows the cumulative control surface deflections for Phase 2 (cruise) of the Turn in Glide Phase engagement. The total cumulative deflections vary between 20-70 degrees across the ranges and off bore-sight angles tested. However, for the Turn in Cruise Phase engagement, the amount of cumulative control deflection varies between around 50 and 150 degrees. It can be seen from figure 3.14 that as off bore-sight angle increases, the cumulative control deflections increases and close range, high off bore-sight angles, and long range, high off bore-sight angles, require higher levels of cumulative control deflections.

In both the Phase 3 (terminal) engagement types similar levels of cumulative control surface deflections can be seen of around 60 degrees (see figure 3.15 and 3.16). However, at the upper and lower limits of range and off bore-sight angles (combined) there is an increase in the cumulative control surface deflection required and some cases are omitted due to inaccuracy or too high a control surface deflection required.

Figures 3.17 and 3.18 show the overall total control deflection needed for all phases of flight.

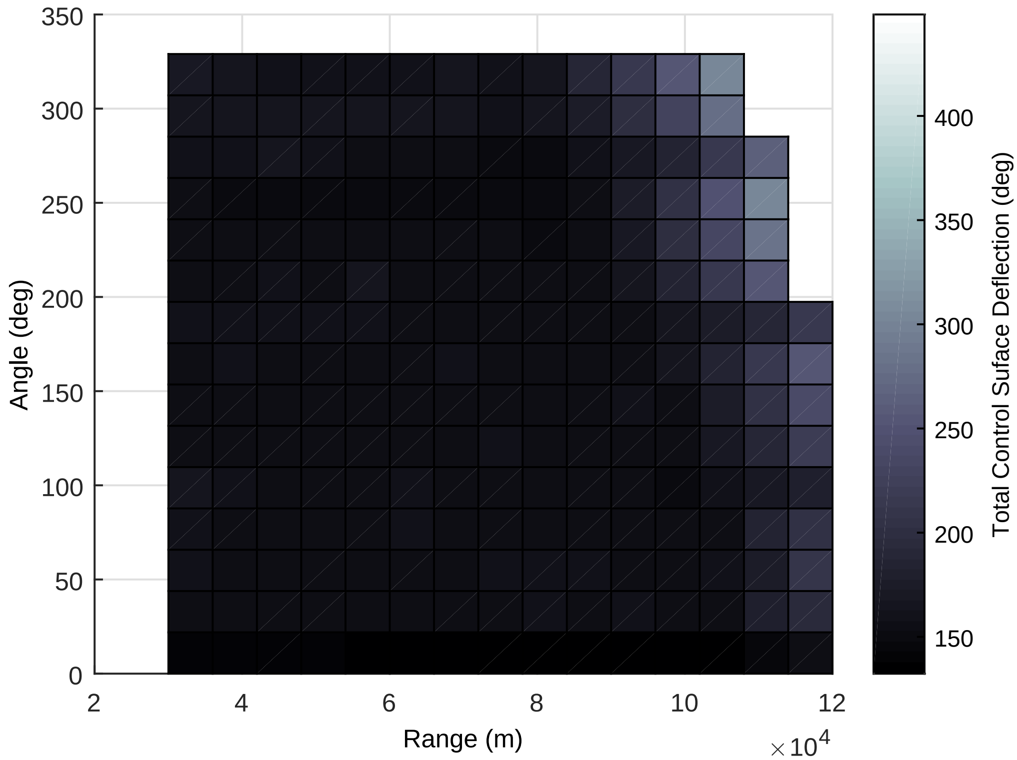

Figure 3.17: Turn in Glide - Total Cumulative Control Surface Deflection
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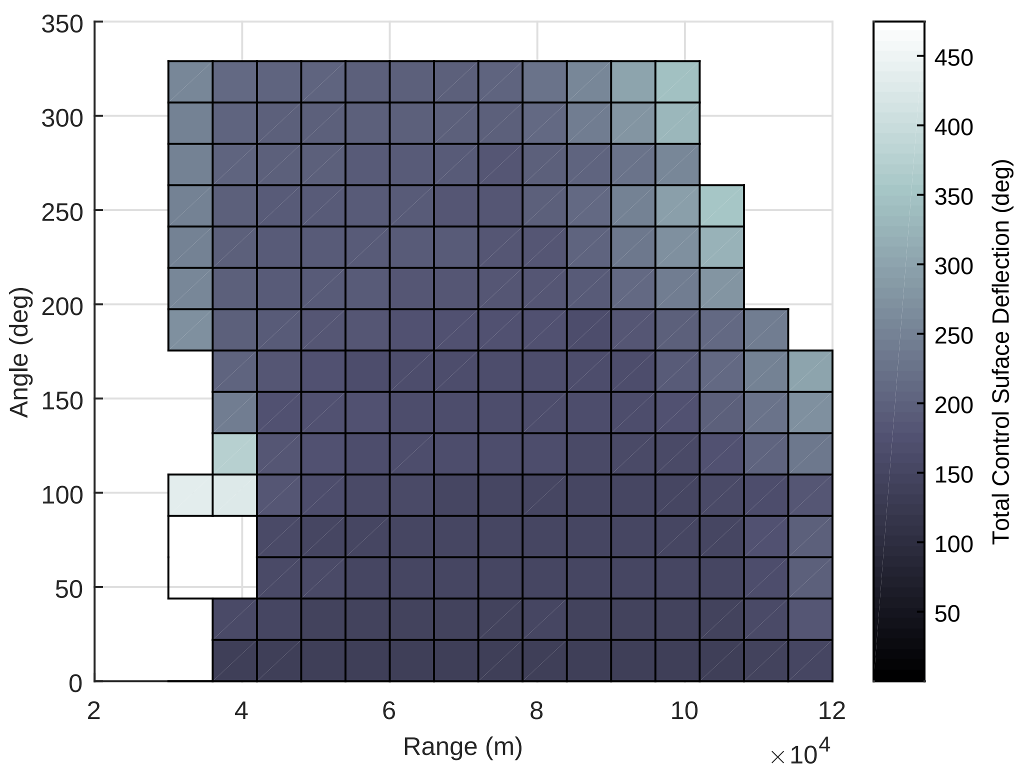

Figure 3.18: Turn in Cruise - Total Cumulative Control Surface Deflection

Figures 3.19 and 3.20 show the accuracy of the LRAGM across all of the cases for the Turn in Glide and Turn in Cruise phase engagements respectively. The cases where too much control deflection was needed have been removed, as well as erroneous cases outside of the weapons manoeuvrability. Further, cases where the accuracy exceeded 2.5 metres have been omitted. It can be seen that turning in the glide phase offers an increased range and off bore-sight capability than when conducting a turn in the cruise phase. However, the weapon system developed allows for a very large RS in relation to the GBU.

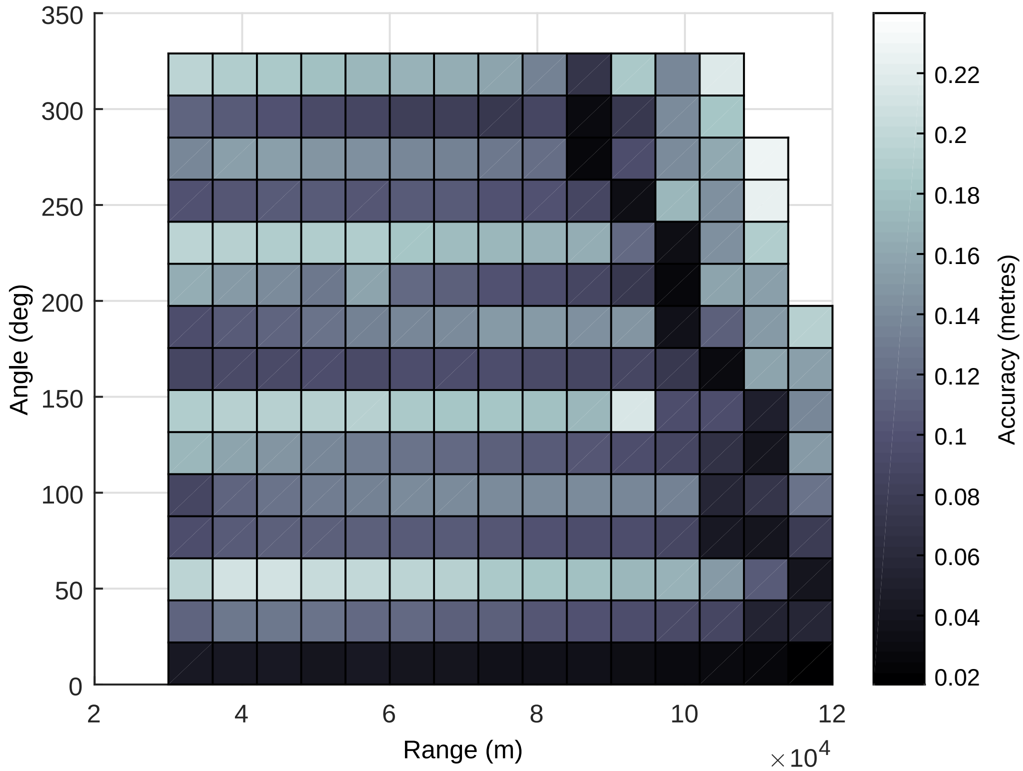

Figure 3.19: Turn in Glide - Accuracy for Acceptable Cases

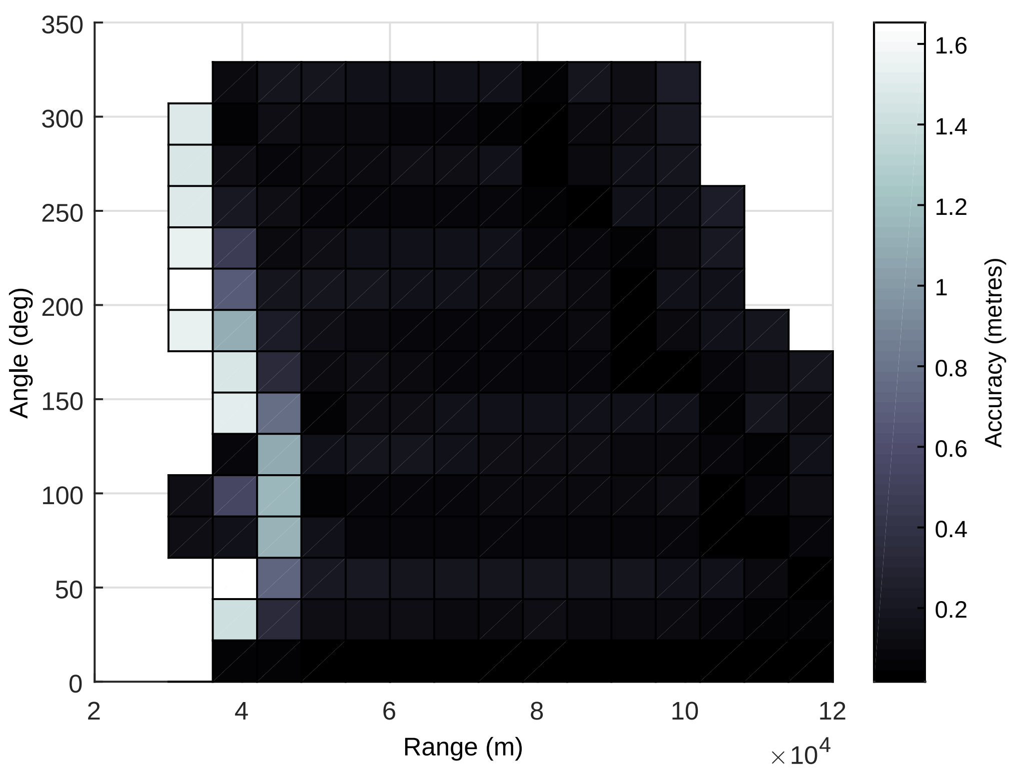

Figure 3.20: Turn in Cruise - Accuracy for Acceptable Cases

In general, the accuracy of the LRAGM is very good and of comparable accuracy to those seen in programs such as AMSTE (3m Circular Error Probable) [25]. It is important to remember that the test cases were run in an idealised simulation environment with controlled variables. There is some variability with the accuracy, and particularly in areas where the range is low, the accuracy reduces to around 1.6m. Accuracy levels of greater than 2.5m were omitted as indirect hits against small armoured targets would likely prove ineffective.

As already alluded to, the main contributing factors to the RS of the LRAGM are the turn radius and the powered range of the system. Targets that are at a range that is less than the glide slope range of the weapon from launch can still be prosecuted, but will require the weapon system to deliberately extend its range and make a large turn to prosecute the target effectively. The turn radius of the weapon is designed around a maximum roll angle of 60 degrees. Figure 3.21 shows the two engagements of an initial target off bore-sight angle, and an update in cruising flight for eight off bore-sight angles.

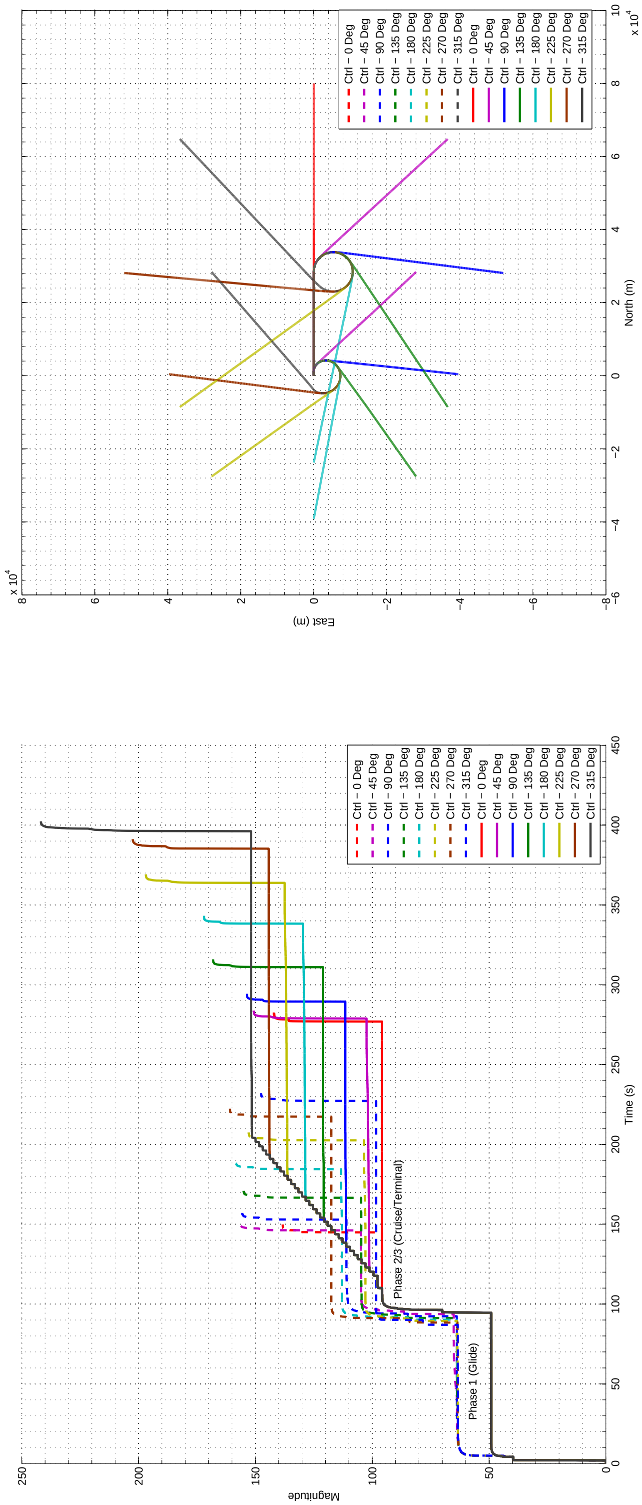

Figure 3.21: Figure of Cumulative Control Surface Deflections for Selected Trajectories (Left) Top Down View of Trajectories (Right)

In banked turns, a change in heading is achieved through rolling the airframe. This offsets the normal vector such that there is a vertical and horizontal component of the total lift force. The vertical component must match the weight of the airframe to maintain altitude, and the horizontal component then acts to turn the airframe. The following expressions can be used to calculate the overall lift force needed to maintain altitude in a turn:

$$L \sin \phi = \frac{mv^2}{r} \tag{3.42}$$

$$L = \frac{mg}{\cos \phi} \tag{3.43}$$

$$r = \frac{v^2}{g \tan \phi} \tag{3.44}$$

Figure 3.22 shows the velocity profile of the LRAGM in a typical flight, with the different phases of flight marked. Given that radius of a turn is proportional to the square of the airspeed and inversely proportional to the tangent of the bank angle, the turn radius for the LRAGM therefore varies between approximately 2500m (at 205m/s) to 5500m (at 305m/s). This is quite a large variation, but can be used to estimate the minimum turn radius that the LRAGM can achieve en-route to its target, or any other potential targets.

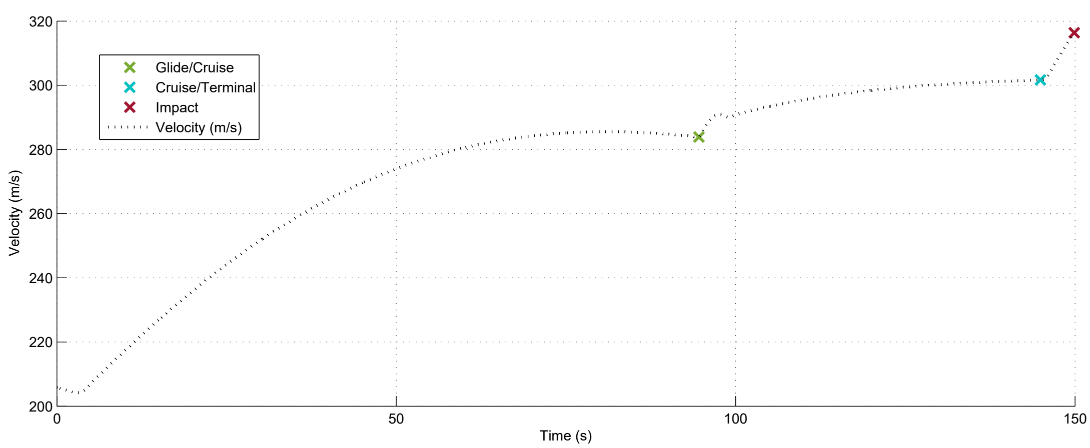

Figure 3.22: LRAGM Velocity Profile

3.1.1.5 Real-Time Simulation Adaptations, Constraints and Validation

Simulation models are limited in speed of execution by the processing power of the computer being used, the efficiency of the code developed and the complexity of the model's equations. The frequency of the time step needed for simulation and the requirement for graphical output in MATLAB place significant strain on a computer's processing abilities. A small enough time step should be used so that the errors that occur in the integration process are small enough to be acceptable for the model such that it does not affect the stability and accuracy of the model. If the time step is too large then many guidance actions may be omitted from the simulation, and a control input to correct a manoeuvre may not be able to be effected quickly enough to prevent a model from becoming unstable. However, reducing the time step too much may cause unnecessarily long simulation execution time. Adapting a simulation so that it runs in real time is dependent on finding a time step that provides the resolution needed to maintain accuracy and stability whilst taking less time to execute computationally than the time step in the real world. In this case the LRAGM was run at 200Hz.

3.1.2 Target Systems

Simulation of target models was carried out to ensure that the two weapon types were able to hit mobile vehicle targets of different types. To do this several vehicle model types were simulated and used as targets for weapon system validation. The trials presented in Chapters 5 and 6 did not use mobile targets, however, the use of the two weapon systems against mobile targets was an important feature to build in for the longevity of the research project.

3.1.2.1 Vehicle Simulation

Simulation of five typical types of road vehicles were developed and their properties are listed in Table 3.2 [120, 121].

Table 3.2: Typical Road Vehicle Dynamics

Vehicle	Length		Max Velocity		Max Accel		Max Braking		Jerk	
	ft	M	mph	m/s	ft/s^2	m/s^2	ft/s^2	m/s^2	ft/s^3	m/s^3
Passenger Car	14	4.27	75	33.528	10	3.048	15	4.572	7	2.134
Single-Unit Truck	35	10.67	75	33.528	5	1.524	15	4.572	7	2.134
Semi-Trailer Truck	53	16.15	67	29.952	3	0.914	15	4.572	7	2.134
Dbl. Trailer Truck	64	19.51	61	27.269	2	0.610	15	4.572	7	2.134
Bus	40	12.19	65	29.058	5	1.524	15	4.572	7	2.134

An overall object class was coded in MATLAB to simulate each vehicle with a standard set of functions. The simulation model works by moving the vehicle object through a series of way-point coordinates. These way-point coordinates are passed to the object from a master code. The vehicles then use vehicular dynamics to drive along these routes. These routes could be made up of way-points that represent road networks. There is therefore a handle to attach road network speed limits so that the vehicle will aim to cruise at the speed limit rather than accelerate to its maximum speed. Further, the vehicle has been developed to slow down and reduce lateral acceleration in turns to replicate normal driving conditions.

Vehicle turning is simulated through the creation of additional route way-points around corners. These way-points smooth the corners such that a variable turn radius is used rather than snap turning. The minimum radius for turns is based upon information from the National Cooperative Highway Research Program Report 348 [121] and is used for turns greater than or equal to 90 degrees. Although there are differences in road layout style between countries, the minimum turn radius of 7.62 metres is used for standard vehicles. Larger radiuses are required for vehicles such as buses and trucks and a minimum of 10-15m turn radius is used. Lateral g-force is used as a limiting factor for the speed of a turn. Passenger comfort requirements set a lateral g-force limit of 0.41g (4m/s^2) which at 90 degrees gives a speed limit of 5.52m/s (12.35mph). When a turn angle is less than 90 degrees the radius of the turn increases using the following:

$$R_{turn} = \frac{turnRadius_{min}}{\tan \frac{\Delta\phi}{2}} \tag{3.45}$$

where: $turnRadius_{min}$ is the minimum turn radius for a 90 degree turn, and ϕ is the required turn angle between legs of a route.

The increase in turn radius increases the limit speed limit for the turn. The upper limit of velocity in m/s can be found using the following:

$$V_{max} = \sqrt{lataccel_{max} R_{turn}} \tag{3.46}$$

where: $lataccel_{max}$ is the maximum lateral acceleration tolerated by passengers (comfort = $4m/s^2$).

Acceleration and deceleration occur using the simple SUVAT formulae. The formulae are used to find the acceleration and deceleration points when vehicles must slow down before making a constant velocity turn. This can be the case when sharp turns require the vehicle to drive slower than the road's current speed limit.

Each time step the simulation model starts by holding the previous time step output states for turning, heading, and speed. Then the model clears any manoeuvre flags so that the model presumes that it is travelling straight and at constant speed. Then the model finds the next way-point and the current road type speed limit. Following this it calculates the heading difference between the heading between the previous and current way point, and then the current way-point and that immediately following it. This allows for a calculation of the required change in direction needed at the next way-point. Using this information an expected speed for the turn is calculated so that the vehicle does not have too much lateral acceleration.

If the distance to the way-point is equal to or less than the `turn_start_dist` then the vehicle will begin turning. Further, if the vehicle `req_turn_speed` is lower than the current road speed limit then the model will estimate the point at which braking should occur to slow the vehicle for the turn. If the vehicle has passed the turn, it may need to accelerate back to the speed limit. Based upon these additional way-points and conditions, flags are set that indicate the state of the vehicle in accelerating, braking and turning. The flags are then used when executing the main time step to move the vehicle. This inspects the flags and changes the dynamics of the vehicle if necessary to satisfy the manoeuvre requirement.

3.1.2.2 Route Planning

The Open Street Map (OSM) database is much like open source software packages. The website hosts mapping information similar to mainstream commercial map makers, however, all of the data used to create these maps is freely downloadable in XML format. OSM XML files can be imported into MATLAB structures using OpenStreetMap Functions for MATLAB [122].

Upon running the function `parse_openstreetmap` on a downloaded openstreetmap.xml file the resulting two structures are: `parsed_osm` and `osm_xml`. Both files contain the same information although the formatting of the `parsed_osm` structure is more favourable as it has fewer sub structures and simpler formatting. The `parsed_osm` structure is as follows:

- `parsed_osm.bounds` [minlon, maxlon,minlat,maxlat];
- `parsed_osm.node` struct
- `parsed_osm.node.id` [1xn] vector of node id values
- `parsed_osm.node.xy` [2xn] vector of node xy coordinates in long, lat decimal degrees
- `parsed_osm.way` struct
- `parsed_osm.way.id` [1xm] vector of route id values - routes are sets of nodes
- `parsed_osm.way.nd` {1xm} [1xk] vector of node ids that make route
- `parsed_osm.way.tag`{1xm}{1xj} set of information varies from 1-3 containing the following:
- `parsed_osm.way.tag`{1xm}{1xj}.Attributes

- `parsed_osm.way.tag`{1xm}{1xj}.Attributes.k string type of attribute ('natural', 'highway', etc.)
- `parsed_osm.way.tag`{1xm}{1xj}.Attributes.v string sub type of attribute ('coastline', 'primary', etc.)
- `parsed_osm.Attributes` contains string information about the source copyright etc.

The OpenStreetMap Functions also contain connectivity functions. The following three functions are used in sequence:

- `[connectivity_matrix, intersection_node_indices] = extract_connectivity(parsed_osm);`
- `intersection_nodes = get_unique_node_xy(parsed_osm, intersection_node_indices);`
- `dg = or(connectivity_matrix,connectivity_matrix');`

The output from these functions can be used to find the shortest path between two nodes using Dijkstra's algorithm [123]. The limit of the built in `route_planner` function is that it will only work if both the start and end points chosen are intersection nodes. This is because the `connectivity_matrix` only contains nodes that are intersections. Consequently the output route provided by the `route_planner` is made up of only intersection nodes. This would suffice if each road between intersection points were made up of only one point to point line, however, it is far more common that the roads in-between these intersection nodes contain a number of nodes that represent the road between them.

In order to have a robust node-to-node shortest path algorithm that is not dependent on intersection nodes, and provides the complete route with all nodes between intersection points, a new function was created named `route_planner_any_node`. The function uses several key steps in order to find the complete route.

- Check if Start and End points are intersection nodes.
- If they are not intersection nodes, find the 'ways' (roads) that they belong to.
- On those roads, find the nearest intersection nodes.
- Use those intersection nodes to run the `route_planner` algorithm.
- Append the nodes needed to get from the Start point to its nearest intersection node.

- For each intersection–>intersection node route leg provided by `route_planner` append the way nodes between them.
- Append the nodes needed to get from the last intersection node to the End point.
- Extract the Latitude and Longitude for the complete route. The `route_planner_any_node` returns a number of vectors containing information about the complete route. These are:
- `Route_id` - holds the actual id number of the nodes used in the route [1xn].
- `Route_index` - holds the index within the `parsed_osm.node` array.
- `Route_LL` - holds the decimal degrees [longitude;latitude] pairs in a [2xn] array.
- `Way_id` - holds the actual id number of the way to which the node belongs [1xn].
- `Way_index` - holds the index within the `parsed_osm.way` array.

The `way_id/index` values are output for use by the moving target's simulation. Each way has a set of attributes that contain a 'key' and a 'value'. The 'key' is used to identify the type of information contained in the way - for example 'natural' for geographical features, or 'highway' for road networks. The 'value' then contains information about the type of the key, for example the 'highway' key contains values to describe the type of road, 'motorway', 'primary' etc. This information can be used by the moving targets simulation to infer speed limits along the different sections of the route to be driven.

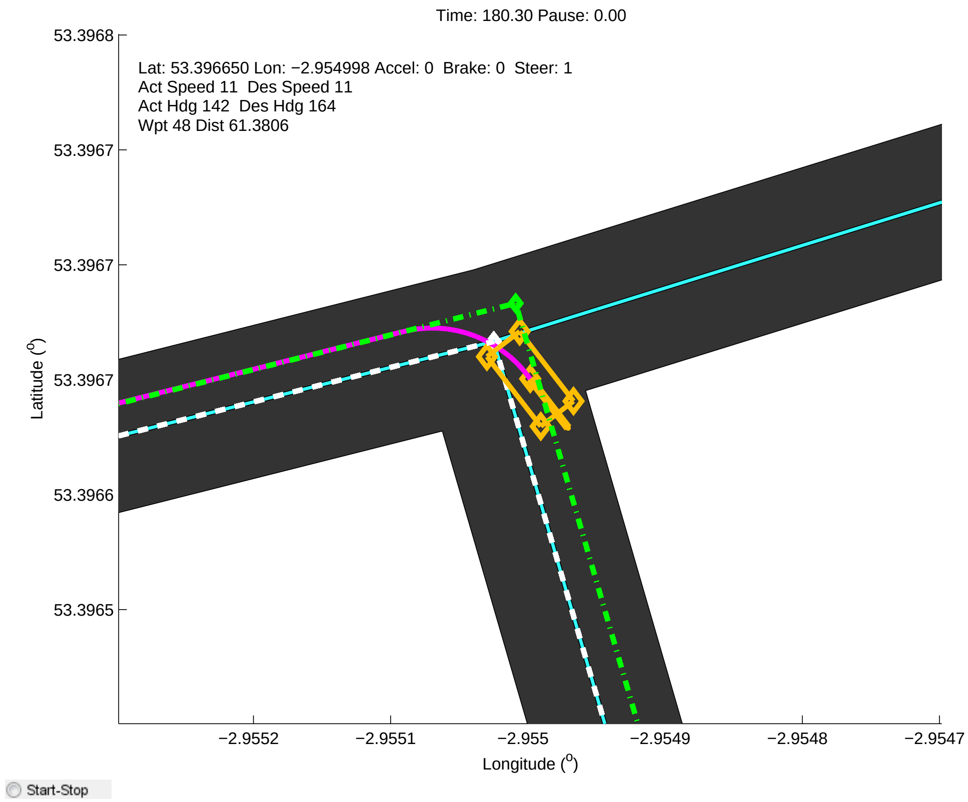

Figure 3.23: Simulation of a Car Type Vehicle in MATLAB Driving on OSM Roads

Figure 3.23 shows the overview of a simulation of a car type vehicle on roads loaded in from an OSM database. Actual speed, desired speed, actual heading and desired heading are shown, as well as the current position and the desired mode that the vehicle is in – accelerating, braking and/or steering.

3.2 Networking

The NEC requires a well established digital communication network that includes both the traditional Radio Frequency (RF) channels as well as Internet Protocol (IP) based systems. Within NEC, the remote re-tasking of air-to-surface weapons requires links between a number of assets. The delivery aircraft, the weapon itself, and a ground station, all need to be within the same network to allow remote operators to re-task weapons in flight. These systems are independent and remote from each other, requiring RF data links to be used to establish these networks.

An RF Data Link system consists of a host Tactical Data System (TDS), an IDM and a Combat Net Radio (CNR). These systems work in tandem to generate the relevant data on-board the host system, for example positioning information, convert the data information into a standardised message format with appropriate header, convert the digital message to analogue format for broadcasting using the CNR.

RF communications are limited primarily by the power used by the radio system and line of sight between the sending and receiving systems, and these need to be taken into consideration when simulating the communication network without the use of real RF systems. This section will describe the method of simulating an RF communications network using Local Area Network (LAN) and Wide Area Network (WAN) IP.

3.2.1 Military Communication Standards

Military organisations both within sovereign states and overarching organisations such as NATO have set standards for data communications. These standards are used to ensure the compatibility of hardware and software used in the field. Variable Message Format (VMF) is a Military Standard (MIL-STD) for digital data communications which is ideally suited for Fire Support, CAS, and SA purposes. Older message standards such as Link 11 and Link 16 are limited in their flexibility due to the way in which information must be coded into pre-defined data words. This means that messages have defined lengths, and that whole message structures need to be sent, even if some data fields are redundant. This limitation is particularly problematic when the longevity of military systems is considered. New capabilities are being developed at such a prolific rate that the hardware of TDLs is becoming a limiting factor rather than the technology.

A typical VMF system configuration has three main elements, a Bearer, Message Header and the Message to be sent. Each element is defined in a separate MIL-STD. The breakdown of standards is as follows:

- CNR Protocols: MIL-STD-188-220 - Interoperability Standard for Digital Message Device Subsystems

- Header: MIL-STD-2045-47001 - Interoperability Standard for Connectionless Data Transfer Application Layer Standard

- Message: MIL-STD-6017 - K-Series Message Set [Classified]

A typical data stream is packaged with CNR Protocols leading the Header, followed by the Message and then by the terminating CNR Protocols. Figure 3.24 shows the form of the transmitted data stream [124].

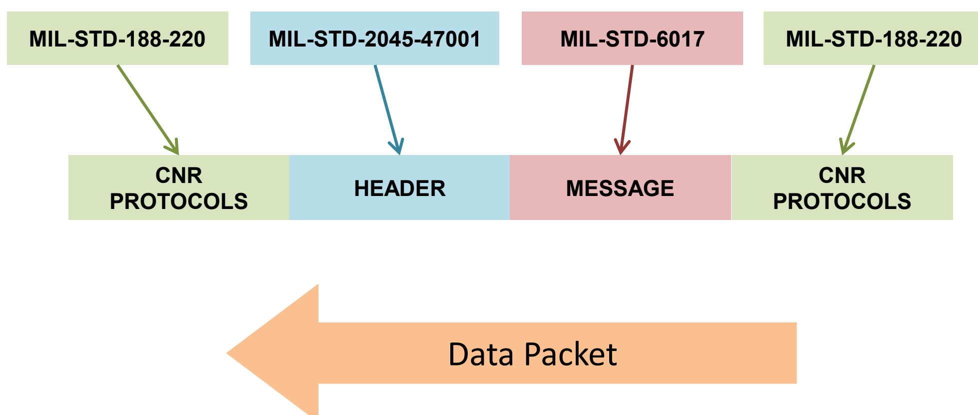

Figure 3.24: Data Packet Structure and Relevant Standards

Implementation of the VMF 'K-Series' message set requires detailed knowledge of MIL-STD-6017, which is a classified document. However, small parts of its structure are available from indirect sources [124].

The message set is categorised into Functional Area Designators, followed by the message number. For example, K05.1 is Functional Area Designators (FAD) 05 (Land Combat Operations), Message 1 (Position Report). In this case, the Position Report includes several nested structured entries. These data entries are preceded by flags that indicate the presence of certain elements within the message:

- Field Presence Indicator (FPI)

- Field Recurrence Indicator (FRI)

- Group Presence Indicator (GPI)

- Group Recurrence Indicator (GRI)

Some fields are marked as mandatory (M), mandatory for implementation (X), or optional (blank). For those fields marked mandatory there will not be a preceding field presence indicator. GPIs are used to identify the presence of a group of fields, for example see Index Number 1.8 for G1 in the K05.1 Position Report message, which contains course and speed data (see Figure 3.25 [124]). FRIs and GRIs indicate whether the messages contained will be repeated within this message.

MESSAGE NUMBER: K05.1

MESSAGE TITLE: POSITION REPORT

MESSAGE PURPOSE: TO PROVIDE FRIENDLY UNIT LOCATION DATA.

INDEX NO.	REFERENCE DFI/DUI	DUI NAME	# BITS	CAT	GROUP CODE	REPEAT CODE	RESOLUTION, CODING, ETC.
1.1	4045 001	GRI	1	M		R1(64)	GRI FOR R1.
1.2	4004 012	URN	24	M		R1	
1.3	281 402	UNIT LATITUDE	25	M		R1	
1.4	282 402	UNIT LONGITUDE	26	M		R1	
1.5	4119 002	LOCATION DERIVATION	4	M		R1	
1.6	4014 002	FPI	1	M		R1	
1.6.1	4119 005	LOCATION QUALITY	4	X		R1	
1.7	385 003	EXERCISE INDICATOR (EX IND)	1	M		R1	
1.8	4014 001	GPI	1	M		R1	GPI FOR G1. COURSE/SPEED DATA.
1.8.1	371 015	COURSE	9	X	G1	R1	
1.8.2	367 403	UNIT SPEED, KPH	11	X	G1	R1	
1.9	4014 002	FPI	1	M		R1	
1.9.1	4130 001	ELEVATION, FEET	17	X		R1	
1.10	4014 002	FPI	1	M		R1	
1.10.1	365 033	ALTITUDE, 25 FT	13	X		R1	
1.11	4014 001	GPI	1	M		R1	GPI FOR G2. IFF MODES.
1.11.1	4014 002	FPI	1		G2	R1	
1.11.1.1	293 003	MODE I CODE	5		G2	R1	
1.11.2	4014 002	FPI	1		G2	R1	
1.11.2.1	294 002	MODE II CODE	12		G2	R1	
1.11.3	4014 002	FPI	1		G2	R1	
1.11.3.1	295 002	MODE III CODE	12		G2	R1	

Figure 3.25: Position Report K-Message Series

Data from the message is then concatenated in the order listed in the index. Mandatory fields are always included, as are FPIs and GPIs. However, if the FPI or GPI is zero, this means that the message following is not present and is omitted from the concatenated data. Repeat codes (R1) mean that a group may be repeated, and a number in brackets after such a code indicates the maximum number of group occurrences permitted.

Although a complete K-Series message set library is unavailable due to classification, the FAD are known to be as follows:

0. Network Control
1. General Information Exchange
2. Fire Support
3. Air Operations
4. Intelligence

5. Land Combat Operations
6. Maritime Operations
7. Combat Service Support
8. Special Operations
9. Joint Task Force Ops
10. Air Defence/Airspace Control

The communication protocols for the re-tasking of air-to-surface weapons need to exist within this framework of the VMF FAD structure. Re-tasking can be seen as an extension to the CAS function, where airborne bombs and missiles are considered to be air assets that can be called upon for CAS. If this is the case then within the scope of VMF, CAS exists as part of the Fire Support FAD. A CAS Request and engagement is made though a series of messages [125]:

- K02.27 - Close Air Support Request
- K02.28 - Close Air Support Mission Battle Damage Assessment Report
- K02.31 - Mission Request Rejection
- K02.32 - Close Air Support Request Acceptance
- K02.33 - Close Air Support Aircrew Briefing
- K02.34 - Aircraft On-Station
- K02.35 - Aircraft Depart Initial Point
- K02.36 - Aircraft Mission Update
- K02.57 - Aircraft Attack Position and Target Designation
- K02.58 - CAS Aircraft Final Attack Control
- K02.59 - Request for K02.57

These messages bear some similarity to the NATO CAS 9-Line Brief, which includes the following information:

- Destination ID
- Callsign
- Initial Point

- Target Distance from Initial Point
- Target Position
- Target Elevation
- Target Description
- Mandatory Attack Heading
- Friendly Distance
- Time on Target
- Marker
- Laser to Target

Without access to the VMF message set in more detail it is unclear what specific data would be included in the K02 messages. However, it is clear that certain data, such as position and elevation of the target are imperative, as well as data relating to the unit tasked to prosecute the target, and data relating to the unit that has identified and marked the target, will be included in this data structure. A typical scenario may involve a number of steps to transfer the relevant information between an attack aircraft and the FAC who is calling in the attack. Figure 3.26 shows this scenario, highlighting the different messages that may be sent in such an engagement.

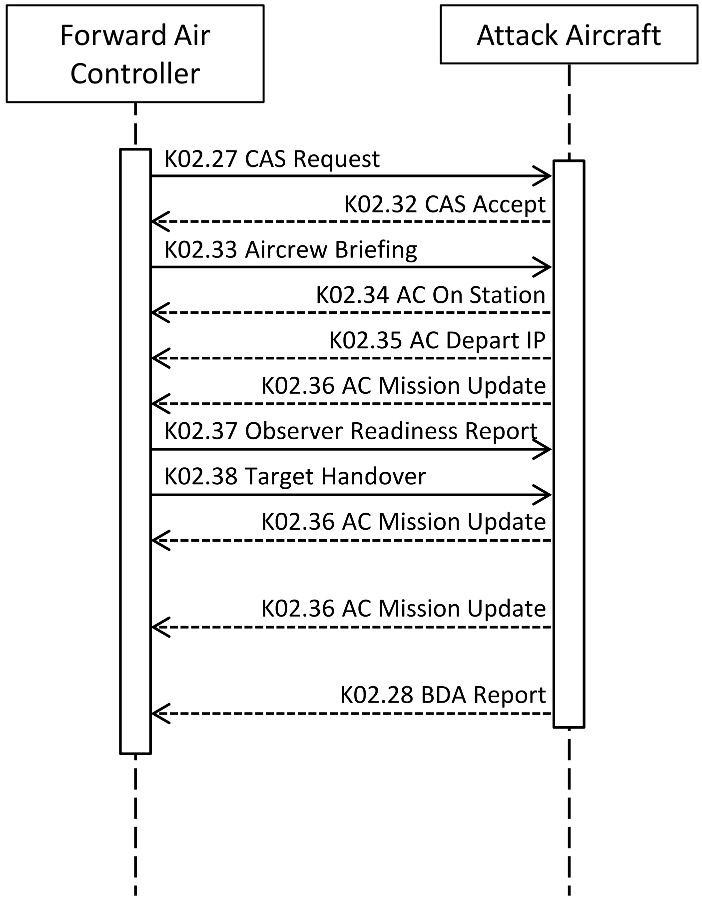

Figure 3.26: Messages Sent in CAS Mission Using VMF K-Series Messages

3.2.2 Types of Digital Networking Communications

One of the communication principles behind the development of VMF was that it uses Ethernet type principles. For example, all computers that exist on a LAN or WAN listen and receive data, however, computers only process data that is addressed to them individually, or those addressed to a whole sub-network (LAN). VMF is organised into LANs of up to 12 units, then using IP are connected to other LANs in a WAN. This allows for messages to be transmitted to individuals, groups, or all units within a force.

With modern computing capabilities, several simulations of different functioning roles can be simulated side by side on the same computer system. However, in order to sufficiently represent a military CNR network each independent entity was simulated on a physically separate computer system. The computers were set up initially in a LAN using the Campus Area Network for access to the Internet. To be able to communicate directly between computers a Transport Layer is needed. This acts much like the CNR MIL-STD-188-220 and handles various services that allow for communication to occur. Several different Transport Layers exist and so analysis as to which best suits the architecture of Military RF Networks was needed. The main transport layers are:

- User Datagram Protocol (UDP)
- Transmission Control Protocol/Internet Protocol (TCP/IP)
- Stream Control Transmission Protocol (SCTP)
- Datagram Congestion Control Protocol (DCCP)

Table 3.3: Transport Layer Specifications

Feature	UDP	TCP	SCTP	DCCP
Packet Header Size (bytes)	8	20-60	12	12/16
Transport Layer Packet Entity	Datagram	Segment	Datagram	Datagram
Connection Oriented	No	Yes	Yes	Yes
Reliable Transport	No	Yes	Yes	No
Preserve Message Boundary	Yes	No	Yes	Yes
Ordered Delivery	No	Yes	Yes	No
Flow Control	No	Yes	Yes	No
Congestion Control	No	Yes	Yes	Yes
Explicit Congestion Notification	No	Yes	Yes	Yes
Multiple Streams	No	No	Yes	No

Table 3.3 shows the different features present in each Transport Layer. Each feature listed provides a particular service or characteristic of the transport layer protocol as described below:

- Packet Header Size is the number of bytes that needs to be present at the beginning of a data packet to enable the receiver to successfully identify the message and its transport layer properties.
- The Transport Layer Packet Entity can take two forms, Datagram or Segment. Datagram means that the entire intended message is sent as a discrete packet. Segment means that a message is split into segments when sent and then reconstructed at the receiver using information in the packet header.
- A Connection Oriented architecture means that the Transport Layer protocol locks the specific channel that is being used for communication. These channels are known as ports and have a specific numerical value.
- Reliable Transport means that the Transport Layer accounts for each packet that is sent and ensures that each message is received without corruption. If the

message received is corrupted, or there is a missing packet in a stream, the sending system will continue to send the packet until acknowledgement of successful receipt of the packet is received.

- Preserve Message Boundary means that the message is sent complete, rather than in segments.
- Ordered Delivery means that, if several packets of data need to be sent, in a particular order such as individual words in a sentence, then the order in which packets are sent is maintained.
- Flow Control is then a feature that controls the flow of consecutive ordered packets of data.
- Congestion Control is a feature that controls how congestion is handled when a receiver cannot process incoming packets as quickly as they are being received.
- Explicit Congestion Notification allows for transmitting systems to slow their packet transmission to prevent congestion.
- Multiple Streams is the ability to send multiple packet streams at the same time.

CNRs have very limited bandwidth and are affected by a range of propagation issues and losses. It is suggested that UDP is therefore the preferred type of Transport Layer used in these systems [126]. UDP allows for data to be sent in bursts or individual packets rather than requiring a complex continuous structure as used in TCP/IP which would lock up a communication channel on the CNR network until a message had been successfully been sent.

Within UDP are several types of routing schemes for packets. Some of the more applicable schemes are listed below and are represented in Figure 3.27, 3.28, and 3.29. These routing schemes define how information is directed around a network:

- Unicast - Transmission of messages to a single network destination identified by a unique IP address.

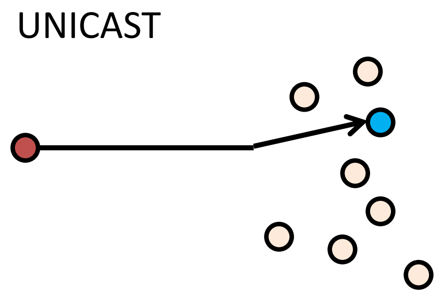

Figure 3.27: Unicast Routing Scheme

- Multicast - Transmission of messages from one to many network destinations identified by a unique IP address that exist as part of a group of recipients.

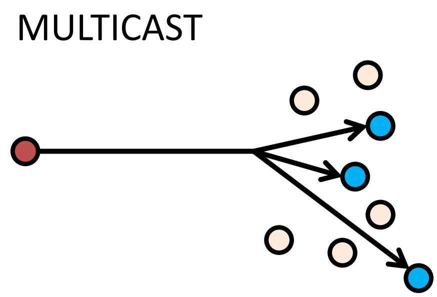

Figure 3.28: Multicast Routing Scheme

- Broadcast - Transmission of messages to all recipients simultaneously. It is largely used to send messages to all members of a LAN.

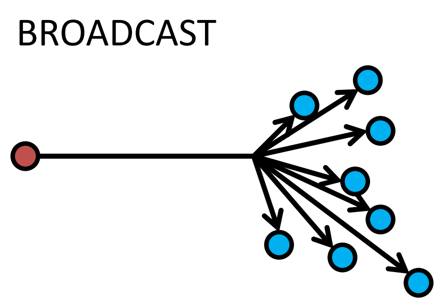

Figure 3.29: Broadcast Routing Scheme

The network used in the simulation facility needed to link weapons, operational and simulated aircraft, and ground operator terminals, but maintain the individual host systems as separate entities. Seven different computer systems were used to run the simulation environment as a whole. Figure 3.30 details the system architecture.

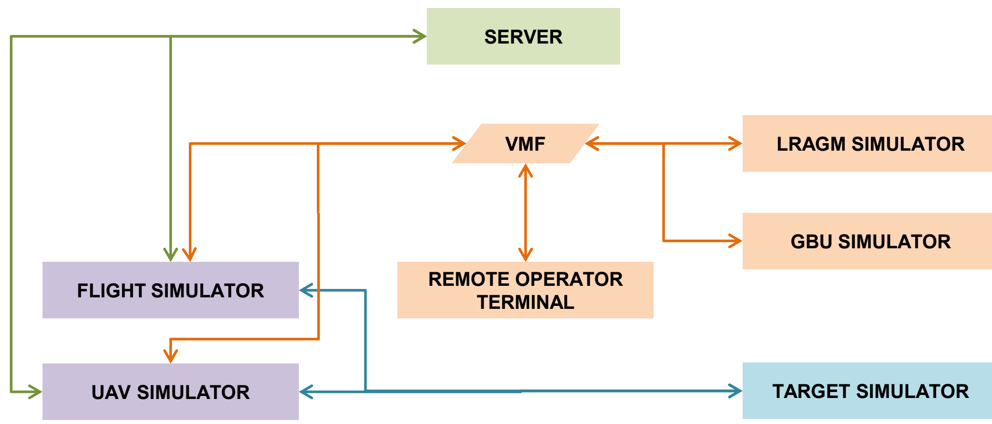

Figure 3.30: System Architecture for Distributed Simulation Environment

The VMF type messages are transmitted between distinct points in the network. Each block in Figure 3.30 represents an individual computer system. The LRAGM and GBU simulations are linked to the Remote Operator Terminal using only VMF type messages. They are unaware of each other on the network, but have additional communications protocols with their launch platform up until the point of handover to the Remote Operator Terminal. Targeting is handled initially through the flight simulators; the sensor pods are used to locate and identify targets generated by the Target Simulator. Once the weapon is released this information is passed to the Remote Operator Terminal using VMF, and then if necessary sent as target updates from the Remote Operator Terminal to the weapon that needs its target updating. Figure 3.31 shows the network message protocol for transferring targeting information to the weapon before launch (using a direct link), and then during flight (using VMF).

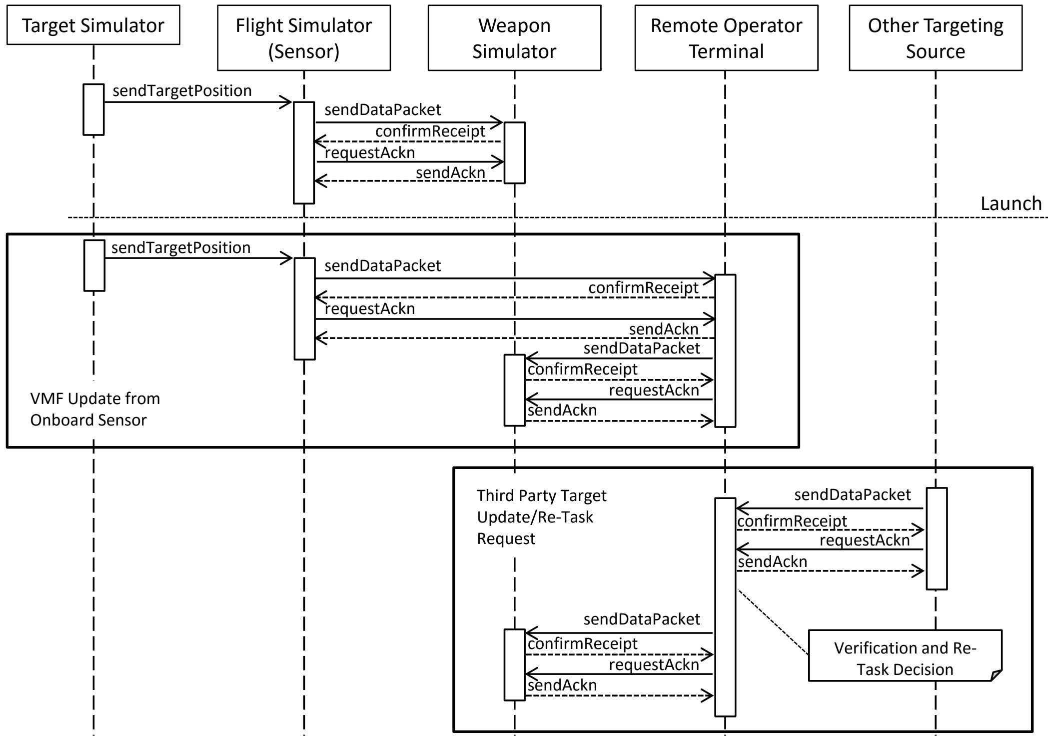

Figure 3.31: Network Message Protocol for Transferring Target Information Amongst Entities in Distributed Simulation Environment

Unicast UDP routing was used as it provides the simplest addressing format for the networked messages. However, the implementation of the unicast system within the messaging program means that the network representation is essentially multicast. The messaging software sends the same message out to all known unicast routes. Due to the rules on the use of the university network, broadcast UDP was not allowed and the physical distance between the different simulation computers used meant that a bespoke LAN was not possible. Therefore grouping all of the unicast addresses and then sending the messages to all allows a representative broadcast network to exist.

3.2.3 Handover, Acknowledgement and Handshake Procedures

As all messages are transmitted to every entity on the network, the bespoke architecture needs to maintain appropriate identification and acknowledgement principles. When sending VMF/CAS type messages, there must always be a Destination ID and Callsign attached to each individual asset within the simulation environment. When a message is received the first few bytes are decoded that contain the Destination ID and Callsign of the intended recipient. These are then cross-checked with the Destination ID and Callsign of the receiving unit. If they match, the rest of the message is processed, otherwise the message is ignored.

One of the missing features of UDP is a reliable and coherent message receipt acknowledgement architecture. This required the inclusion of a custom read back acknowledgement and handshake system. The requirements of the messaging system mean that a receiver of a message must first read back the entire message to ensure that no corruption has occurred. Then the receiver must relay whether they are acting on the message or not. With reference back to Figure 3.31, also shown is the flow diagram of a single CAS request using the custom UDP VMF system. Firstly the message is converted into the correct format and sent to all listeners on the network. It is received by the intended system and the message is sent back with an acknowledgement of receipt of the message. The initial sender then transmits that the message is intact and correct. The receiver then replies whether they have accepted or rejected the mission. The flexibility of UDP to be able to include a customised acknowledgement was important such that the network system was representing a robust but imperfect system where packets could potentially be dropped, rather than a perfect system where there is no risk of communication failure.

3.2.4 Delays and Missed Messages

As there is a defined structure for acknowledgement of messages, the message creator and sender will know if the message has been received or not. In a condition where the message is missed, due to dropped packets or drop out of the network, the acknowledgement procedure has a built in time-out. This time-out only listens for responses to the sent message for 15 seconds before timing out the message. This accounts for any delays in the transmission of messages, or delays due to processing time at the receiving end by an automated system or a human operator receiving a message. In the latter case, the operator will only be presented the information on which to make a decision after the first three stages of the acknowledgement procedure have occurred.

3.3 Interactive Simulation

Personal computing and the computer games industry have developed significant capability for presenting a user with interactive and graphically representative simulations of the real world. The hardware in most medium specification personal computers or laptops is capable of driving significantly complex graphics engines. In tandem, the computer games industry have produced virtual worlds with stunning detail. The role of interactive simulation in this body of research is to allow pilots as well as ground operators to interact in a large scale simulation environment.

3.3.1 Visualisation Environments

Flight simulation has been a vitally important industry for its utility as a training tool for the airline industry and the military, as a research tool in academia and as a gaming environment for enthusiasts. Several different companies have released bespoke flight simulation software, such as Microsoft (Microsoft Flight Simulator series), Laminar Research (X-Plane series), and Flight Gear. The complexities of these visualisation environments has developed to a point where the terrain modelling includes real world road networks, ground vehicles, real world buildings, airports and aviation traffic.

3.3.1.1 XPlane vs. MSFSX

At the outset of the project the selection of appropriate software was key. X-Plane 9 (Later upgraded to 10) was already pre-installed onto the Avionics Testbed Facility (ATF) Simulator, however, another and arguably the largest PC format flight simulator on the market is Microsoft Flight Simulator X (MSFSX). These two simulators were selected as main contenders due to their leading positions in the simulation software market. A comparison between the two was key to making an informed decision between the software. The following areas needed consideration before making a decision as to which software was better suited to the application in this body of research.

- Realism
- Data Accessibility and Control
- Software Updates and Effects

It was important to identify a strong visualisation tool that would be maintainable for the longevity of the project and the facility, as there are significant learning overheads associated with the familiarisation of coding practices for each piece of software. Should a function be needed later in the development of the facility that was not properly identified early in the project there could have been serious delays in the project. The three main areas for consideration will be discussed in the next few sections:

3.3.1.1.1 Realism

The two simulation suites offer different levels of both visual and physical realism, where visual realism is the degree to which the simulation represents the real world in terms of graphics and physical realism is the degree to which the simulation represents the aerodynamics and flight characteristics of the aircraft being flown.

The visual representation of the graphics capabilities of both X-Plane 10 and MS-FSX are high. What is particularly relevant is that X-Plane 10 has accurate road map data for the UK, and indeed almost the entire globe, as it uses OSM as its data source [127]. This was deemed particularly useful as the scope of this research project included targeting moving vehicles. Further, as the Remote Operator Terminal would be developed using map data from the same source, it would make integration simpler.

In terms of physical realism X-Plane 10 also out-performs MSFSX in how it calculates the dynamics of aircraft within the simulation. Whilst MSFSX uses the industry standard Total Forces and Moments Method, X-Plane uses Blade Element Theory which slices each aerodynamic surface into several sections which results in an increase in accuracy by approximately 20% [128]. Blade Element Theory is typically used to find the forces on helicopter rotors [129] and has been modified to analyse the aerodynamic surfaces of aircraft in X-Plane [130]. Whilst the weapon systems are represented by external MATLAB models, the release aircraft were not modelled and default aircraft from the simulation software were used.

3.3.1.1.2 Data Access and Control

X-Plane and MSFSX offer a Software Development Kit (SDK). A SDK allows for additional feature implementation through writing code that can be called from the simulation software in its internal runtime. The ability to develop within the SDKs is still limited by the scope of the SDK, and the areas that plug-in software can be developed must be considered in relation to the custom functionality that might want to be added to the simulator.

MSFSX is split into four core categories [131]:

- Core Utilities Kit
- Environment Kit
- Mission Creation Kit
- SimObject Creation Kit

X-Plane is split into eight core categories [132]:

- Data Access
- Processing
- User Interface
- Graphics
- Camera Control
- Navigation and the Flight Management Computer (FMC)
- Aircraft
- Widgets

Whilst both software applications offer considerable customisation and development tools, one critical element not provided by MSFSX is Weaponry. MSFSX is tailored towards civil flight simulation and does not include a system for weapons. X-Plane 10 has a range of weapon types implemented into the simulation from guided air-to-air missiles, rockets and bombs. The limits on the X-Plane built-in weapons system is its inability to guide weapons to ground targets. The guidance of air-to-surface weapons has not been developed in X-Plane.

3.3.1.1.3 Software Updates and Effects

Considerations of the effect of version updates on the development of plugin code were also made when deciding which simulation environment to choose. X-Plane 10 (released in 2012) has full backwards compatibility with plugins generated for X-Plane 9.70. The plugins built for Microsoft Flight Simulator 9 (2004) are not compatible with MSFSX, nor are they with Microsoft's latest Flight Simulation software, "Microsoft Flight". This makes the longevity of software plugins in the Microsoft Flight Simulator franchise through future releases very difficult, and will require re-development of plugins with each new release.

3.3.1.1.4 Overall Considerations

The final decision was made to use X-Plane as a visualisation environment for this body of research. There is a larger scope for data access and control through the use of plugins. There is more longevity of plugin development with backwards compatibility. X-Plane has a far more realistic flight model dynamics for piloted aircraft, and has comparable graphical fidelity with the inclusion of OpenStreetMap road networks.

3.3.2 MATLAB Weapon Simulation Integration with X-Plane Plug-ins

X-Plane has a range of data which it can either send over a network via UDP packets or a larger set that can be accessed via DataRefs in plugin development [132]. A DataRef is an internal memory address within X-Plane that allows for reading and writing specific properties used within the simulation. For example, setting the altitude property to 5000 (ft), would place the user aircraft at that altitude.

The complete DataRef list is expansive, with over 4800 items that can be interacted with through plugins developed using the SDK [133]. DataRefs are accessed with a string handle (a data type made up of characters) that navigates through the DataRefs structure. The specific set of DataRefs that are of significance to the integration of MATLAB weapon simulations are accessible through the '`sim\weapons\...`' leader, followed by the string related to the specific data needed.

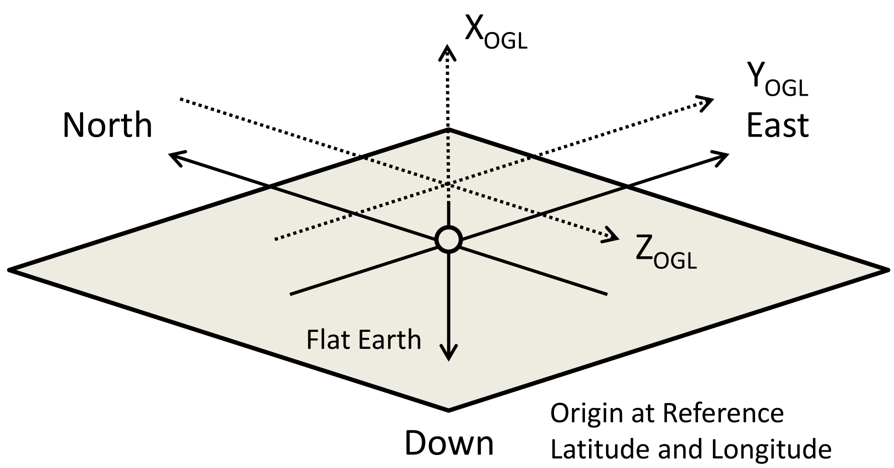

Figure 3.32: Open GL Coordinate System and NED Flat Earth System

The main variables that need to be set to show weapons within the X-Plane environment with data generated from MATLAB are positional and attitude information. The X-Plane 3D environment uses the OpenGL coordinate system, and attitude is set using the quaternion rather than Euler angles. This data can be written to the simulation using the 'x', 'y', 'z', and 'q1', 'q2', 'q3', 'q4' handles. x, y, z in OpenGL relate to NED as shown in Figure 3.32. The quaternion is a form of representing rotational information in three axes with four unit quantities. The Euler Angle representation of orientation can be obtained by converting the quaternion as follows:

$$\begin{bmatrix} \psi \\ \theta \\ \phi \end{bmatrix} = \begin{bmatrix} \arctan 2(2(q_1 q_2 + q_3 q_4), 1 - 2(q_2^2 + q_3^2)) \\ \arcsin(2(q_1 q_3 - q_4 q_2)) \\ \arctan 2(2(q_1 q_4 + q_2 q_3), 1 - 2(q_3^2 + q_4^2)) \end{bmatrix} \tag{3.47}$$

Conversion from Euler to quaternion is achieved using the following:

$$q_1 = \cos(\phi/2)\cos(\theta/2)\cos(\psi/2) + \sin(\phi/2)\sin(\theta/2)\sin(\psi/2) \tag{3.48}$$

$$q_2 = \sin(\phi/2)\cos(\theta/2)\cos(\psi/2) - \cos(\phi/2)\sin(\theta/2)\sin(\psi/2) \tag{3.49}$$

$$q_3 = \cos(\phi/2)\sin(\theta/2)\cos(\psi/2) + \sin(\phi/2)\cos(\theta/2)\sin(\psi/2) \tag{3.50}$$

$$q_4 = \cos(\phi/2)\cos(\theta/2)\sin(\psi/2) - \sin(\phi/2)\sin(\theta/2)\cos(\psi/2) \tag{3.51}$$

where q_n is the nth quaternion (total of 4)

In addition to the weapon DataRefs, the MATLAB simulation needs to know where to set the origin of its NED coordinate system so that the MATLAB simulation and the X-Plane environment share a common position. The LLA above sea level are used as a common geo-referencing system. The weapon simulation in MATLAB is initialised at point of release with the current LLA. This becomes a Reference LLA and is stored for the duration of the simulation of each weapon (GBU or LRAGM). This Reference LLA is set to zero altitude and is then used to position the NED coordinate system's origin, placing the weapon at 0 metres North, 0 metres East and at the initial altitude in metres in the Down direction.

As the weapon simulation is running, position updates are sent to X-Plane for visualisation. The positions of the weapon in MATLAB are first converted from NED to LLA to be sent to X-Plane. When X-Plane receives the position update in LLA, with attitude information in a Quaternion, X-Plane then converts the LLA into the OpenGL XYZ reference system and updates the DataRef that holds the weapon data, as well as the Quaternion. The graphical object in X-Plane then updates its position in the simulation environment.

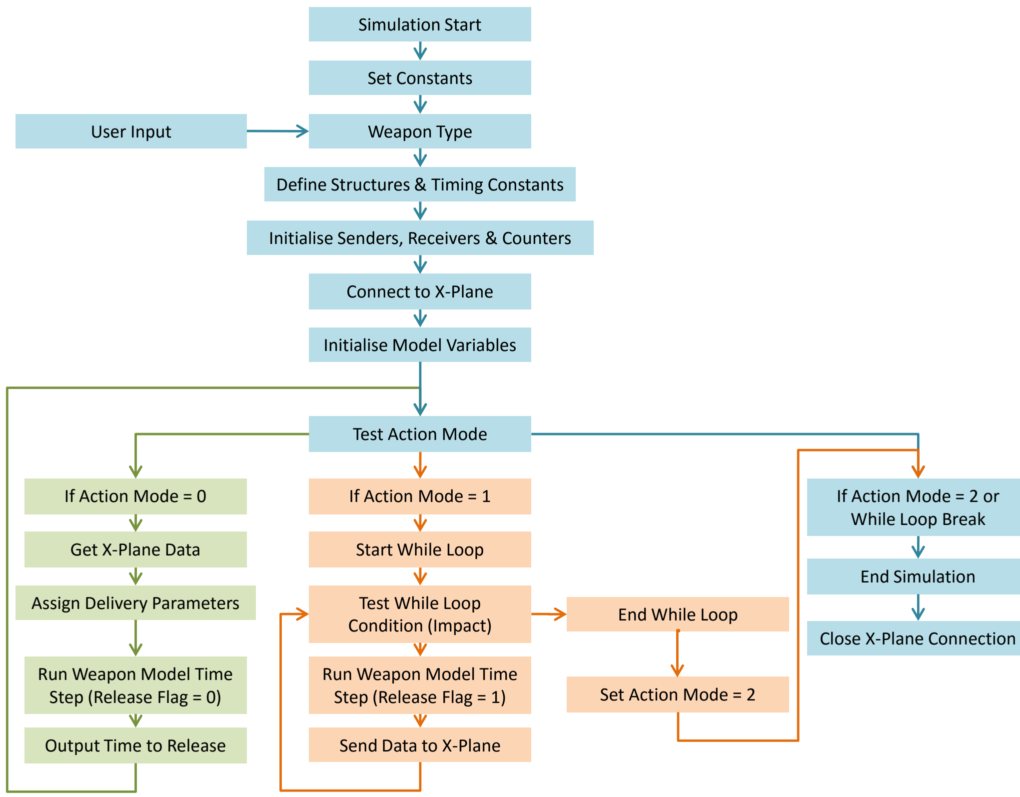

Figure 3.33: Flow Diagram of Weapon Simulation Including Networking Links With X-Plane

The MATLAB simulation of the weapon will only cease when an impact condition is met. This is defaulted to be when the weapon hits the ground. However, the MATLAB simulation is run in an idealised flat earth NED representation and cannot detect ground elevation information from within X-Plane. Instead, X-Plane must handle the condition of when a weapon hits the ground. A flag is then sent to the MATLAB simulation indicating that the weapon has hit the ground in X-Plane. X-Plane also has an SDK function that allows the ground elevation data to be read at a specific set of coordinates. When the impact flag is set, the SDK function 'terrainYTest' is run to obtain the ground elevation data at the position of weapon impact in the X, Z plane. The weapon is then set to this position in OpenGL coordinates and converted to LLA to be sent to MATLAB. Figure 3.33 shows a diagram of this process, from initialisation of the weapon to the handling of an impact condition. This process is common between the GBU and LRAGM weapon simulations.

The data structure used to transfer model information between X-Plane and the MATLAB simulation is shown in Figure 3.34. The structure includes several additional pieces of information that are required for initial targeting of the weapon, and to provide launch information to pilots in X-Plane. It is used to initialise the weapon with a target and update the physical location of the weapon in the X-Plane simulation environment, and differs from the VMF Re-tasking message structure in its message content and requirement for acknowledgement.

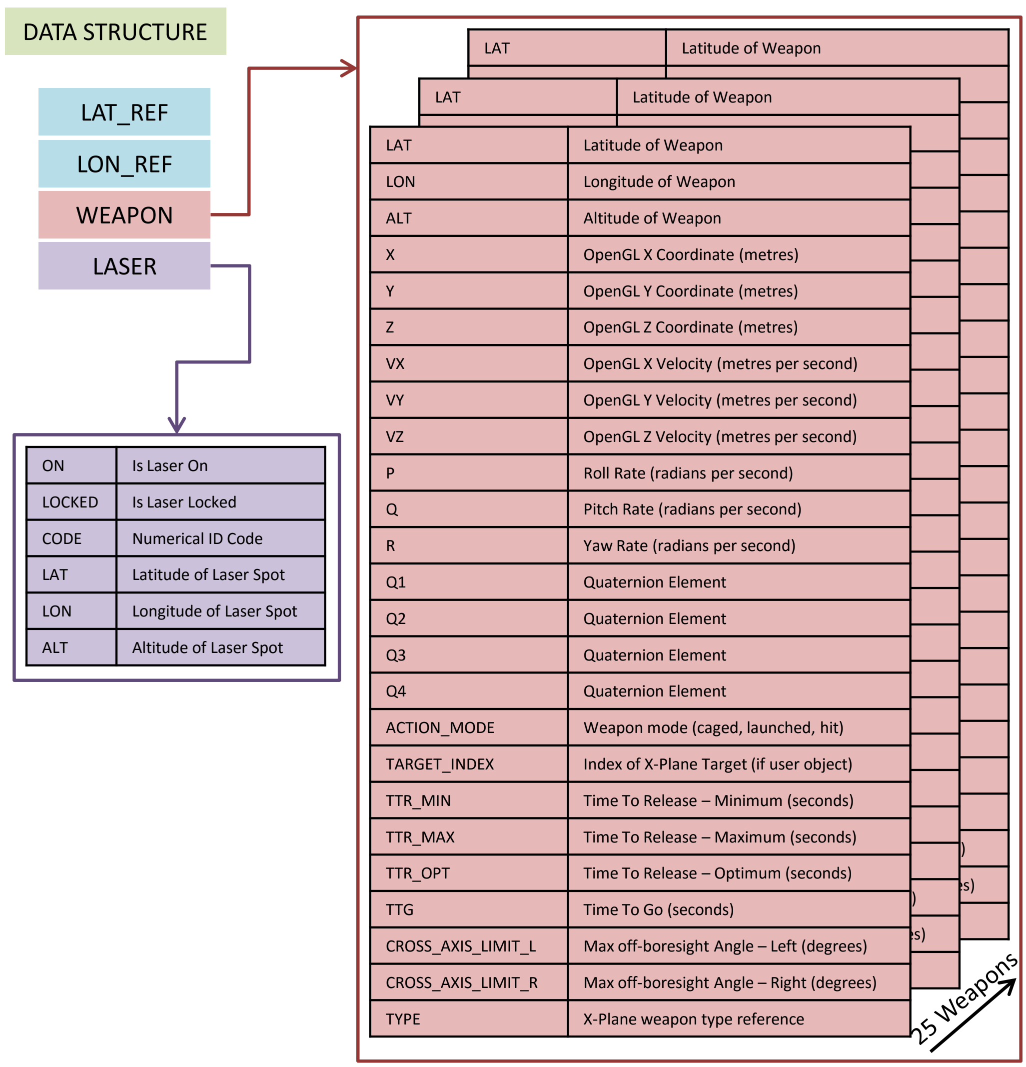

Figure 3.34: Flow Diagram of Weapon Simulation Including Networking Links With X-Plane

3.3.3 MATLAB MEX Functions for UDP Messages

MATLAB MEX files allow for compiled C++ code to be included as functions within the MATLAB native environment. This additional functionality was used to generate a UDP message sending and receiving service between different instances of MATLAB (for the different simulations) and other programs such as X-Plane. The advantages of using compiled MEX code are that the execution speed is faster than using the MATLAB runtime environment and the structure of messages must be declared before compiling the MEX files.

Figure 3.35 shows a screen shot of two moving armoured targets simulated in MATLAB and visualised in X-Plane using graphical objects. MATLAB MEX files are used to send positioning information from MATLAB to X-Plane for real-time simulation.

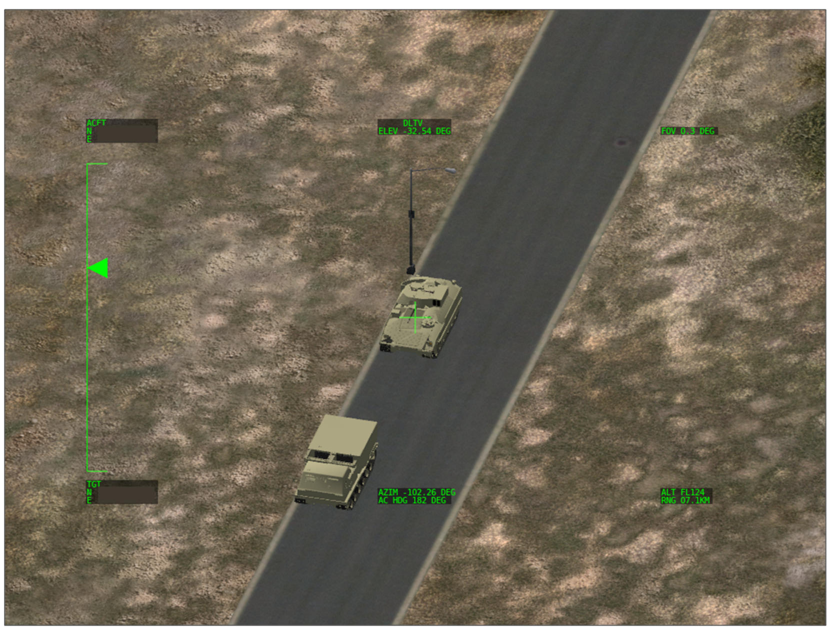

Figure 3.35: Two Armoured Vehicles on an OSM Road in X-Plane

Figure 3.36: Test GBU Launch Against a Mobile Armoured Target

Figure 3.36 shows a simulated test firing of a GBU against a mobile armoured target moments before impact. Debug graphics can be seen overlaid onto the screen including launch aircraft status, a radar and a high visibility cross to show weapon position.

Chapter 4

Real-Time Task Allocation for Remote Weapon Operators

4.1 Introduction

Over the last ten to fifteen years, there has been a rapid increase in the use of digital communication networks to share data between military systems. NCW in the US [7] NEC in the UK [1] allows a commander to link many sensors spread across a number of platforms, and then to distribute the resultant picture to personnel at the front line. This sensor-to-shooter capability can provide real-time situational updates to weapon operators [9], the main aim being to enhance effectiveness whilst reducing the risk of collateral damage/casualties.

The ultimate example of the NCW approach is the use of UAVs and remotely operated weapon systems. This is a major area of growth for the US [134], the UK [135] and an increasing number of countries around the world. The use of such platforms raises a number of legal and ethical issues that have been the subject for much recent debate [136]. One of the chief concerns in such discussions is the role of the operator and the ability of the operator to make informed, reasoned and ethical decisions when he/she is remote from physical danger [137]. This is an important area of active research that touches on ethical/legal constraints, human-computer interaction, the psychology of decision-making and the physical limits of the technologies involved [138]. In such complex multi-faceted systems, it is crucial that great care is taken to ensure that all factors are addressed.

A key decision in the development of any remotely operated system is the level to which tasks are delegated to an automated or autonomous sub-system, with the human operator retaining supervisory control over the whole system. The distinction between automated and autonomous sub-systems is important. An automated system reacts to input data in a predefined and well-regulated way, whilst an autonomous system is able to make reasoned decisions, based upon a range of possible input data. Automated systems are common; ranging from simple central heating systems to complex aerospace flight control systems. Autonomous systems are rapidly becoming more common; as physical robots that can sense, explore and reason about their environment and software internet bots to take much of the drudgery out of repetitive analysis tasks.

It is essential that a human operator retains the final decision regarding the prosecution of a valid target because only a human operator has the legal (and ethical) authority to commit a weapon to a target. Whilst current doctrine and RoE require an operator in the loop, electronic systems are required to provide all of the relevant information to enable them to make their final decision within operational, legal and ethical constraints. It is important, therefore, to ensure that the information is timely, appropriate, and that it adapts to the changing situation on the battlefield.

An evolving area of applying automation techniques to support military decision making is though automatic task allocation problems. If there are a given number of assets, with different types of effects that can be delivered, how best should they be distributed in a given scenario for optimum effect and efficiency? There are a range of different optimisation techniques that can be applied to these types of distribution problems where the aim is to either minimise or maximise some function. The scenario used for configuring the task allocation software was focussed in the air-to-surface weapon domain. A number of aircraft, with different payloads, were available to be tasked amongst a mixed set of targets that require different effects.

This chapter presents an investigation of the applicability of resource-task allocation algorithms when run in a real-time environment and incorporated into an operator terminal. The resource-task allocation algorithms take into account the resources available for deployment; including the physical limitations on aircraft and guided weapon systems moving in to engage a target, the operational constraints around using certain types of weapon against certain targets, the occurrence of targets of opportunity and the need for sensors to be deployed to provide positive target identification and potentially laser designation of the target [13].

4.1.1 Remote Operation of Multiple Air Platforms

UAVs or Unmanned Weapon System (UWS)s in use today tend to be remotely piloted systems, with some automated systems largely responsible for the non-critical elements of the flight management systems. An operator might be responsible for flight, weapon and sensor systems. Some advanced reconnaissance UAVs have a wide range of sensors, including multiple wide field of view imagers, multi-spectral thermal imagers, imaging radars and electronic warfare systems. Each of these systems often requires a dedicated operator to manage the sensor, make assessments and relay the intelligence gleaned.

Weapon loads for armed platforms tend to be more limited than their sensors. An armed UAV will have a limited number of guided weapons that can be deployed against ground targets or in self-defence, often far fewer weapons than a manned platform: a mixture of precision guided bombs, anti-armour missiles and air-to-air missiles. Added to this is a new generation of small UWS, loitering munitions, which have a limited duration compared to a full-sized UAV but far longer flight duration than a conventional weapon system.

This chapter examines a situation where the current generation of remotely piloted systems has advanced to a stage where more of the flight-critical tasks can be delegated to autonomous systems and a remote operator has more of a supervisory role. This supervisory role could cover a number of different UAVs and UWSs and may involve a range of different tasks and targets. Tasks may be subject to different operational constraints (e.g. risk of collateral damage, priority tasks due to troops in contact, or laser designation required). The air platforms may have different capabilities (maximum speed, duration, time on station), and each platform may have a different weapon load, which depends on the weapons loaded at launch and the targets/tasks that have been assigned previously to that platform.

As already discussed in Chapter 2, research in the field of remote weapon operations for TLAMs [36] has found that a remote operator can supervise up to 12 weapons, but that operator effectiveness is significantly degraded when an operator is required to supervise 16 weapons. Similar performance degradation has been noted for ATC staff supervising similar numbers of aircraft [101]. In both of these examples, the platforms that the operators/controllers were responsible for were of a similar type and had similar roles. For example, all weapons of the same type in the TLAM scenarios and all piloted aircraft with similar performance in the ATC example. The factors associated with the different platforms/weapons and the tasks complicate the job of the operator and are likely to lead to reduced operator effectiveness if too many platforms/tasks are assigned.

In light of these studies, the algorithms discussed, although designed to deal with an arbitrary number of platforms and tasks, are optimized to be able to provide information to an operator in real-time (at a refresh rate of approximately once per second or once per two seconds) for up to about ten platforms and a slightly larger number of tasks. It would not be possible to guarantee real-time information for arbitrary numbers of platforms and tasks because the allocation problem is an example of optimal scheduling, which is known to be NP-complete. The time taken to find an optimal solution therefore scales in a non-polynomial way as the number of tasks and assets increases (assuming a deterministic algorithm).

4.2 Scenario Generation

Forming a representative scenario is a limiting factor due to the potential issues surrounding security and classification of documentation. Further, a true test of the resource task allocation algorithms is to be able to find a solution to a range of different scenarios rather than optimise for a single case example. There are three main variables that exist for the establishment of a scenario. These are the platforms available, their respective weapon and sensor payloads, and the targets in the scene.

The platforms used in the examples are of four types, taken to represent a range of possible scenarios:

1. an unarmed reconnaissance UAV
2. a weaponised Unmanned Combat Air Vehicle (UCAV)
3. a loitering UWS
4. a manned CAS aircraft

With the exception of the unarmed reconnaissance UAV, each aircraft may be loaded with ordnance selected from five weapon types:

1. an inertially-guided bomb equipped with an impact fuse (GBU)
2. an inertially-guided bomb equipped with an air-burst fuse (GBU)
3. a Laser-Guided Bomb (LGB) with an impact fuse (LGB)
4. an Autonomous Anti Armour Weapon (AAAW)
5. a Laser-Guided Anti Armour Weapon (LGAAW)

In the case of the UWS, it may contain a unitary warhead corresponding to one of these types of weapon or it might dispense sub-munitions corresponding to these warheads. This set of weapons were included to represent a range of operational scenarios and a range of guidance requirements (fully autonomous once deployed or requiring semi-active laser guidance). The targets represented are of four general types:

1. Personnel
2. Vehicle
3. Building or Structure
4. Unknown

An unknown target type was included to allow the scenario to evolve dynamically and allow a reconnaissance UAV to be tasked to interrogate the target. The unknown target could then be removed if it was determined to be non-threatening, or assigned to one of the other three classes of task if it was identified as a threat, possibly requiring a reassignment of assets/resources. A sixth (non-weapon) resource was required to represent such a sensor scan and can only be allocated to non-UWS platform types. Typical load-outs for each aircraft type are shown in Table 4.1 along with the performance characteristics of the platform.

Table 4.1: Aircraft Capabilities and Load-Outs

	UAV	UCAV	UWS	CAS
Station Time (minutes)	127	60	30	30
Attack Speed (Knots)	49	103	75	247
Weapon Count	0	4	1(self)	10
GBU	0	0	1	0
LGB	0	4	0	4
AAAW	0	0	0	0
LGAAW	0	0	0	6
Seeker Scans	99	9	0	99

The scenario generator also allows for tasks to be added and/or removed at different times to represent the changing nature of the battlefield. Whilst the operator supervises the automated allocation of assets to tasks via the interface, it is crucial that a platform is only finally assigned to the task when the operator confirms (or amends) the allocation. A re-allocation of platforms suggested by the algorithms in an evolving scenario can be flagged to the operator in the system, but the operator takes all re-assignment decisions. The system is not truly autonomous since it requires human supervision and intervention. However, decision making within the allocation algorithm is logical and subject to the same operational constraints that the human operator is subject to, and allocations may be analysed in a debrief mode.

4.3 Real-Time Sensor-Effector Allocation

The allocation of tasks to platforms is performed using two allocation matrices, the allocation matrix (A) and the resource matrix (R):

$$A_{m,n} = \begin{pmatrix} n_{1,1} & n_{1,2} & \cdots & n_{1,N_t} \\ n_{2,1} & n_{2,2} & \cdots & n_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ n_{N_p,1} & n_{N_p,2} & \cdots & n_{N_p,N_t} \end{pmatrix} \tag{4.1}$$

$$R_{m,n} = \begin{pmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,N_t} \\ r_{2,1} & r_{2,2} & \cdots & r_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ r_{N_p,1} & r_{N_p,2} & \cdots & r_{N_p,N_t} \end{pmatrix} \tag{4.2}$$

The allocation matrix has a row for each platform (1 Np) and a column for each task/target (1 Nt). For each platform, the entries are either zero meaning that the task is not allocated to that platform or a number, indicating the order in which the tasks are to be performed. The resource matrix has the same size as the allocation matrix and contains the resources to be used for that task: weapons to be deployed or sensors to use. These matrices are used within the allocation algorithms and an output task list is produced and passed to an operator interface, using a standard CAS-like format and VMF type network protocols (see Chapter 3).

The allocation is a multi-stage process that starts by taking into account a set of practical and operational constraints:

- Required Time on Target.
- Platform Maximum Speed.
- Maximum Time on Station of the Platform.
- Availability of a Suitable Weapon/Sensor.

If the platform cannot reach the task/target location within the time frame required or the platform does not carry a suitable weapon or sensor, then the task cannot be allocated by the algorithms. There are some combinations of resources (weapons) and tasks (targets) that are strictly forbidden and these are not included in the solution search e.g. a weapon may be deemed to carry too high a risk of collateral damage when used against certain targets. For each search step a sub-list of permitted tasks is generated to enforce these constraints.

Once the tasks/platforms have been checked against constraints, the tasks are allocated randomly to each platform. The algorithms then optimise the assignment against a cost function using three separate operations:

- random shuffle of three or more tasks between platforms
- reordering of tasks allocated to each platform
- random task removal

In addition, a final check is performed to allow for two platforms to be allocated to one task to allow co-operative laser designation if the weapon/task requires it.

The operations used in the allocation optimisation process were selected because previous work on related tasks [13, 139–141] has shown that these operations have relatively low computational overheads and rapidly converge to optimal or near-optimal solutions. For the optimisation process itself, a standard simulated annealing algorithm was used [142]. Simulated annealing allows a non-monotonic cost function to be optimised/minimised whilst searching a number of local minima to arrive at the global minimum.

The cost function that is optimised is a sum of costs associated with a number of factors. These factors can be split into two main types: those associated with the cost of the assignment (CA), and those associated with time dependent costs (CT,i). The total cost for a particular candidate assignment is then calculated using:

$$C_{Total}(A, R) = \sum_{alltargets\&resources} C_A + \sum_{alltimedelays} C_{T,i} \Delta t_i \qquad (4.3)$$

where Δt_i are time delays

The costs associated with the assignments were agreed with a non-attributable source within the defence industry and are formalised as follows:

- Weapon Types Allocated - different weapons are optimised for different types of target/role. E.g. anti-armour weapons are better used against vehicles than against personnel, but they may have a secondary role against buildings if no primary weapon is available. Certain weapon types are prohibited for certain tasks (see above), but some tasks may be allocated to several different weapon types. In such cases, there will be a preferred weapon and other non-preferred weapons. Non-preferred (but allowable) weapons incur a penalty cost, whilst the allocation of a prohibited weapon is not possible.
  E.g. Cost(vehicle, anti_armour) = 0, Cost(building, anti_armour) = 50.

- Missed Target given the complexity of the allocation task, it is not always possible to guarantee that all tasks are achievable within the constraints that have been applied. It is possible that a task might not be allocated to allow the allocation of other tasks.
  E.g. Cost(missed_target) = 200.

- Missed Priority Target - some targets are flagged as priority if there are troops in contact that require immediate CAS. Missing such targets carries a high penalty cost.
  E.g. Cost(missed_priority_target) = 2000.

- Time between Targets - even if two targets may be prosecuted in rapid succession, a minimum gap is required between each task to be supervised to allow the operator to process and confirm the attack. This is to avoid the operator workload rising to the point where he/she cannot make reasoned assignments of resources to tasks.
  E.g. Cost(time_between_targets <2_mins) = 200.

- No Laser Designation - some weapons require a coded laser designation signal to operate effectively. This can be provided by a platform with a suitable sensor and laser system, but some platforms (notably UWS) would be unlikely to have this type of facility and would require the presence of a second platform to be allocated to provide the laser signal. The lack of such a designator has a high penalty cost for laser guided weapons.
  E.g. Cost(LGB_No_laser_designation) = 500.

The time dependent costs are as follows:

- Late on Target - each task has a specified Time on Target. If a platform is allocated but may not arrive by the scheduled time, a penalty cost is applied.
  E.g. Cost(late_target_per_min) = 2, Cost(late_priority_target_per_min) = 20.

- Total Time of Tasks/Distance Travelled - where a number of tasks are allocated to one platform, the shortest distance between tasks should be preferred so a relatively small penalty cost is attached to the total time used or distance travelled between tasks.
  E.g. Cost(per_min_total_tasks) = 1 per minute.

The final stages of the algorithm re-evaluate the optimisation process using small perturbations to the costs (5% variations in each contributing factor) to ensure that the final solution is stable and insensitive to small variations in the parameters. Whilst it is important to obtain an allocation that is optimal, a near-optimal solution that is robust may be preferred over a slightly lower cost solution that is unstable to small variations in the cost function. Figure 4.1 shows the overall flow of the task allocation algorithm.

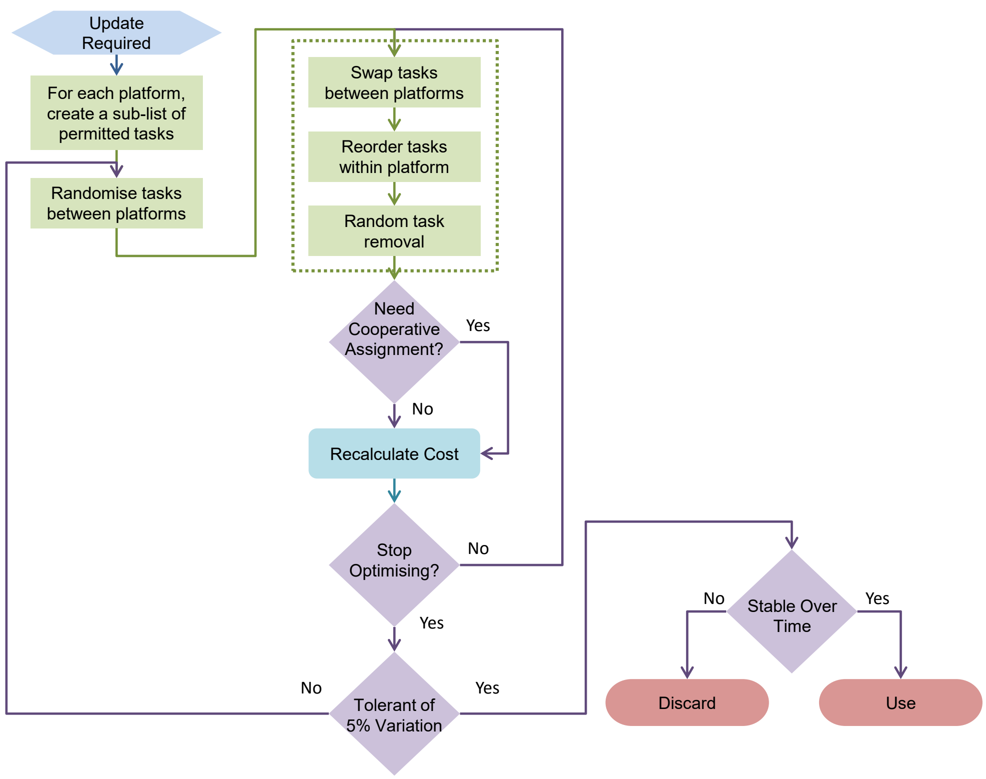

Figure 4.1: Flow Diagram Showing Allocation Search Strategy

4.4 Remote Operator Interface Developments

This section will build upon this and detail the aims and requirements of the remote operator interface that was needed, discuss the features that were developed, and finally will review the overall remote operator terminal that was designed to display the Task Allocation Algorithm output.

4.4.1 Aims of the Display

DSS are required when facilitating complex decision making in dynamic real-time environments – such as the real time task allocation of a set of aircraft to a set of targets to achieve some military (or other) objective. The first element of designing these systems is to identify the source of information and the way in which it might be natively represented. In this case the information presented is sets of allocations for each aircraft and the associated times for each task, along with associated costs and timings. There were three main areas to include in the interface:

- Map display showing the positioning of aircraft and targets in the scene
- Scheduling of tasks and which tasks are to be carried out by each aircraft
- Network status, displaying whether the connections to each aircraft operating as expected

4.4.2 Implementing the Main Display Elements

4.4.2.1 Map Display

The majority of the remote operator terminal is used to display a large map of the engagement area. Overlaid on top of this map are icons representing the different assets and targets in the engagement area. Also displayed are the routes that each asset is due to fly. Icons used to represent the entities take on standard forms and colours for the type of object. Friendly aircraft are coloured blue/cyan and known enemy threats coloured red – as is standard for NATO guidelines for displays [20, 143]. It is also important to represent the aircraft heading with a line pointing from the centre of the object in the direction of travel. The map window can be zoomed in and out, and panned side to side to allow the user to position their view in the most appropriate way for their current engagement. The map can also be switched between different types; from Terrain, to Satellite and Hybrid variants.

4.4.2.2 Schedule Display

The aircraft-to-target schedule list is shown in the bottom right hand corner of the user interface and is used to list the order in which the targets will be prosecuted by the available aircraft. The time on target is displayed in the column relevant to the aircraft that has been tasked to that target. This provides the operator with a complete overview and an estimate of how long until each task will have been completed. As the scenario evolves, the loss of assets or the repositioning of targets may change the tasking of aircraft or the ordering of attacks. Furthermore, if an urgent request for CAS is added during the scenario, the schedule list will display this to the operator to ensure the new information is available. Any changes are updated on the aircraft to target schedule list and are displayed to the user in real time. Changes in the ordering or task allocation are indicated to the operator by flashing the changed data.

4.4.2.3 Connection Data

The status bar at the top of the window is present to indicate the current system state to the user. Green statuses show that there is good data for the selected element. For example a green 'A/C DATA' indicates that positional and other information is being received from the aircraft in the engagement. An orange indicator indicates missing information. For example an orange 'TGT DATA' indicates that there is information missing from the target data set. This could be shown because a target is of the 'Unknown' type and has not yet been scanned by available sensors to be identified. The status bar also displays the current 'ZULU' time (Coordinated Universal Time – UTC) and the local time for the area in which the engagement is taking place, as well as a user triggered stopwatch timer.

4.4.2.4 Additional Functions

At the bottom of the Remote Operator Interface is a list of clickable buttons (soft keys) used to control the interface. The first set of soft keys is used to re-centre the map screen on the selected relevant aircraft or target. This is particularly useful if the operator loses track of the aircraft and targets on the map. The next functions are those that aid the targeting process. A manual update function is available which allows the user to enter an updated target position manually for any of the targets on screen. The 'Click for Tgt Lat Lon' button places a cross-hair on the mouse and allows the user to interrogate the objects on-screen and have their positions displayed in a window on the bottom bar (in decimal degrees).

The remote operator also has the ability to draft or forward a NATO standard CAS 9-Line Brief order [144] by clicking on the 'Create CAS 9 Line Brief' button. It allows 9-line briefings to be created, and/or edited and then sent to an aircraft. This aircraft will then attempt to prosecute the assigned target as a matter of urgency. This is likely to cause the task allocations to change once the algorithm has found the new optimum including the high priority target.

4.4.3 Display Overview

The information displayed on the main page of the Remote Operator Interface can be seen in Figure 4.2 with an expanded view of the Task Allocation Table (TAT) in Figure 4.3. The different features on the display are shown including both a long format CAS 9-Line Brief window and a short format Target Update box.

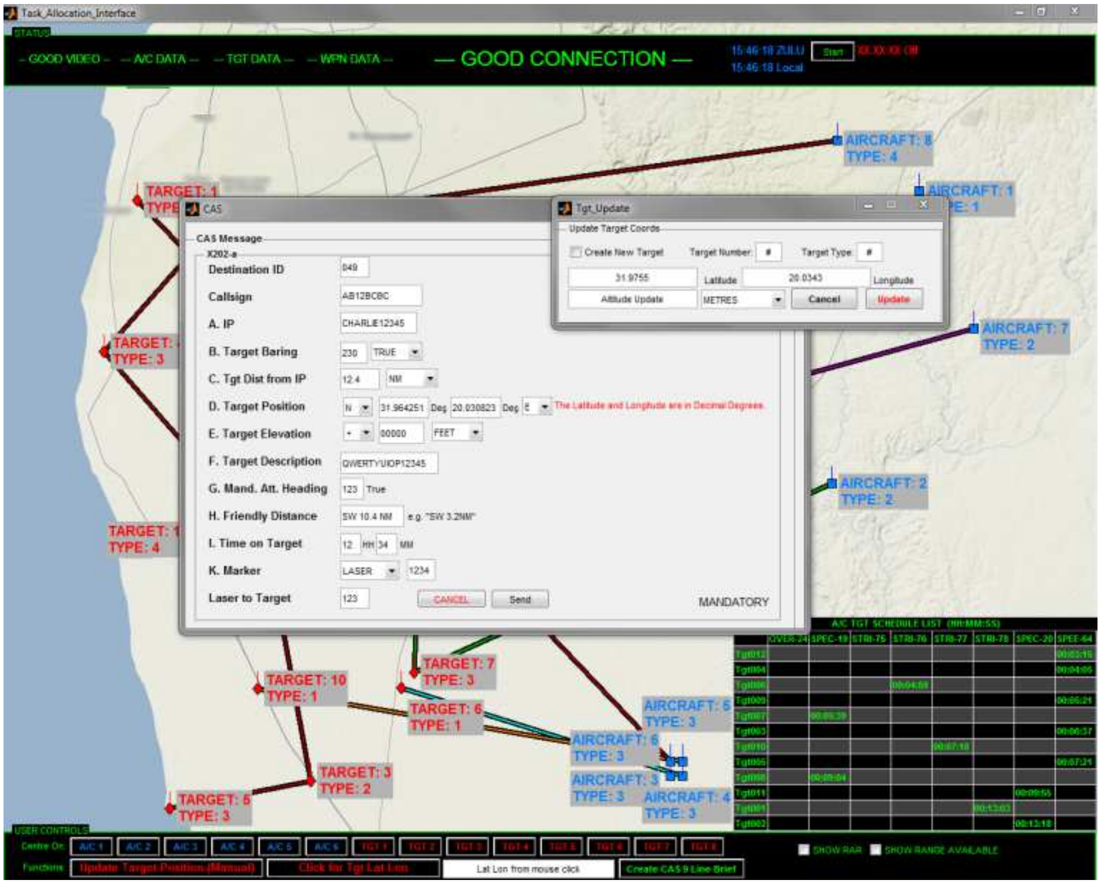

Figure 4.2: An Example of the Remote Operator Interface, Showing a Range of Targets and Assets with an Example 9-Line Brief Overlay

A/C TGT SCHEDULE LIST (HH:MM:SS)								
	OVER-24	SPEC-19	STRI-75	STRI-76	STRI-77	STRI-78	SPEC-20	SPEE-64
Tgt012								00:00:29
Tgt004								00:01:19
Tgt006			00:02:02					
Tgt007								00:03:36
Tgt008							00:04:02	
Tgt009		00:04:15						
Tgt003								00:04:22
Tgt010					00:04:33			
Tgt011		00:05:05						
Tgt002							00:06:53	
Tgt005		00:08:24						
Tgt001						00:10:18		

Figure 4.3: An expanded view of the Task Allocation Table (TAT)

4.4.4 Networked Elements of the Display

The remote operator terminal communicates with other elements within the distributed simulation environment. The remote operator has the ability to see the full environment, including piloted aircraft, unmanned aircraft, and weapon systems. The aircraft may be purely simulated or be a manned flight simulator; current capabilities allow two full motion and two fixed flight simulators to be interfaced to the remote operator terminal. These links include digital data transfer and broadcast and/or person-to-person voice links. The environment also includes a number of stand-alone computers that run reconfigurable autonomous weapon models, which can emulate radio data link protocols to simulate networked weapons.

In order to simulate the distributed environment, a UDP is used to transmit/receive information between the different elements of the system. The content of this UDP communication channel is constrained to digital messaging standards currently in service, in particular the NATO standard VMF [124, 145]. The benefit of using a distributed simulation system employing a VMF style communication protocol ensures that each element only has information that would typically be available during NCW, and that individual systems are not over-aware of other platforms' behaviour via an unintentional hidden channel.

4.5 Example Scenario

As already expressed, there are limitations to the number of tasks an operator can supervise. With this in mind, an 8 asset, 12 target scenario has been drawn up. The scenario effectively has 12 tasks, possibly more should a co-operative assignment be necessary in order to deliver a laser-guided weapon from a platform that does not have its own laser designator. Figure 4.4 shows the scenario overview.

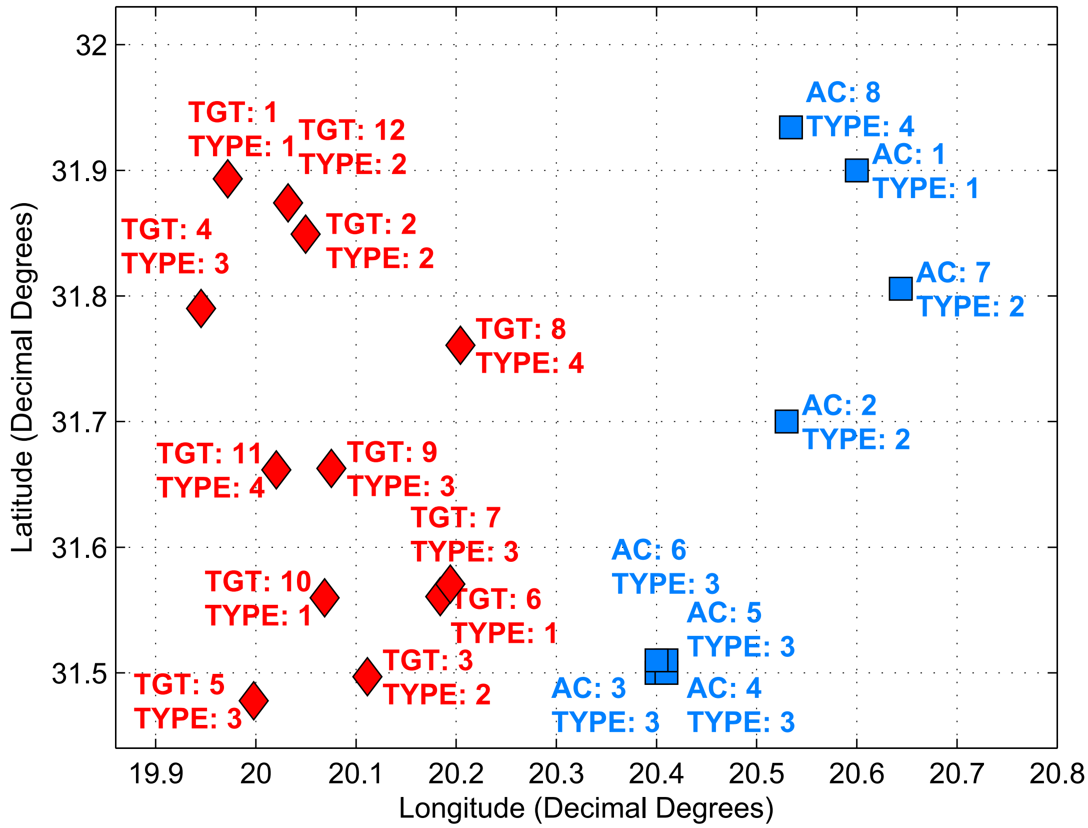

Figure 4.4: Overview of Example Scenario

To start the scenario, a random area was chosen to be the engagement area. The geographic areas represented in the example scenario are just for visualisation purposes and are in no way related to any previous or future military engagements. Assets and targets have been placed to the left and right of an imaginary vertical line representing the boundary between allied and enemy territories. It is assumed that the red team have no aircraft or air defence systems.

The positioning of targets and aircraft are random within their territories. However, a rule has been incorporated to cluster UWS whilst loitering. The aircraft capabilities and load-outs are shown in Table 4.1. Table 4.2 shows the breakdown of the number of aircraft and targets, and their types for the example scenario.

Table 4.2: Number of Aircraft (A/C) and Targets (TGT) in Example Scenario

Type	Description	# of A/C	# of TGT
A/C 1	UAV	1	
A/C 2	UCAV	2	
A/C 3	UWS	4	
A/C 4	CAS A/C	1	
TGT 1	Personnel		3
TGT 2	Vehicle		3
TGT 3	Building		4
TGT 4	Unknown		2

Running the Task Allocation Algorithms on the current scenario provides the task listing as shown in Table 4.3. The aircraft callsigns are listed across the tops of the columns. UAVs, UCAVs, UWS and CAS A/C have the callsigns 'Overwatch', 'Spectre', 'Striker' and 'Speeder' respectively, followed by a two digit numerical identifier. The first column shows the target prosecution order. Each aircraft column is then used to represent the target/targets that the aircraft has been tasked to, and the time it will take until the target is prosecuted.

Table 4.3: Task Allocation Table (TAT)

	AC 1	AC 2	AC 3	AC 4	AC 5	AC 6	AC 7	AC 8
	OVER 24	SPEC 19	STRI 75	STRI 76	STRI 77	STRI 78	SPEC 20	SPEE 64
TGT02								00:03:15
TGT12								00:04:05
TGT08				00:04:59				
TGT06								00:05:21
TGT07		00:05:39						
TGT09								00:06:37
TGT10					00:07:18			
TGT11								00:07:21
TGT04		00:09:04						
TGT03							00:09:55	
TGT05						00:13:03		
TGT01							00:13:18	

The numerical values populating the TAT show the time on target for the aircraft of that particular column onto the target for that particular row in HH:MM:SS format. As most aircraft are capable of carrying more than one weapon, a single aircraft may be tasked to prosecute several targets. Furthermore should a cooperative task arise, where an aircraft is required to laser designate for a platform that does not have that capability, there will be more than one column containing a time for a specific target row. Lastly, should an aircraft not have any tasks in the current engagement, its corresponding column will remain blank.

In the example scenario shown the time to prosecute all the targets in the engagement is 13 minutes 18 seconds. However, in this scenario there are unknown targets. Upon being scanned by sensors the unknown targets may be classified as legitimate targets. If this occurs the algorithms will update the TAT and may re-assign aircraft to different targets in order to prosecute the new threat along with the current or remaining threats in the scenario.

Figure 4.5 shows a schematic diagram of the engagement routing between the targets for each aircraft. This schematic is not the actual flight path but rather the way-point routings. Once programmed in, the UAVs, UCAVs, UWS and CAS A/C will fly the optimum routes to engage the targets, taking into account any mandatory attack headings.

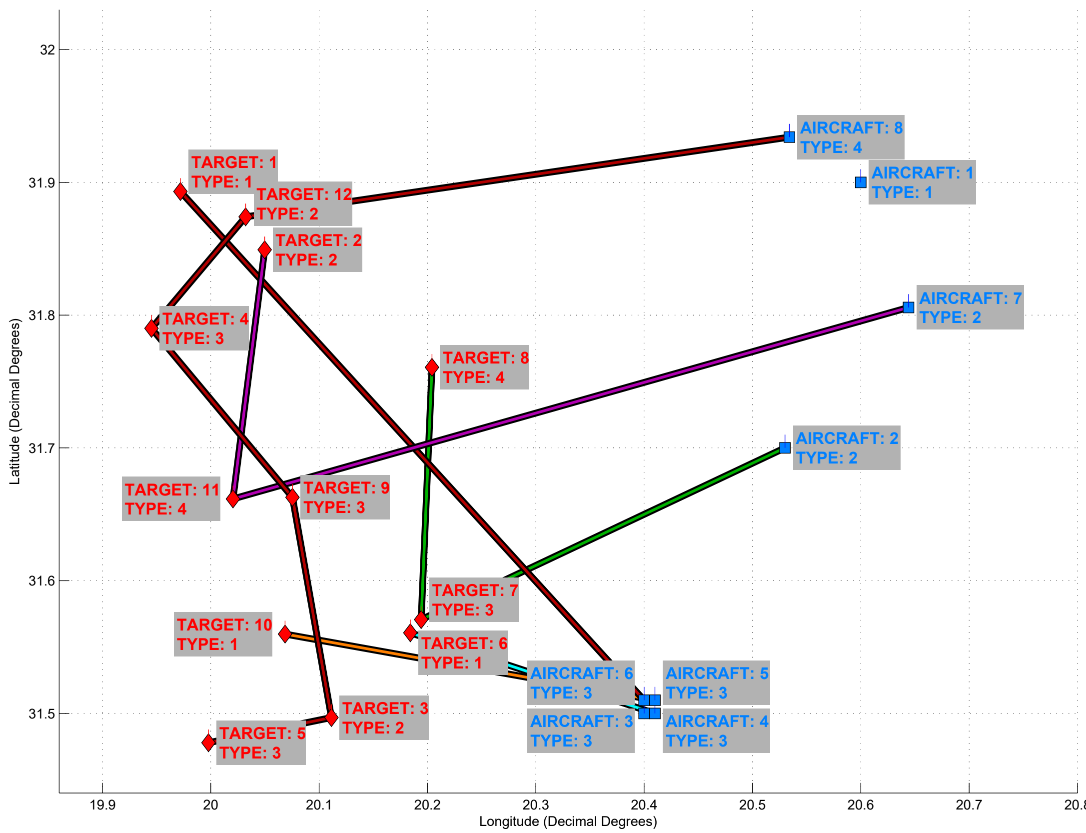

Figure 4.5: Overview of Example Scenario with Aircraft Routes

4.6 Results

The scenario used in this chapter is an example only. It was selected to represent the complexity of a resource-task allocation problem that could be encountered by a remote weapons operator. The algorithms described above were developed to operate in real, or near-real, time. The two main factors in designing the algorithms were the time taken in finding a solution to the allocation problem and the efficacy and the robustness of the final solution. The average time taken by the algorithms for different numbers of targets and assets is shown in Figure 4.6; the average was calculated by selecting random sub-sets of targets and platforms from the scenario and performing the search on a standard laptop computer (running as a background process on a multi-core medium specification laptop PC). Even for the full scenario with 8 platforms and 12 targets, the update rate of once every 2.5 seconds is sufficiently fast for the algorithms to be used with the remote operator interface.

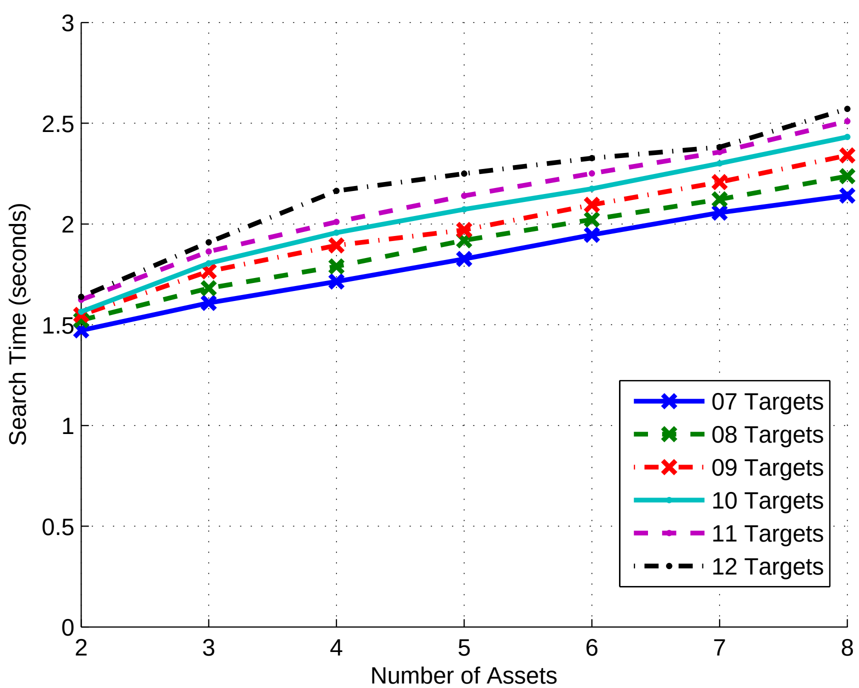

Figure 4.6: Average Time to Find Search Result for Example Scenario for Variable Number of Assets/Platforms and Different Number of Targets (both randomly selected)

The robustness and the efficacy of the solution is a more complicated problem. Finding a single perfect solution, where each target is to be prosecuted by the ideal platform and weapon combination at the desired time on target, cannot be guaranteed for a general problem. There may be a number of different ways to allocate platforms and weapons to targets and tasks, or there may not be any ideal way to allocate the assets. If there are insufficient resources to prosecute all of the targets, the algorithms need to be able to prioritise the targets according to their importance and the urgency with which they may be prosecuted. This is achieved using the cost allocation described earlier; some tasks, such as the priority targets have a sufficiently high cost that they will be allocated before any other tasks (e.g. troops in contact). As long as the overall cost of the allocation solution is less than the costs associated with these essential tasks, then these tasks must have been allocated and this fact can be flagged to the remote operator through the interface. Equally, where a priority target cannot be prosecuted, this fact must also be flagged to the operator and the operator engaged to find an alternative solution through the request of additional resources or external assistance – or, in the absence of external resources, a low level fly past by a platform or a show of force to inhibit the opposition forces movement on blue troops.

The numerical robustness of the individual solutions is checked within the algorithms themselves, using a perturbative assessment of the cost function around the preferred solution. The temporal robustness of the solutions is also important, in dynamically changing engagements in particular, where the numbers of targets and assets may vary whilst the engagement is under-way. To this end, the individual solutions generated by the allocation algorithms are monitored by the remote operator interface. In cases where multiple solutions are found with similar costs, the interface tracks the solutions being generated and selects the solution with the most temporal persistence, as determined by the frequency of occurrence and the stability over a period of time determined by the times on target in the engagement. For the example considered in this chapter, the time interval for the engagement is approximately three to thirteen minutes first target to last. It is worth noting that this temporal robustness function is also used in Satellite Navigation aids that use live traffic data to provide updates to the quickest route to a destination. These systems only offer faster options to the users rather than changing them automatically due to the confusion this could cause.

For an operational system, the algorithms should also allow for other factors to be included in the optimisation, such as the distribution of known threats, such as air defence systems, and the risk of collateral damage. Understandably, the risk of non-combatants being injured and/or friendly fire is seen as a major factor influencing the ability to prosecute ground targets. Even a precision weapon will have an area of effect, which is often characterised in terms of a RED [19], and this area can be asymmetric and potentially include features such as the protective effect of cover (terrain, buildings, vehicles, etc.). To minimise the risk of collateral damage and to allow the weapon platforms to navigate around known threats, the allocation algorithms could be extended to define angles of approach to the targets (preferred attack headings), which could be included in a route-planning tool.

4.7 Conclusions and Summary

This chapter has described a set of real-time task-resource allocation algorithms previously developed as part of a non-real-time battlefield analysis tool [13]. The algorithms provide an allocation of the available platforms and weapon loads to the set of targets currently identified, taking into account a range of different operational factors: priority of target, preferred time on target, platform speed, and the suitability of the weapon to the target type and the danger of collateral damage. The algorithms also allow for co-operative attacks involving multiple platforms using laser designation systems. The algorithms are based on the minimisation of a cost function, which is defined as the sum of the individual costs that reflect these operational factors. The number of allocations to be searched is reduced by vetting the targets against the ability of the platform to reach the target and the ability of the weapons on each platform to prosecute the target. Forbidden weapon/target combinations or unreachable platform/target pairs are excluded from further searches. The remaining candidate allocations are searched using a simulated annealing minimisation method combined with a series of allocation/re-allocation methods, including multi-platform/task swapping, single platform task reordering, and task removal.

With this type of capacity to optimally task and re-allocate aircraft and payloads amongst targets, the next logical step is then to increase capability to a stage where an operator can instead re-task the weapons after they have been launched. As the stand-off range of modern air-to-surface weapons increases, the increase in weapon flight time creates the opportunity for the situation on the ground, or the mission objectives, to change. Where the focus of this chapter was to generate adequate user interfaces to allow operators to obtain and effect task allocations to aircraft, the new focus will be to re-task weapons in flight. If all of the weapons in the scenario described in this chapter were already launched, could a remote operator perform the same role by interfacing directly with the weapons themselves? This is a paradigm shift that may occur in the air-to-surface weapons domain and must be investigated thoroughly.

The following two chapters will now detail the investigation into such an interface system with, in Chapter 5, a single short range air-to-surface bomb, and then in Chapter 6, multiple medium-long range air-to-surface missiles.

Chapter 5

Participant Study 1

This chapter develops the initial investigation into the resource-task allocation optimisation algorithms presented in the previous chapter. Due to the extended stand-off range of modern air-to-surface weapons, there is an implication that once data-linked, future systems will be able to be re-tasked remotely during flight. It is necessary therefore to investigate the way in which this will impact on an operator carrying out re-tasking of remote weapons. This chapter will present an investigation into the re-tasking of individual short range data linked bombs against emerging targets in short time frames.

5.1 Introduction

Re-tasking of Remotely Operated air-to-surface bombs and missiles requires knowledge of the bomb or missile's capability to be re-tasked to alternative targets. The previous chapters have highlighted how a bomb or missile's current flight conditions, and remaining fuel if available, can be used to calculate a Re-task Availability Region (RAR). The RAR is the area on the ground to which a weapon may be successfully be re-tasked. The potential issue with the use of RARs for re-tasking weapons in flight is that they are not static. RARs change their shape over time – in general reducing in size as the weapon gets closer to the target. This prompts the research question of how best to display the RAR to operators to support their remote re-tasking duties.

Operators of remote systems require information to be presented to them in a way that facilitates decision making. This information can be verbal, audible and/or visual in form depending on the context. The information displayed visually must be supporting of the task at hand and displayed in a way that is not confusing or distracting. Chapter 2 has already highlighted the range of research conducted into the development of DSS as well as the underpinning theories of SA and decision making. With these theories and studies in mind, there is a need to apply these to the novel area of re-tasking remotely operated weapon systems.

This chapter presents a participant trial that tested the suitability of two modes of displaying RAR information on a remote operator terminal Graphical User Interface (GUI). Participants took the role of a remote operator in charge of re-tasking guided bombs to new high priority emerging targets. Their performance was measured in a range of tasks in which new targets appeared either within or outside of the capability of the guided bomb, or no new target appeared at all. The participants' performance and responses to other metrics and demographic data are presented and discussed in relation to the applicability of the two different display modes to adapting existing remote operator terminals.

5.2 Summary of Trial

A NEW, in this trial the GBU, was launched from an aircraft against a static target. The control of the GBU was handed over from the launch aircraft to a remote operator in a ground control station immediately after launch. The remote operator then became responsible for the GBU during its flight. The participants acting as the remote operator saw a total of 15 different scenarios. In each scenario there was a chance that a higher priority target would emerge (66% of scenarios). The participant must then decide whether or not to re-task the GBU in flight to this new emergent target using graphical overlays of weapon capability presented on the remote operator terminal. Some targets appeared within the RAR and some appeared outside (50% of scenarios with new targets). It was explained to participants that RoE were satisfied, and that the weapon in flight must be re-tasked to the new high priority target if it were safe to do so.

The scenarios were constrained such that only one action was required to either re-task or deny the re-task request. This allows for the accuracy and reaction time of participants to be measured in a controlled manner. The scenario itself could exist in a much larger dynamic environment of air-to-surface weapon engagements, examples of which include friendly troops under fire requesting CAS, or a high value 'target of opportunity' emerging. In these situations the additional capabilities of NEC and NEW will increase the range of roles a Remote Operator may have, adding to their workload. Any DSS developed must be designed to work effectively as possible, and human factors issues must be explored early in the design phases of Remote Operator Terminals for NEW [146, 147].

5.3 System Development

Chapter 3 discusses the overall facility development for remote operation of simulated weapon systems. For this trial there were three main functioning programs that facilitated the experiment. These were; the Remote Operator Terminal software, the Network Protocol Code for Re-tasking messages, and the GBU weapon simulation.

5.3.1 Remote Operator Terminal

The Remote Operator Terminal, is a map display which represents key information to the user (shown later in Figures 5.1 & 5.2). This information is pulled from the data available from VMF type messages received from the weapon and from remote targeting systems such as an aircraft mounted targeting pod or a FAC CAS 9-Line Brief. These messages must be processed by the remote operator terminal system before being displayed to the user. The main functions within the Remote Operator Terminal software are:

- Map Function - loads the background map based on the current world position being interrogated by the user. The function loads relevant map tiles from open source mapping databases in either satellite, map or hybrid views.
- Objects Function - loads objects onto the map view to represent assets, targets and other information about objects within the battle-space.
- Status Function - displays the current weapon status to inform users of the state of the weapon that they are controlling.
- Key-press Function - records the human interaction with the keyboard control device and carries out the appropriate command. In this interface the potential keyboard commands are minimised to; 'R' re-task weapon, 'O' keep the original target, and 'Return' proceed to next scenario.
- Decision Aid Function - displays one of two variations in display type used to aid decision making by the user.
- Network Function - reads data from the network protocol used to send and receive information between the user interface PC and the NEW simulation PC.

The Remote Operator Terminal developed is similar to those developed for the B-1B weapon operator interface [34,35]. The B-1B weapon operator interface displays circular shapes on a digital map along with the expected flight path of the aircraft. These circles represent the LAR for the weapons to be launched against pre-configured targets. When the aircraft is within these LARs the weapon operator can release the weapons onto their targets. However, the interface does not produce RS – areas on the ground that can be hit from the current launch position of the aircraft. The Remote Operator Terminal display for this trial is fixed in position, displaying a map with moving objects to represent the current weapon in flight and the target(s). Rather than LARs being produced for each target, a single RAR is generated for the weapon. This can then be displayed to operators to aid them in assessing the validity of re-tasking an air-to-surface weapon to a new target.

A current UK capability to re-task weapons in-flight exists in the C2 of the Hellfire missile system used in the Apache. The Hellfire uses semi-active laser homing to guide itself to the target, which is lased by either the firing platform or a third party (note some later variants of the Hellfire have been updated to include an active radar seeker). As a mechanism of aborting the weapon, an operator can, in real-time, move the laser designator away from the target to a safe location for the weapon to ditch. Similarly this technique could be used to re-task the weapon to an alternative target whilst the weapon is in-flight. Given the relatively short range, the time window for these types of re-tasking are very minimal. The operator's terminal is not specifically configured for re-tasking roles, but this is an example of how existing systems could be used to perform such tasks.

Two methods were chosen to display decision cueing information to participants. The first, a geo-spatial graphical overlay, and the second a digital numerical display. These displays were configured to represent the maximum extended range to which the weapon in flight can be re-tasked to safely. Using a combination display was considered, however, the purpose of the trial was to establish direct differences between the two displays. Using a mixed display would have removed the ability to distinguish which decision aid element participants were using to support their decision making, introducing unnecessary confounding factors into the study.

The RAR graphical representation is a non-filled polygon shape which has the general appearance of a semicircle. This semicircle protrudes forwards in the direction of travel of the weapon with the flat edge facing the weapon, and the arc spanning from the left most extent of the weapons range if it were to turn full left, through the weapons forward maximum range, to the right most extent of the weapons range if it were to turn full right. However, due to the dynamic nature of a weapon engagement and ultimate descent into the target/surface, an air-to-surface weapon's RAR reduces to zero over time.

In the early stages of GBU flight the RAR remains approximately the same size and shape. However, as the GBU descends the area of the RAR reduces, with the overall shape collapsing inwards to the centre. The main issue with this dynamic feature is that the reduction in area overall is not uniform in all directions. The reduction in off-boresight capability is the most obvious change in the shape of the RAR. This is the reduction in the GBU's ability to change its heading to prosecute other targets. In Chapter 3, 3.9 shows an example of the change in shape of the RAR in 2 intervals from launch until target impact. The use of polygons is common to display this type of information (as seen in the B-1B WO display [34, 35]). It is also used in nuclear power station control rooms [148] as it has been shown that people are good at detecting departure from a 'normal' system state using polygon displays [149]. A detailed map is projected underneath the decision cues to ensure that all information required is in a position to allow for efficient focus and eye movement of participants [150].

The numeric display used a digital number representation rather than an analogue dial to represent the numerical values associated with the ability to re-task the GBU weapon. This is because digital displays provide greater levels of precision [151]. Analogue dials also rely on a participants ability to distinguish difference within graphical forms, rather than from comparing numerical values. Participants were shown two different numbers, a numeric value representing the capability of the GBU, and a numeric value of the capability necessary to re-task to the new target. This requires participants to use basic mental arithmetic to ascertain whether the new target is within the RAR of the GBU.

This calculation could be quickly made by the computer system and a number could have been shown representing the difference between the maximum range available and the range to the target. This was avoided in order to prompt participants to make an assessment based upon the relative closeness of the new target to the maximum range of the weapon, which is not directly visible to the participant if they are only provided with a numerical value instructing them that the new target is inside or outside of the range capability of the weapon. It also does not provide the participants with direct information to assess the rate of change of the maximum range of the GBU. Any understanding of the rate of change is inferred by the rate of change of the numbers on the display. The Range To Target was placed immediately above the Range Available so that the two numbers could be easily compared with each other. The numerical format provides the operator with no geo-spatial cues to build SA, however, there is still sufficient information available for an operator to develop the third 'Projection' level of SA [56].

When using a map display it is important that the decision cues are made more easily available to participants by increasing their graphical salience on the single display [152]. The colours used for the two different decision cues were applied in order to achieve the required increase in salience, as they do not interfere with high level emergent features such as the shape of the RAR [153], and colour has been shown to increase both decision making accuracy and reaction time [154].

The data refresh rate of the user interface is dictated by the time it takes to generate the RAR for the GBU. The time taken for each calculation of the RAR is based upon the resolution (number of points in the polygon) and the type of RAR calculated (open loop/closed loop solutions). This information is detailed in Chapter 3. An appropriate refresh rate of 10 Hz was used as it provides a suitably high frame rate to show motion, whilst allowing for a high enough resolution for a good RAR calculation. Low refresh rates have been shown not to degrade performance of participants in dynamic tasks [155], and so a refresh rate of 10Hz should not impact on the performance of participants within this trial.

5.3.2 Network Protocol

A custom developed UDP was used to send and receive information on both the NEW and Remote Operator Terminal PCs. Chapter 3 discusses the message format in more detail.

The information sent from the NEW to the Remote Operator Terminal are Position, Attitudes and Velocity. The Remote Operator Terminal sends Target Position and Velocity information to the NEW. It is assumed, for the purpose of this trial, that the targeting information received from a third party source by the Remote Operator Terminal is both timely and accurate.

5.3.3 Weapon Simulation

The weapon simulation is a full 6DoF model of a GPS/INS GBU. The GPS/INS guided weapon is an unpowered guided bomb in the 1000lb class. It is canard controlled, uses proportional navigation guidance and standard approximations for the aerodynamic coefficients [114, 156]. This model is also discussed in detail in Chapter 3.

5.4 Study Aims and Methodology

5.4.1 Aims

The aim of this study was to compare the efficacy of two different display methods for providing decision aid information to users of a NEW Remote Operator Terminal. In this trial, participants were asked to make decisions as to whether a NEW in flight could be re-tasked to a new target using either:

1. The RAR graphical display overlaid onto a map (shown in Figure 5.1), or

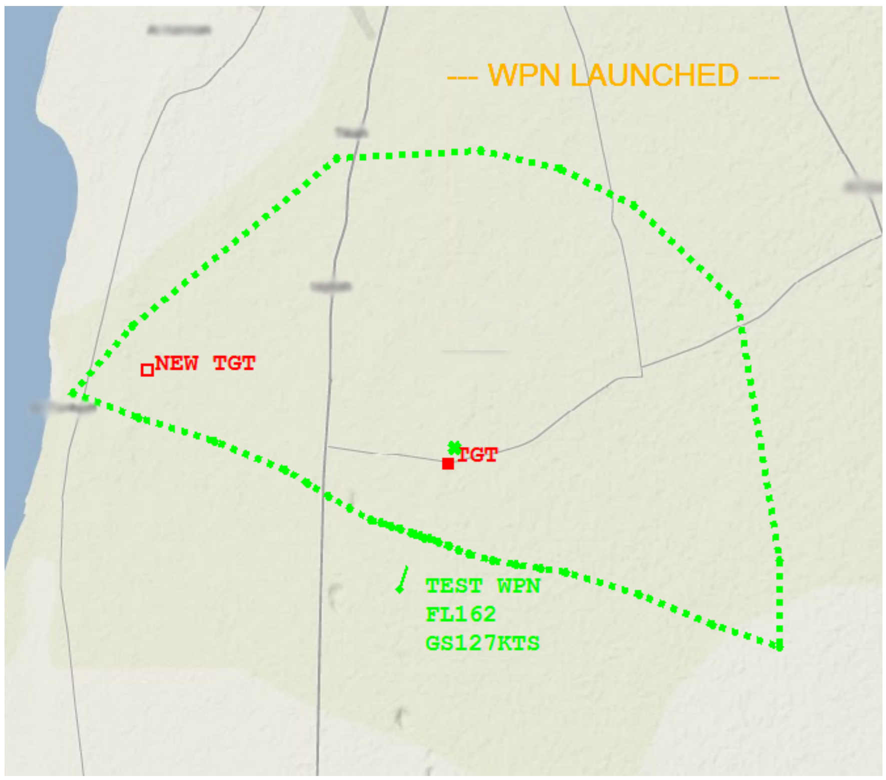

Figure 5.1: Graphical Display Method

2. The Range Available and Range to Target numerical Displays (shown in Figure 5.2).

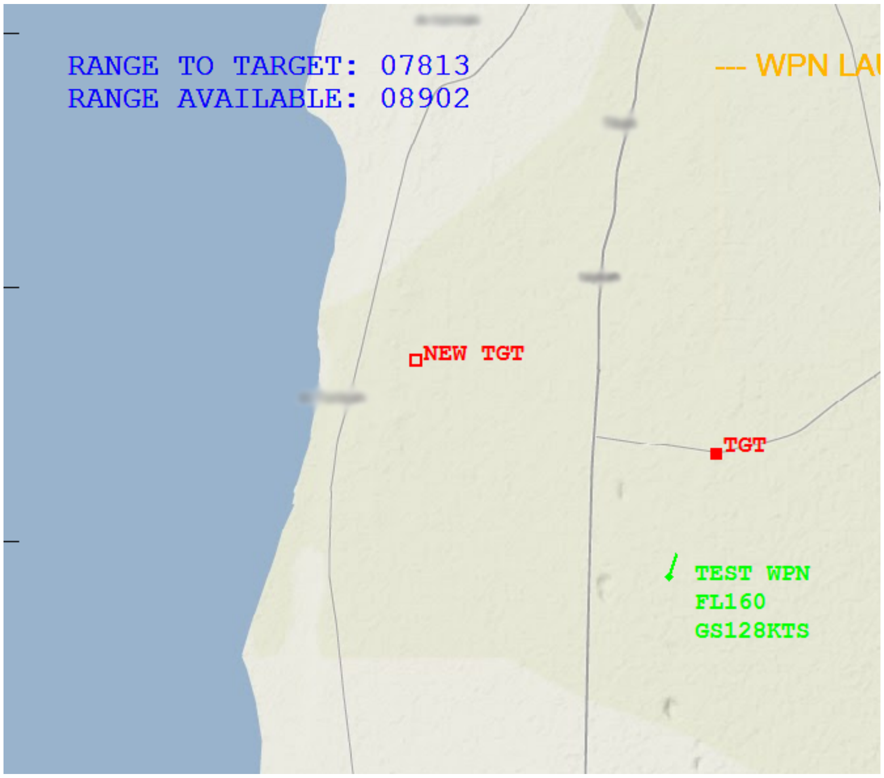

Figure 5.2: Numerical Display Method

Participants were required to complete 15 simulated tasks in which they monitor the flight path of a network-enabled guided bomb. In some scenarios the NEW must be re-tasked in order to hit a new target. Participants were instructed that if a new target appears on the display it always takes priority over the initial target. The participants were required to make their decisions in real-time and as quickly as possible, taking into account that re-tasking the NEW may not always be possible as a new target could appear outside of the weapon's range capability. The typical flight time of each NEW in this trial varied from 30-60 seconds depending on the specific scenario, with re-task scenarios typically requiring more time because the weapon must travel further to reach its new target.

The aim was to establish the suitability of each display method to the task and to compare the two methods directly against each other. This was achieved by using performance metrics recorded during the trial, information from cognitive load tests (designed to test how mentally demanding a task is) and participant experience surveys.

5.4.2 Methodology

A single screen simulation test bed was developed which allows participants to monitor the current flight path of the NEW during the trial. The display shows the position of the NEW and any targets on-top of a map (see Figure 5.1 & 5.2). The map allows the participants to gain a spatial understanding of the area of engagement. The display represents the weapon position with a green diamond and a solid line extending outward from its centre to represent the heading. The marker is tagged with 'WPN' 'FLXXX' and 'GSXXXKTS'. 'FLXXX' is used to display the weapon's flight level in hundreds of feet, 'GSXXXKTS' is used to indicate the weapon's ground speed in knots. The display represents the initial target position with a filled red square and a 'TGT' tag. If a new target appears, the display represents this with a red square outline and a 'NEW TGT' tag. When a decision is made as to which target to prosecute, the approved target marker becomes, or remains, a filled red square and the denied target marker becomes a red cross (X).

The two types of display differ in their method of displaying the re-task capability of the weapon in flight. Figure 5.1 shows the RAR information in a graphical display consisting of a polygon made from a series of points linked together with a thick dashed line. This represents the current area that the weapon can be re-tasked to at that moment in time. The green 'X' at its centre represents the current unguided impact point of the weapon. This is important to display as it provides participants with a reference point to allow them to more easily interpret the distance of the new target when it appears.

Figure 5.2 shows the numerical display layout. RAR information was displayed with two numbers. The top number was the 'Range to Target' and the bottom number was the 'Range Available'. These numbers correspond to both the distance between the current target location and the relative locations in the scenario. To calculate the Range to target, the position of the original target and new target were inserted into the standard normal distance equation 5.1. The Range Available was calculated by finding the intercept point of the RAR and a line of infinite length extending outwards from the original target, in the direction of the new target location. This intercept point was then used in the adapted standard normal distance equation 5.2.

$$Range_{Target} = \sqrt{(Position_{NewTarget} - Position_{InitialTarget})^2} \tag{5.1}$$

$$Rng_{Available} = \sqrt{(RARIntersection(Position_{InitialTarget}, \psi) - Position_{InitialTarget})^2} \tag{5.2}$$

where: ψ = Heading to New Target from Initial Target

The two lines displaying the 'Range to Target' and 'Range Available' are always visible on the screen, even when there are no new targets and hence no numerical values to display. In this case the numbers are replaced by text which reads 'No New Tgt'. This keeps the display clear of misleading information that might lead participants to make incorrect decisions.

There were three main prime types for the 15 scenarios. These were Re-task, Deny Re-task and Do Nothing. Each case occurred 5 times within the scenario set, and appeared in a random order. Additionally, a rotation and translation of the initial attack heading and target location was made for each scenario, and the location of the initial target was varied. Further, the time at which a new target appeared and its location on the map were varied. This aimed to prevent the learning effect, where participants perform better after being exposed to a repetitive trial numerous times and become able to predict the time and location of new stimuli. Therefore, the window of opportunity for participants to re-task was varied from 4-16 seconds, and the time that a deny re-task prompt appears is varied from 5-21 seconds. The distance of the new target away from the edge of the RAR when it appears was also varied from between -3km (inside = re-task) and 4km (outside = deny).

Figure 5.3 and 5.4 show the RAR size and positions of the weapon, original target and new target at the point when the new target appears for the two scenario prime types; Re-Task and Deny Re-Task respectively. Table 5.1 shows the time a new target appears and the window of opportunity for each scenario in sequence. The sequence was randomised before being set for all participants and upon reflection the ordering should have varied for each participant to remove any session effects.

Table 5.1: Scenario Sequence, Prime Type and Window of Opportunity

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Prime (Re-task/Deny)	-	R	D	-	R	D	D	R	R	D	-	R	-	D	-
Time Tgt Presented	-	8	9	-	12	17	13	12	8	5	-	20	-	21	-
Window Of Opportunity	-	4	-	-	8	-	-	12	16	-	-	4	-	-	-

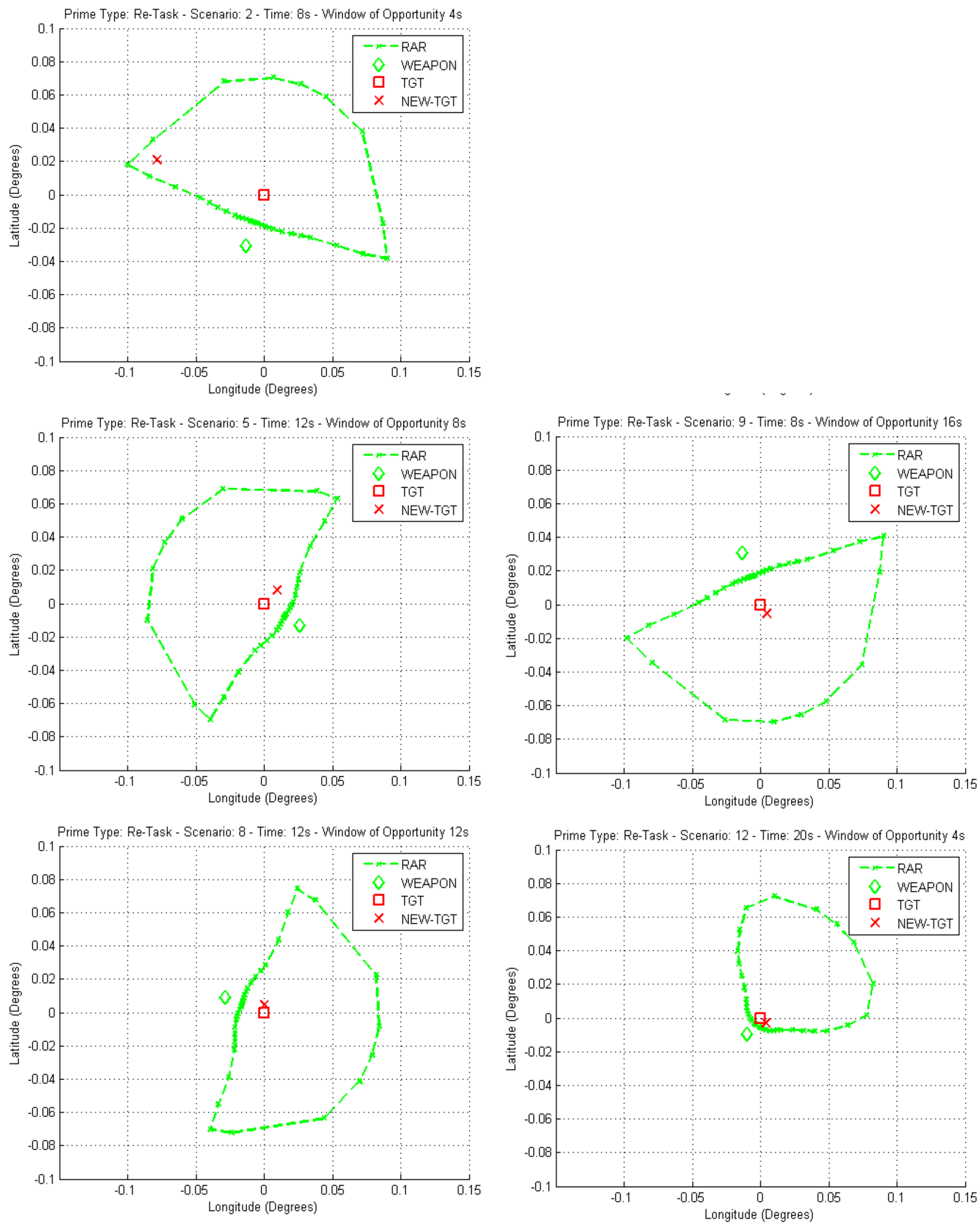

Figure 5.3: RAR Imagery at Point of New Target Appearing for Re-Task Primed Scenarios

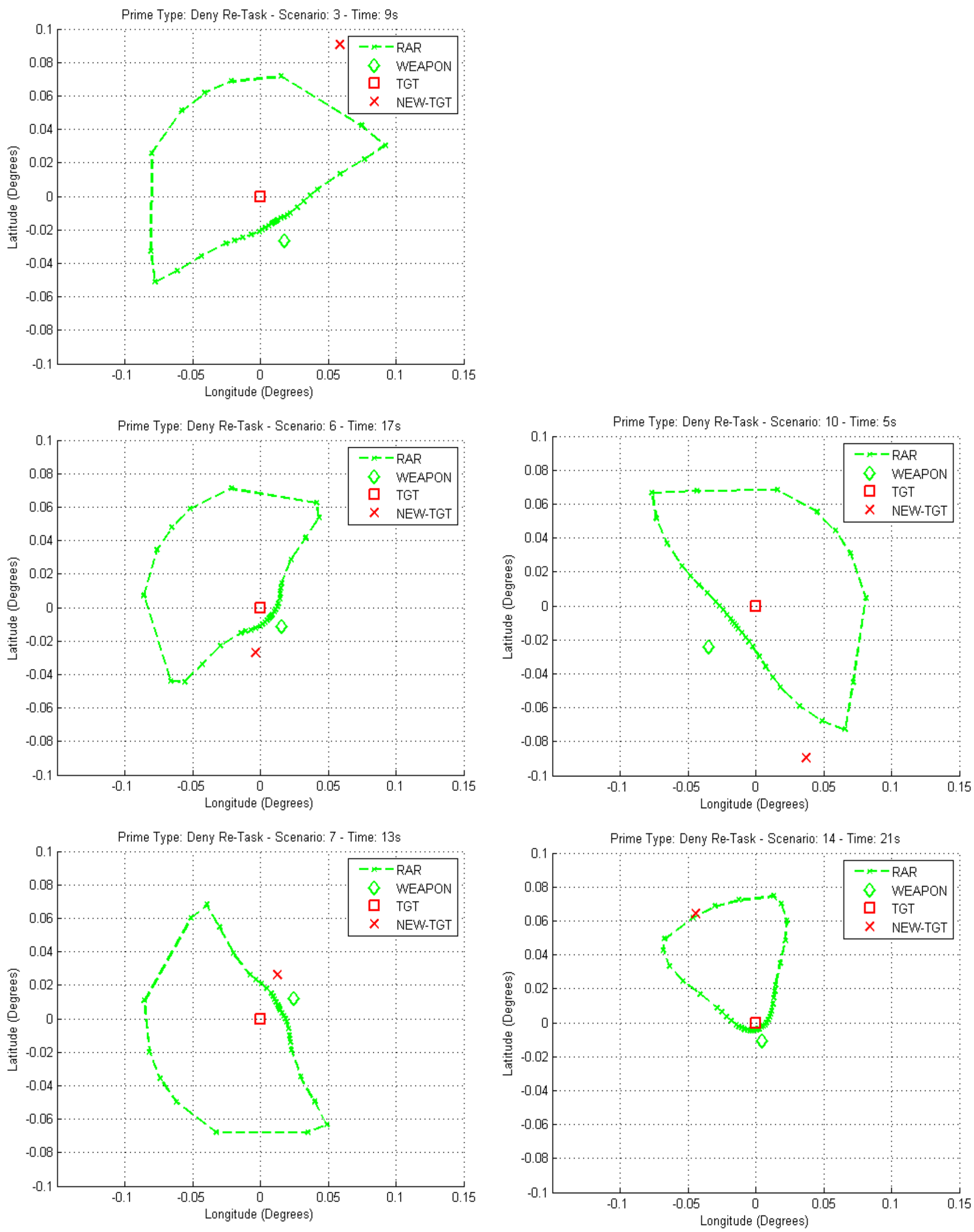

Figure 5.4: RAR Imagery at Point of New Target Appearing for Deny Re-Task Primed Scenarios

5.4.3 Statistical Design

This experiment was a mixed factor design with the top level between subjects factor (balanced) of display format as the main independent variable. The task priming was a within subjects factor independent variable. Each participant saw the same set of 5 control, 5 re-task primed and 5 deny re-task primed scenarios and the same window of opportunity/time target presented, regardless of the display format used in order to maintain a completely crossed design. The window of opportunity and time that a new target was presented were varied in order to test a range of datum points, and moreover, to stop participants having the ability to predict when a new target may appear in each scenario. Further, the incoming angle of the weapon was varied randomly to further differentiate between each scenario. These changes act as within subjects random effects variables, used for differentiating the scenarios. The main aim of this experiment is to look for the influence of the main Independent Variable of display format on reaction time and accuracy between the two display groups. Additional variations in the scenarios regarding time and location of new target positions were included to maintain internal validity of the experiment, and are not intended to be Independent Variables.

5.4.4 Participants

A total of 34 individuals participated in the study. Participants were randomly assigned to experimental groups. Half of the participants (n=17) were presented with a graphic display to aid their decision making and the other half were presented with a numeric display for a between subjects design. Participants ages ranged from 18 to 34 years of age and the majority of participants were male (n=24).

5.4.5 Procedure and Materials

Training: Approximately one week prior to the experiment, participants attended a group-based training event where they received information about the study. They were each provided with the following information:

"*You are asked to participate in a simulated exercise. You are the ground operator of a military guided-bomb system. You will be sat at a computer and asked to use the digital map and keyboard. You are responsible for updating the trajectory of a manoeuvrable weapon whilst in mid-flight.*

The weapon will be travelling towards an original target which has been pre-selected however sometimes a new target may be detected by the system. A new target will always take priority over the original target. Your job is to analyse whether it is possible to re-task the weapon to the new target or whether the new target is outside of the *weapons range. Your decision will be based on the graphical (numeric) display on the computer screen*

Targets are updated in real-time. Therefore a target may only be in range for a very short time. This means that you must make your decision as fast as possible."

Participants were told that they must use the keyboard to control the weapon. If they wanted to re-task the weapon they were instructed to hit the R key. If the new target was outside the RS of the weapon they were instructed to hit the O key. If no new target was displayed they were instructed to do nothing. Participants were then randomly assigned to either Group A (graphical display) or Group B (numeric display) and given paper instructions to take home and study. The paper instructions contained screen shots of what the screen would look like for each tasking option (re-task, unreachable target, no new target) depending upon which group they were assigned to (graphical or numeric).

Pre-trial measures: On the day of the trial participants were measured for the following:

- Pre-test Control Measure - Participants conducted a pre-test to check that they understood how to operate the system. If they were successful they were allowed to progress to the full experiment. All participants passed this test.
- Digit Span Task - Participants completed a verbal assessment of their working memory capacity and executive function-updating using the Digit Span Task to measure their baseline cognitive functions [157]. This was to help measure participants' levels of 'cognitive load' during the simulation.

The trial: Once pre-trial measures were recorded, participants progressed into the experiment room where they were sat at a computer. They were left alone in this room and told that the experiment would start once they hit the Return key. They were then presented with 15 randomly ordered scenarios where they had to either re-task the weapon (n=5), maintain the original target (n=5) or do nothing. Measurements from this task included: (i) speed of response; and (ii) accuracy of response.

Post-trial measures:

- Digit Span Task - Immediately after completing the trial, participants once again completed the Digit Span task to gather a post-trial measure of cognitive function [158].
- Questionnaire - Participants completed a questionnaire to measure experiential feedback through open questions. Participants also rated their perceived difficultly of the task by marking responses to a set of questions on a 14 point rating-scale, adapted from the NASA TLX [159].

5.5 Results

IBM's Statistical Package for the Social Sciences (SPSS) [160] was used to analyse the data produced by the trial. Due to the study being a between-subjects design, the majority of tests were conducted to establish the difference between the two groups' performance. The total number of participants was 34 and were split between each group evenly (N=17). Due to the small sample population several checks were necessary to establish whether the data could be assumed normally distributed and that the assumption of Homogeneity of Variance between groups could be satisfied. In general it was found that the assumption of normality could not be upheld, meaning that non-parametric tests for statistical significance were used, rather than the more conventional t-tests and Analysis of Variance (ANOVA)s, that are only valid when data is normally distributed with homogeneity of variance satisfied.

5.5.1 Reaction Time

Figure 5.5 shows the reaction time of participants from each group for each scenario. The reaction time data has been analysed at four different levels of detail in order to look at data produced per scenario, prime type, display group and overall averages.

5.5.1.1 Per Scenario Reaction Time

Each scenario was investigated on an individual basis between groups. Using the Mann-Whitney U (M-WU) non-parametric tests it was found that participants using the Numeric Display take significantly longer to make their decisions in 8 out of the 10 scenarios than those using the Graphic Display (see Table 5.2). Note: the following abbreviations are used in tables where necessary – Standard Deviation (SD), Mean (M), Significance Value p (p), U-Statistic (U), Z-Statistic (Z).

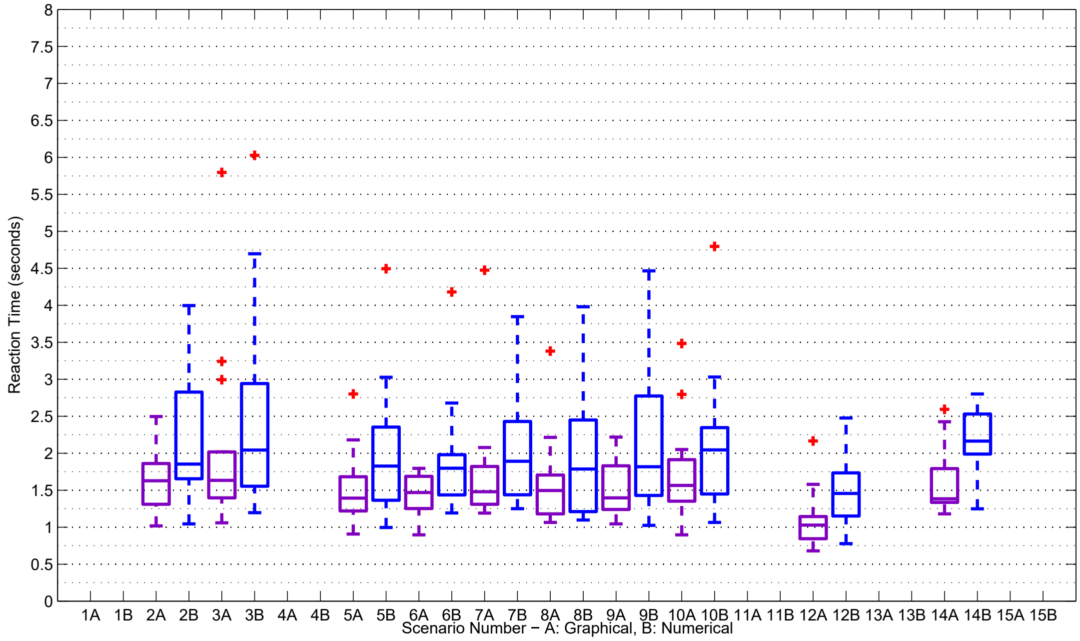

Figure 5.5: Reaction Times for Correct Decisions Per Scenario, A: Graphical Display and B: Numerical Display – Box shows inter quartile range with mean at the centre, and whiskers showing the upper and lower quartiles, outliers are shown as a red +

Table 5.2: Per Scenario Reaction Time Analysis

	Scenario	2	3	5	6	7	8	9	10	12	14
Graphical	Mean	1.469	1.810	1.488	1.401	1.608	1.598	1.504	1.619	1.084	1.282
	SD	0.526	1.309	0.469	0.304	0.867	0.583	0.366	0.747	0.360	0.610
Numerical	Mean	2.337	2.555	1.973	1.891	1.996	1.926	2.023	2.063	1.503	2.182
	SD	0.883	1.384	0.907	0.748	0.722	0.839	0.879	0.906	0.498	0.458
U(17)	U	58	92	93	73	93	109.5	90.5	99.5	59.5	36
	Z	-2.980	-1.809	-1.774	-2.464	-1.774	-1.206	-1.861	-1.550	-2.928	-3.738
	P (exact 1-tailed)	0.001	0.036	0.039	0.006	0.039	0.117	0.032	0.065	0.001	0.000
Difference		0.868	0.501	0.485	0.490	0.388	N/A	0.519	N/A	0.419	0.900

5.5.1.2 Per Scenario Prime Reaction Time

The data generated for each scenario were then grouped by prime type, Re-task or Deny (the control condition was omitted). It was found that for Re-task primed decisions, participants using the Graphical Display performed faster than those using the Numerical Display (Graphical M = 1.42846, SD = .491380, Numerical M = 1.95232, SD .840065, U(85) = 2202, Z = -4.396, p .000 [exact 1-tailed]). Similarly, for Deny primed decisions, participants using the Graphical Display performed faster than those using the Numerical Display (Graphical M = 1.77499, SD 1.093122, Numerical M = 2.13753, SD .905573, U(85) = 2473.5, Z = -3.550, p .000 [exact 1-tailed]).

5.5.1.3 Per Prime Reaction Time

Grouping all of the scenarios by prime type only, i.e. was the correct decision to re-task the weapon or was it to deny the weapon re-tasking, it was found that participants were able to perform Re-Task primed decisions [Scenarios: 2,5,8,9,12] significantly quicker than decisions where the participants were primed to Deny the Re-Task request [Scenarios: 3,6,7,10,14] (Re-task M = 1.6904s, SD = .73471, Deny M = 1.9563s, SD = 1.01714, U(170) = 11633, Z = -3.109, p = .002 [Asymp. est. 2-tailed]).

5.5.1.4 Total Average Reaction Time

Finally, grouping all decisions across all scenarios and prime types, it was found that participants using the Graphical Display took significantly less time to make their decisions overall than those using the Numerical Display (Graphical M = 1.60172, SD = .862632, Numerical M = 2.0449, SD = 0.87578, U(170) = 9314.5, Z = -5.667, p = .000 [Asymp. est. 2-tailed]).

5.5.1.5 Summary

The overall reaction time results show that there is a significant difference between display groups in terms of reaction time. The Graphical Display group took less time to make their decisions. Making re-tasking decisions takes less time than making the decision to deny a re-task request. Further those using the Graphical Display group perform faster in both prime conditions. Lastly, the Graphical Display group perform decision making faster in 8 of the 10 scenarios. Table 5.3 summarises these results.

Table 5.3: Summary of Reaction Time Results

	Graphical Display		Numerical Display		
	M	SD	M	SD	p
RT Scenario Prime RT	1.775	1.093	2.138	0.906	.000
RT Total	1.602	0.863	2.045	0.876	.000
	Re-Task Decisions		Deny Decisions		
RT Scenario Prime Correct Decisions	1.690	0.735	1.956	1.017	.002

5.5.2 Accuracy

Figure 5.6 shows the accuracy of participants in each group for each scenario seen. A participant was deemed accurate if they made the correct decision within the decision time available, incorrect if they made the wrong decision or made the decision too late, and were deemed to have made no decision if they did not interact with the system during a scenario. The following are analyses of the main factors tested against accuracy.

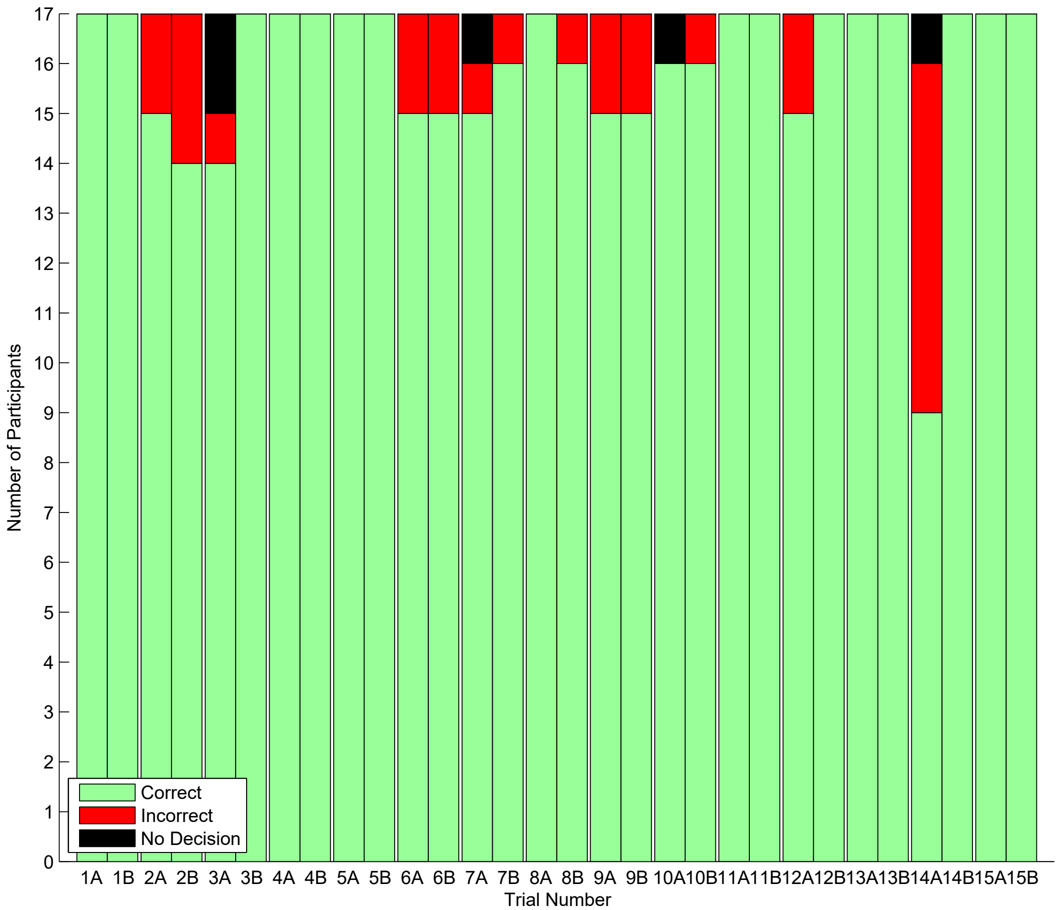

Figure 5.6: Decision Accuracy Per Scenario, A: Graphical Display and B: Numerical Display

5.5.2.1 Per Scenario Accuracy

In general, there was no significant difference found between accuracy on a per scenario basis, apart from scenario 14 (P(Z = 3.234—H0)<5% Zcrit = 1.96, PGraphical $\neq$ PNumerical PG = 0.529 [52.9%], PN = 1 [100%], NG=NN=17, Fisher's Exact Chi-Sq. p .001).

5.5.2.2 Per Scenario Prime Accuracy

When grouped by decision prime type (Re-Task vs. Deny Re-Task) it was found that for Re-Task primed scenarios there is no significant difference between display type groups for accuracy (PG = .929, PN = .929, PG = PN [92.9%]). However, for Deny Re-Task primed scenarios there was found to be significant difference between display groups for accuracy, with those using the Numerical display more accurate (P(Z = 2.857—H0)<5% Zcrit = 1.96, PGraphical $\neq$ PNumerical, PG = 0.812 [81.2%], PN = 0.953 [95.3%], NG=NN=85, Fisher's Exact Chi-Sq. p .004).

5.5.2.3 Total Average Accuracy

Lastly accuracy as a whole was found to be significantly different between display groups, again with participants using the Numerical display outperforming those using the Graphical display (P(Z = 2.229—H0)<5% Zcrit = 1.96, reject null hypothesis: PGraphical $\neq$ PNumerical, PG = 0.871 [87.1%], PN = 0.941 [94.1%], NG=NN=170, Fisher's Exact Chi-Sq. p .020).

5.5.2.4 Summary

Overall it was found that there was only one scenario where the difference between accuracy achieved between groups was significant. For scenario 14, 100% of the Numerical Display group made the correct decision, whereas the 53% of the Graphical Display group made the correct decision. There is no difference between display groups when primed to re-task a weapon. However, there is a significant difference when primed to deny a re-task request, with the Numerical Display being more accurate than the Graphical Display group. Overall, the Graphical Display group are 87.1% accurate across all scenarios, whereas the Numerical Display Group are 94.1% accurate. A difference of 7% (see Table 5.4). It is worth noting that neither of these results are ideal, in a training or exercise environment it would be expected that operators are always accurate in their decision making when using a system that interfaces with a live weapon.

Table 5.4: Summary of Accuracy Results

	Graphical Display	Numerical Display	
Analysis	Accuracy %	Accuracy %	p value
Per Scenario Accuracy (14)	52.9%	100%	.001
Per Scenario Prime Accuracy	81.2%	95.3%	.004
Total Average Accuracy	87.1%	94.1%	.020

Figure 5.7 is a plot showing the change of altitude of the GBU over time, as well as the area of the RAR footprint on the ground. Figure 5.8 then shows the times and distances away from the RAR boundary of all the trial scenarios. These two Figures show the dynamic change in size of the RAR. Early in the scenario, the area reduces in size linearly and at a slow rate. Then at approximately 10 seconds into the flight, there is an increase in the rate at which the RAR size reduces. This continues until approximately 22 seconds, at which point the rate at which the size of the RAR area reduces begins to slow, and tails off as the remaining RAR area reduces from 20km^2 to 0km^2. This non-linear behaviour required the operator to be aware of how the change in rate could affect their ability to make a decision in the scenario so that their SA is complete.

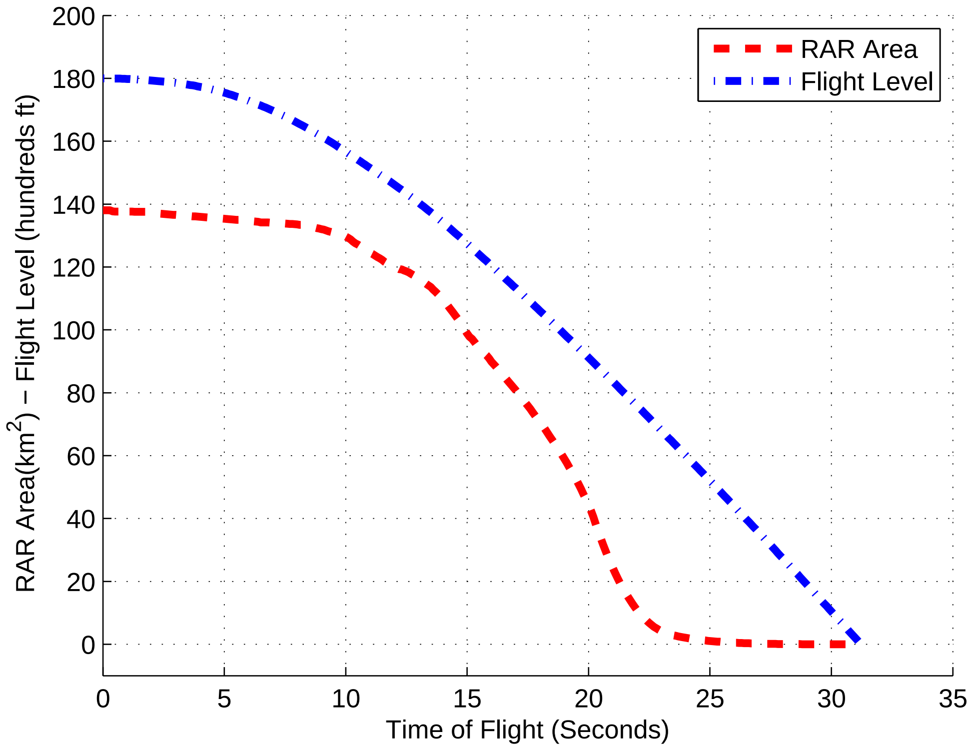

Figure 5.7: Dynamic RAR Area in Example NEW Drop Showing Rate of Change of RAR and Altitude vs. Time

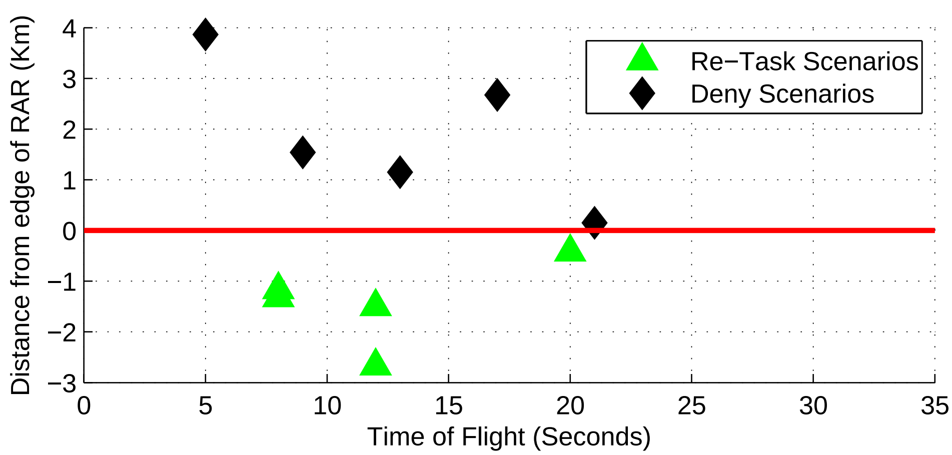

Figure 5.8: Dynamic RAR Area in Example NEW Drop Showing Points at which New Targets Appear and their Distance from the Edge of the RAR

Scenario 14, the trial with the largest accuracy difference between display groups, is the scenario where a new target appears less than 150 metres inside the RAR boundary at 20 seconds into the weapon's flight. At this point, the rate of decrease of the RAR area is at its highest, and the total RAR area remaining is less than 50km. Although no specific difficulty scale was used when generating the scenario set, it is clear that this is the most challenging scenario for making accurate decisions for those participants using the graphical display.

5.5.3 Subjective Experiences

A 14 point scale was used to measure participant responses to the following set of questions:

1. How confident were you in your decision making?
2. How much anxiety did you experience during the task?
3. How easy did you find the task?
4. How worried were you about making the wrong decision?
5. How difficult was the RAR/numerical display to understand?
6. How accurate do you think your decision making was?
7. How much time pressure did you feel during the task?
8. How realistic did you find the look of the display?

From the set of subjective experience questions there were only three with significant differences between the display types. Participants' perceived difficulty was low, with those utilising the numerical display rating their perceived difficulty higher than those using the graphical display, (M 1.59; SD 1.502) vs. (M 3.25; SD 3.088), (U(17) = 89, Z = -1.743, p = .041 [exact 1-tailed]). Perceived accuracy was generally high, with participants in the Numerical display group rating their accuracy higher than those using the Graphical display, (M 11.25; SD 1.77) vs. (M 9.12; SD 2.64), (U(17) = 74.5, Z = -2.506, p = .006 [exact 1-tailed]). Interestingly participants utilising the numerical display felt more time pressure than those utilising the graphical display (M 7.50; SD 3.81) vs. (M 4.35; SD 2.62), (U(17) = 68.5, Z = -2.629, p = .004 [exact 1-tailed]). Figure 5.9 shows the overall results from the subjective experience task ratings.

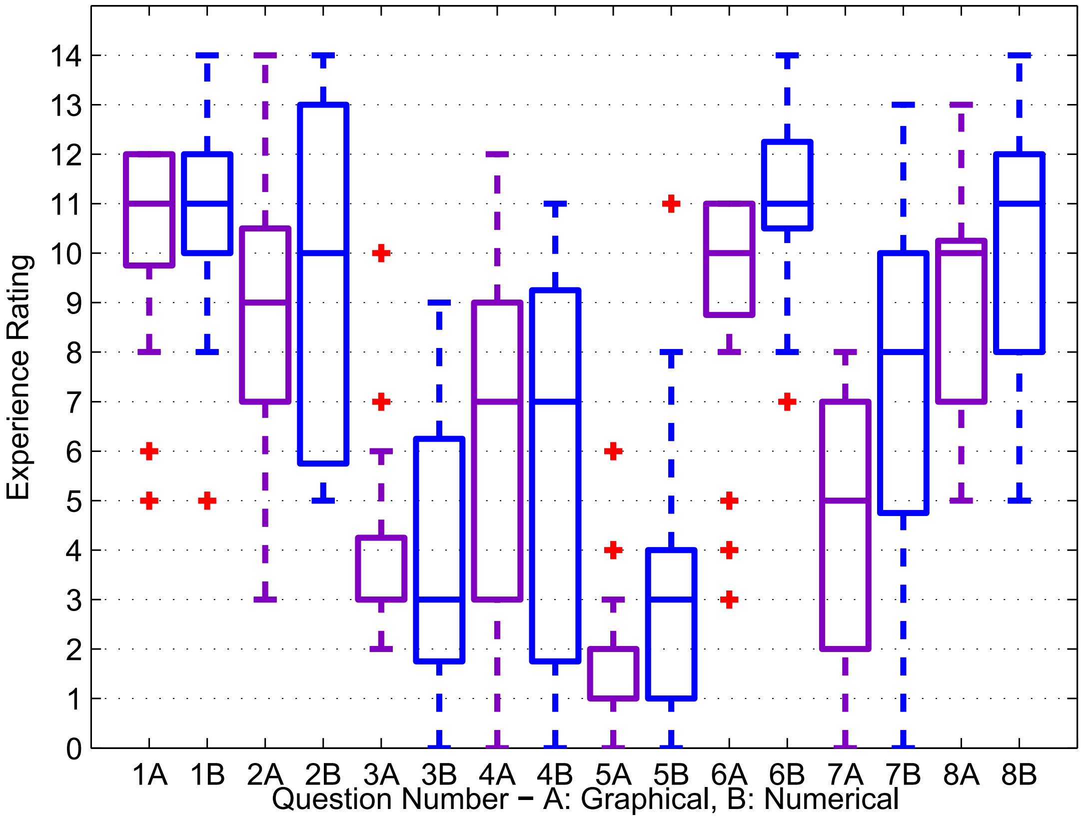

Figure 5.9: Subjective Experience Ratings – Box shows inter quartile range with mean at the centre, and whiskers showing the upper and lower quartiles, outliers are shown as a red +

When asked if the participant had 'missed an opportunity to re-task' 82% of the graphical display said yes, compared to only 24% of the numerical display. In comparison to the actual results, only 17.6% (3 of 17) of participants using the graphical display missed an opportunity to re-task, with a total of 6 missed opportunities overall. Compared to 35.3% (6 of 17) in the numerical display group, with a total of 6 missed opportunities overall. This suggests that participants' awareness of their own performance is poor for participants using the graphical display type in comparison to the numerical group. This difference between participant groups at accurately recalling their success at the task could be representative of findings from Unmanath & Schmell. They found that recall is influenced by the appropriateness of a display type to the decision making task, and that, for spatially oriented tasks, graphical interfaces may enhance participant's recall [161].

5.5.4 Digit Span Task

The before and after Digit Span Task measurements were compared to see if there was any measurable difference which would suggest a cognitively difficult task. A Wilcoxon Signed Ranks test found that there was no data to suggest that the task had any effect on participants' short-term memory function updating after the trial (Graphical Z = -1.427, p = .154, Numerical Z = -1.409, p = .159). There was also found to be no significant impact on participant's executive function updating, in fact, those participants using the Graphical Display showed better digits backwards task performance after performing the trial than their pre-trial scores (Graphical Z = -2.803, p = .005, Numerical Z = -.864, p = .388). The task may not have been difficult enough to have an effect of working memory capacity or executive function updating, meaning that no conclusions can be drawn from the digit span tasks.

5.6 Discussion

The overall findings indicate that although decision making is generally faster when using the graphical interface (1.60s vs. 2.05s), decisions are more accurate when using the numerical display (87.1% vs. 94.1%). It was found that for scenarios prompting a deny re-task action, with a small distance between the edge of the RAR and the new target, the numeric display maintained 100% decision accuracy compared to the graphical display with 53%. It is worth noting that the small sample used in this trial may explain why the difference in accuracy was not significant across all scenarios and this is an acknowledged limitation.

Overall, the time difference between display groups at making their decisions is around half a second. From a practical perspective, the accuracy gained by using the numerical display should outweigh the benefit of making a decision half a second quicker. The large difference in performance of participants using the different display types seems to occur when a new target appears close to, but not inside, the capability of the weapon. However, this specific scenario could be mitigated by using an under-representation of the capability of the weapon. As discussed in Chapter 3, the basic RAR algorithms used in this real-time study, under-represents the true capability of the GBU. A limitation in this particular study was that the reduced number of participants recruited meant that there was not an opportunity to develop the scenarios presented to participants in such a way to further examine the borderline cases.

Post-task feedback adds further insight into causes of error. Some of the graphical display group participants indicated they were not expecting a new target to appear close to the edge of the RAR despite being fully briefed and demonstrating they understood their task. The open question 'What thoughts did you have that led you to miss an opportunity to re-task?' prompted the following responses from group A participants:

- *"Not expecting a new target"* - Participant A3
- *"...it was only inside the green box for a very short time."* - Participant A4
- *"...I did not see that situation in previous trials."* - Participant A5
- *"The new target appeared when the range of the missile reduced very fast so that I didn't have time to re-task."* - Participant A6
- *"...new target was right on the green boundary and I hesitated"* - Participant A9
- *"...the green area was rapidly retracting when the new target appeared"* - Participant A10
- *"...by the time I pressed the key to move the grid lines moved..."* - Participant A13
- *"...the target was initially in the RAR but was outside by the time I had a chance to react"* - Participant A15

Participant A5's comment highlights the possible learning effect of seeing several scenarios where a new target appears a long way outside of the weapon's capability in the run up to a scenario in which a new target appears just inside the RAR boundary. Participants may have performed better if this boundary case scenario had occurred early in the scenario set. The scenario sequence is acknowledged as a limitation of this study with regards to the potential learning effect. Regardless, further improvements could be made by giving clear instructions on the additional procedures when borderline scenarios occur.

It is also worth noting that whilst the significant differences seem small, if 100% decision accuracy is a requirement, only 41% of participants achieved 100% using the graphical display, compared with 59% of participants using the numerical display. Considering the lack of experience the participants had, these results would be improved through training and a stricter set of operating procedures, particularly in relation to new targets that appear close to the border of the weapon's range capability. No participants were removed from the data set.

Given that this trial was the first study to test the effectiveness of the display, the number of decision aids was reduced to the minimum number necessary to allow participants to make their decisions. Participants' general remarks with regards to improvements of the display types typically suggest improvements to the cue for a new target appearing and that the system has received a command from the user. The main themes from the qualitative data surround the inclusion of more active prompts to the user and system feedback for actions made by the user. Further suggestions are to do with increasing the manipulation of the colour of the different elements on the screen. Interestingly, although the Numerical Display is sufficient for decision making and participants perform better when using it, 5 of 17 Numerical Display participants suggested the use of a RAR boundary to aid decision making. Of these five participants, four achieved a score of 100% correct decisions. This supports the notion that improvements need to be made to display the effectiveness of a participant's decision, for example by integrating a Battle Damage Assessment (BDA) tool into the Remote Operator Terminal so that more detailed feedback is provided that the weapon hit its intended target.

5.7 Chapter Summary

This chapter discussed a trial that sought to find meaningful significant differences between different visual displays (graphic or numeric), and how their use influences decision accuracy and reaction time when re-tasking a simulated guided free-fall bomb whilst in flight. Decision making when using the graphical interface had a reduced reaction time by an average of 0.45 seconds. Decision accuracy was higher when using the numeric interface, with which accuracy was higher by 7%. A large difference between accuracy was found when participants were primed to deny a re-task request to a target that was positioned just outside of the RAR. In this case all participants using the Numerical display made the correct decision to deny the request, compared to only 53% of those using the Graphical display.

These results suggest that designers of DSS for remote weapons operators must consider how using different interface styles may have differing effects on the timeliness and decision accuracy of the users of the system. Particular care must be taken when handling cases where targets appear close to, or on the edge of, the RAR boundary as this is where the largest difference in performance between the display types was found. The inclusion of a tolerance level and an under representation of the RAR would alleviate this issue, and logic built into the system would prevent incorrect re-tasking decisions automatically. There is no real applicable benefit of a 0.45 second gain in decision making time in this context. Both from a military and political stand-point the operator of a re-tasking system should not be placed in positions of such expediency.

Whilst this chapter described a complete trial into the use of RARs in the Graphical or Numerical form, it considers only one engagement at a time. However, it is far more likely that in an operational context, more than one weapon will be released against a target in the form of a 'double tap' [162]. Furthermore, there are scenarios in which there may be multiple targets to prosecute simultaneously. The next chapter will discuss the conversion of the findings of this trial into a more complex scenario involving multiple targets in batteries and multiple in-flight weapons.

Chapter 6

Participant Study 2

In the previous chapters the case was made that there is a potential for a remote operator to be able to re-task weapons after they have been launched. Chapter 4 discussed an overview of a system that allowed operators to use resource-task allocation algorithms to assign platforms and their weapons to sets of targets. Then in Chapter 5 an operator terminal for re-tasking individual short-range bombs was designed and tested using human participants. An investigation into the ability of operators to re-task individual bombs in time limited scenarios using two different display types found that the use of a graphical RAR was not strictly necessary for providing operators with the cues needed to carry out re-tasking duties. Instead, a modified numerical display system proved to facilitate more accurate decision making on the whole, whilst delaying the decision making of operators by only a fraction of a second.

In this chapter, the capability of the operator system was expanded to allow for re-tasking of multiple in-flight air-to-surface weapons against numerous targets. An example SEAD scenario was used as a baseline to design the remote operator system. An investigation into the use of the system by participants as part of a human factors trials is discussed, with direct comparison against an 'ideal' automated decision making system designed for this SEAD role. The chapter concludes by presenting the results of the human factors trials which were aimed at finding the limitations of operators when in control of up to 32 missiles against two SAM batteries each with four SAM launchers.

MBDA Systems were consulted in the development of the scenarios herein. The information provided was of great use in positioning the enemy SAM sites and the salvo sizes of own forces. It is an unrealistic scenario when considering the UK's current military and political motivations, and was developed out of academic interest. However, it is envisaged that this type of capability may be possible as the SPEAR program matures.

6.1 Suppression of Enemy Air Defence (SEAD)

SEAD is a mission type in which enemy air defence units are destroyed or disrupted so that friendly aircraft can safely pass through hostile territory without being at risk from anti-air weapons. Typically hostile areas are not defended by just one system. Often, several different types of anti-air system are used, such as SAM sites, and Anti-Air Artillery (AAA). Each type of anti-air system is optimised for a set of ranges, both distance and altitude, and type of target expected. A common air-defence network is a layered approach, in which more than one SAM site are positioned such that two bands of independent defence exist, where one must be defeated, before being able to reach the second. Figure 6.1 shows this type of layered air defence.

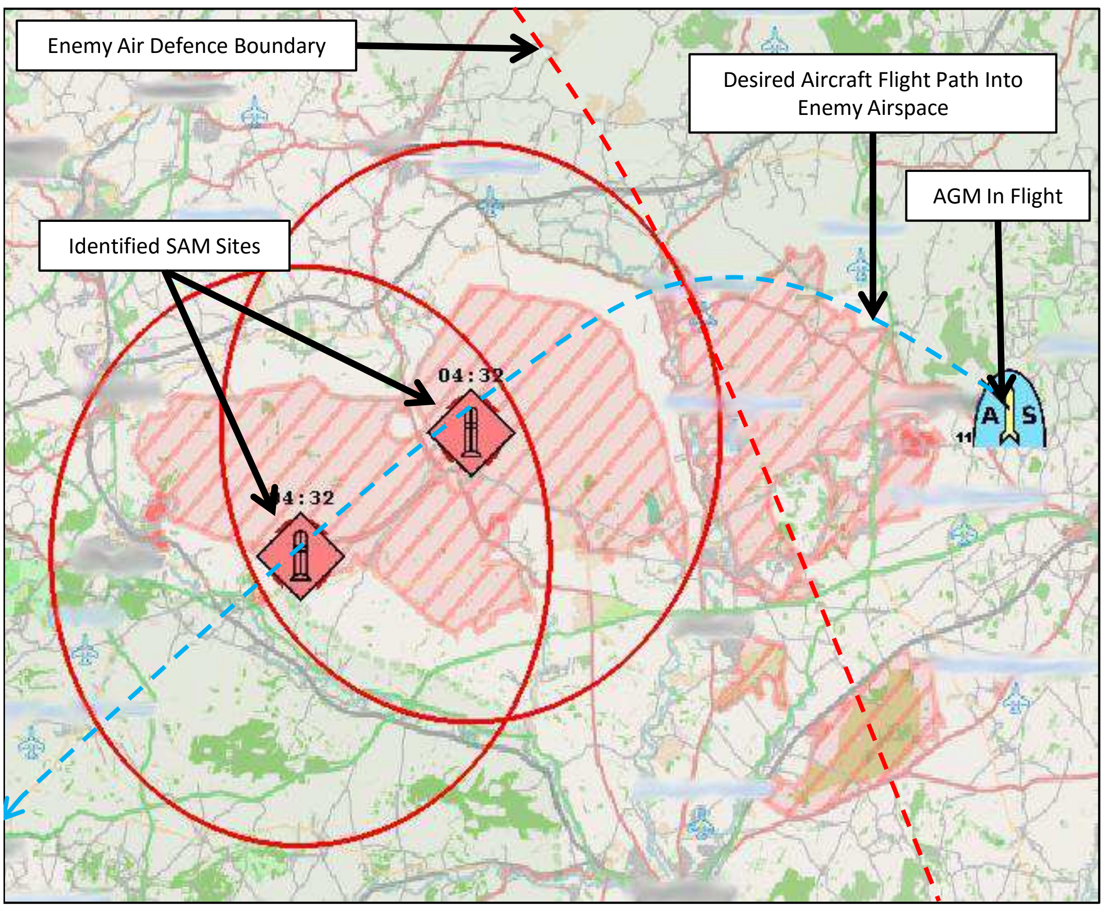

Figure 6.1: Overview of Suppression of Enemy Air Defence Scenario with Layered Air Defences

With the proliferation of advanced radar and tracking systems, SAM sites are now packaged into single Transporter Launcher and Radar (TLAR) systems such as the Russian SA-15 (shown in Figure 6.2 [163]). These highly mobile and sophisticated air defence systems pose great threat to aircraft, with quoted p_{kill} values of up to 0.9 [164]. New precision strike ranged weapons, such as the MBDA SPEAR missile [4] can be carried in large numbers and are capable of destroying armoured targets such as the SA-15. These weapons are capable of being interfaced with over data communications networks under NEC. For the purpose of the research following – the LRAGM weapon, detailed in Chapter 3, will be used as a representative SPEAR missile.

Figure 6.2: SA-15

This layered type scenario was chosen as the scenario type as it forces re-tasking of incoming missiles between SAM sites. The engagement range of SAM systems forces longer range weapons to be launched to protect the aircraft from being shot down. Launching one weapon at a time is inefficient against a SAM site such as a SA-15 battery. In an SA-15 battery, four complete TLARs are arranged in a cluster and are able to assign targets between themselves for greater utility of each system's weapons. Several weapons will be able to be launched to intercept the incoming missile, making it highly unlikely that a single missile launched against an SA-15 battery will be successful in hitting its target. To establish a guideline number of how many weapons it will take to destroy a SAM site, several properties of the TLAR and the attacking missile system are needed.

6.1.1 SA-15 TLAR

Table 6.1: SA-15 Properties

SA-15 Properties	
Maximum Simultaneous Tgts	4
Maximum In Flight Missiles	2
Missile Speed	850m/s
p_{kill} against missile	0.25 (est.)
Maximum Detection Range	25000m
Maximum Tracking Range	12000m
Minimum Range	1500m
Reload Time	10mins

The SA-15 properties used from open source literature can be seen in Table 6.1 [164]. We can consider four TLAR systems as one SAM site. Therefore, a total stock of 32 missiles exists at the SAM site (without reloading). Further, with an estimated p_{kill} of 0.25, it can be predicted that 8 of the enemy's missile stock will hit their targets. If each target at the SAM site must be hit twice, with a 'Double Tap' [162] procedure, this requires 8 missiles to be destroyed by intercepting missiles, and 8 to destroy the four TLARs. One question that must be considered though, is the possibility of losing less than 8 missiles to the SAM site. If the SAM site is overwhelmed, is it possible to lose fewer missiles?

MATLAB was used to create a simulation model of the SA-15 TLAR. This simulation model was designed to control the detection, tracking and launching of SAMs at incoming threats. The above information was used to create an object class that could be loaded into the simulation environment within MATLAB. The SA-15's SAMs are individually launched at incoming targets. When within range of the tracking radar, the next available missile is primed, and a suitable target is chosen (the closest first). The missile is then launched (so-long as there is not a weapon currently in flight) and the object then loops through the time step function until the SAM has reached its target. Three dimensional equations of motion are solved to resolve the angles between the SAM and its target, and provide the correct motion. The guidance of the SAM is not modelled as it is outside of the scope of the project. Instead, a p_{kill} is used to define the likelihood of target intercept in order to determine whether the SAM hit its target or not.

The flow chart in Figure 6.3 shows the model's logical steps when deciding to launch weapons at incoming threats and the differential equations used for the calculation of the SAM's motion over time. In Figure 6.4 is a graphical wire-frame representation of the scenario displaying the two radar cones of detection for both detection and tracking radar systems on the SA-15 TLAR.

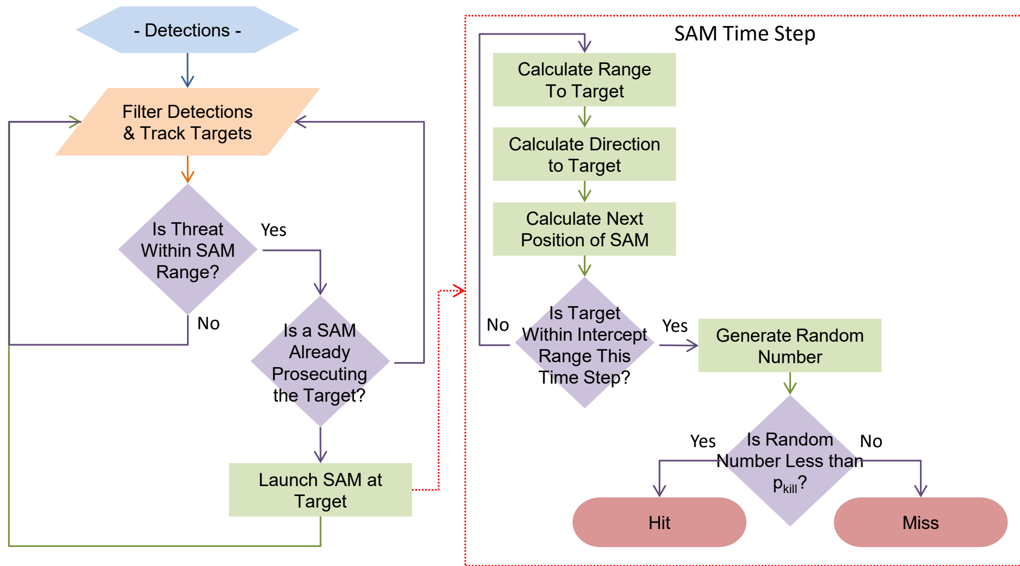

Figure 6.3: Flow Diagram of AA Site Launching Procedure and SAM Model Time Step

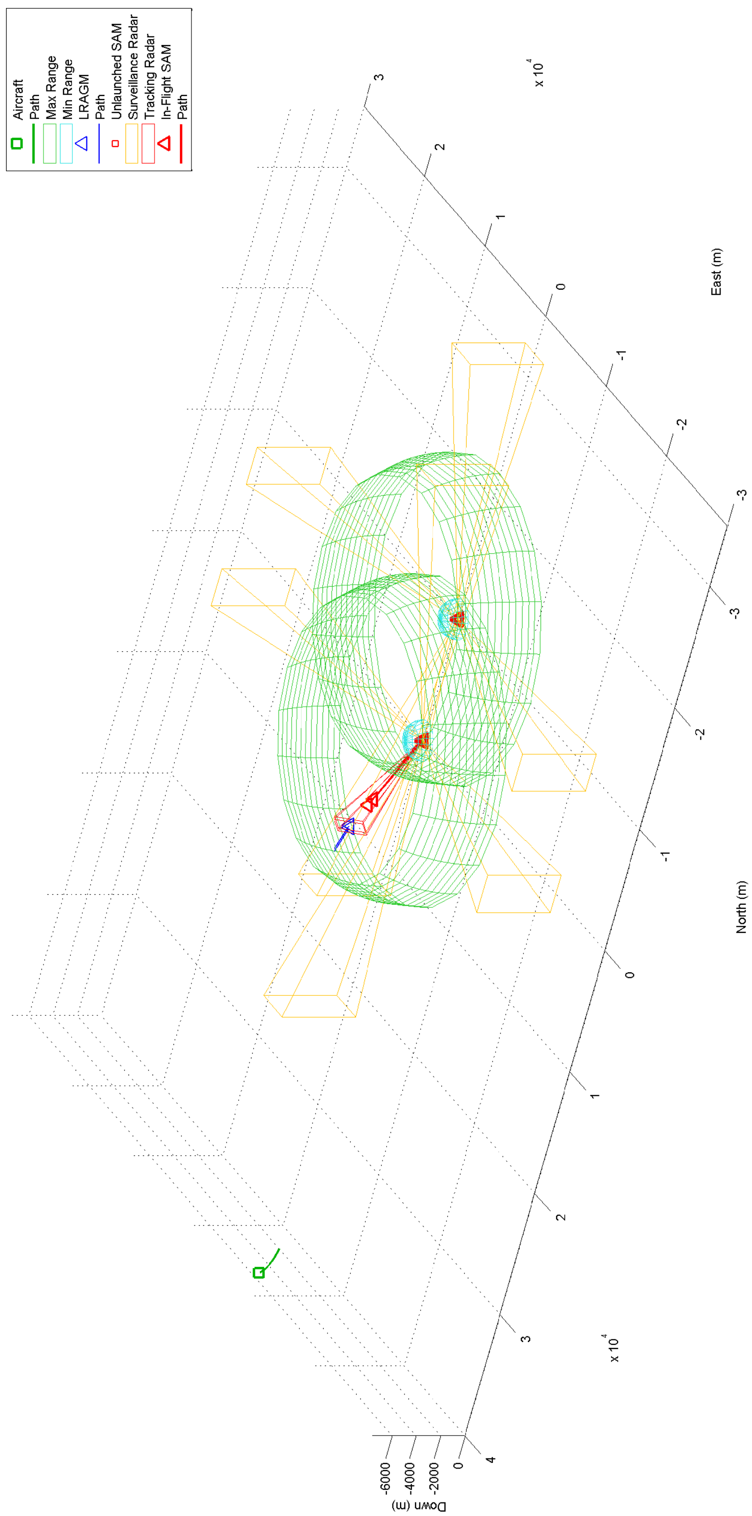

Figure 6.4: Graphical Representation of the Simulated SAM Launching Sites with Visible Missile Range Domes, and Radar Sensor Capability

6.1.2 LRAGM

A brief overview is needed here for completion, however, for a more detailed description of the flight properties of the LRAGM, and how they were calculated, refer to Chapter 3. Table 6.2 shows the range and cruise speed properties of the LRAGM.

Table 6.2: LRAGM Properties

LRAGM Properties	
Maximum Range	120000m
Minimum Range (From FL250)	25000m
Minimum Range (From FL016)	2000m
Cruise Speed	300m/s

The LRAGM has a cruise velocity of 300m/s and approximate cruise height of 500m. The missile has three main phases of flight. From initial launch the weapon glides, unpowered, to its cruise altitude. During cruise the weapon uses altitude hold and initialises the turbojet engine. Bank to turn is used in both glide and cruise phases to aim the weapon towards the target. In the final 5 seconds the weapon switches to terminal guidance, in which a pitch over manoeuvre is performed and the missile dives onto its target. The maximum bank angle of the LRAGM is 60 degrees and provides a turn rate of 3 degrees per second at cruise altitude and velocity, although this is higher during terminal phase to facilitate use against mobile targets.

6.1.3 Scenario Outcome Estimation

An estimation of where and when missiles will be destroyed by the enemy SAM sites can be calculated. The main influencing factor is the velocity difference between the LRAGMs and the SAMs. The SAMs have almost three times the velocity of the LRAGM, meaning that three SAMs can fly the distance of the maximum range of the SAM system, in the time it takes one LRAGM to cover the same distance. This gives the SAM site considerable advantage against the LRAGM. Note that there is a minimum range for the SAM site of 1500m. This is the minimum required distance for safe launch, acquisition of the target and acceleration to an intercept condition. Once through the minimum range of the missiles it is assumed the Air-to-Surface Missile (ASM) will hit their target.

There are a number of launch properties that can be manipulated to maximise the success rate and minimise the total number of weapons needed to hit all four targets. Firstly there is the salvo size. Weapons on aircraft are typically symmetrically paired across the pylons used to attach them to the airframe so as to balance the aircraft by maintaining a cross sectional centre of gravity in a vertical plane aligned with the aircraft's nose to tail axis. When launched there are two settings that are used to control the timing and even launching of the weapons. These are known as Ripple Time and Salvo Size. Ripple Time is the time between subsequent launches of the same weapon type. Salvo Size is the total number of that particular weapon to be launched. For example, a Ripple Time of 1 second and a Salvo Size of 4 will launch four weapons in one second intervals from the pylons on both the left and right of the aircraft, two from each side.

The next property that can be configured is the time between salvoes that are launched. This is an action that must be carried out by the pilot or between pilots if more than one delivery aircraft is being used (for larger number of weapons than can be carried by one aircraft). The smaller the time difference between salvoes the more weapons there are to be shot down at the same time by the SAM site. A combination of high salvo sizes and reduced time between salvoes can result in overwhelming of the SAM site, as there is a limit to the number of targets that the SAM site can shoot at simultaneously.

From an operator's perspective, having weapons spread over time will allow for more time to make any potential re-tasking decisions. Separating out the missiles allows operators to approach the overall task in stages, and allows them to concentrate on the missiles closer to their targets, and then switch their attention to following missiles without becoming overwhelmed. This is the capability estimation this research aimed to expose. At what salvo size and time interval do operators become overwhelmed?

An automated test case was generated to allow the calculation of the effect of salvo sizes and time interval between salvoes on the enemy's ability to intercept incoming missiles. With the p_{kill} of 0.25, and four launchers, the distance and time of each positive intercept of an incoming missile was calculated. An assumption was made for the worst case scenario from the perspective of the attacker. A missile was guaranteed to be intercepted each loop (4 launched intercept missiles with p_{kill} $0.25 = 1$ per intercept). The points of impact are dependent on the size of the salvoes and the time difference between them. The solution is generated using the iteration loop shown in Figure 6.5.

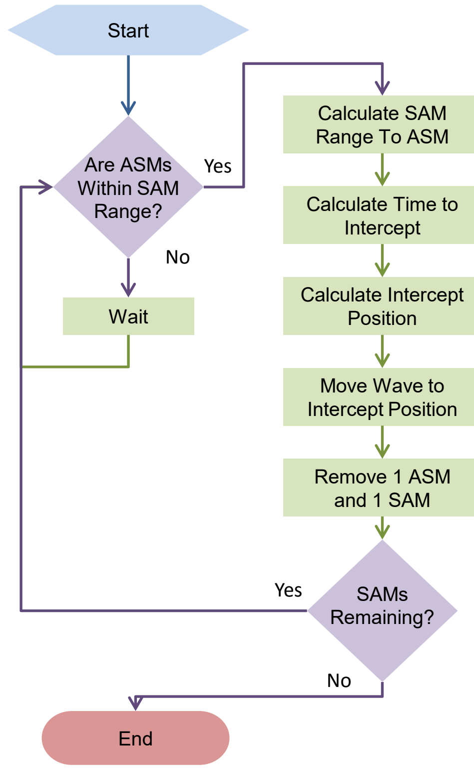

Figure 6.5: Iteration Loop to find SAM vs. ASM Intercept Positions

In the overload scenario, with all missiles launched simultaneously, it can be seen that 7 missiles are destroyed before the weapons break through the SAM site's engagement area (see Figure 6.6). This Figure shows the raid of LRAGM flying towards the SAM site and the impact points of each engagement between the enemy SAM and a LRAGM. However, if the time between salvoes is increased to only 1 second, 8 missiles will be lost to the SAM system. As the enemy SA-15 systems only have 8 missiles each, the SAM site only has the potential to destroy 8 incoming missiles. Therefore, given that once 8 of the LRAGM missiles are destroyed the enemy's stocks will be depleted, there is no need to group weapons closely together over time as it does not give an advantage.

The reload time of the SA-15 system sets an upper limit on the time between salvoes used. The LRAGMs should not be spaced apart such that a system could reload and continue to fire upon incoming missiles. The time interval between salvoes, for LRAGMs grouped in twos, that would give the enemy SAM site enough time to reload can be estimated. Given that the first 8 missiles are wasted, if the following 8 missiles take longer than 10 minutes to hit their targets then these missiles are at risk of being destroyed. This would only occur if the time between salvoes is more than 70 seconds, leaving a time of 71x8 = 568s, plus the time it takes to travel through the enemy engagement zone, $(12000m - 1500m)/303ms^{-1} = 34s$, giving a total of 10 minutes and 2 seconds.

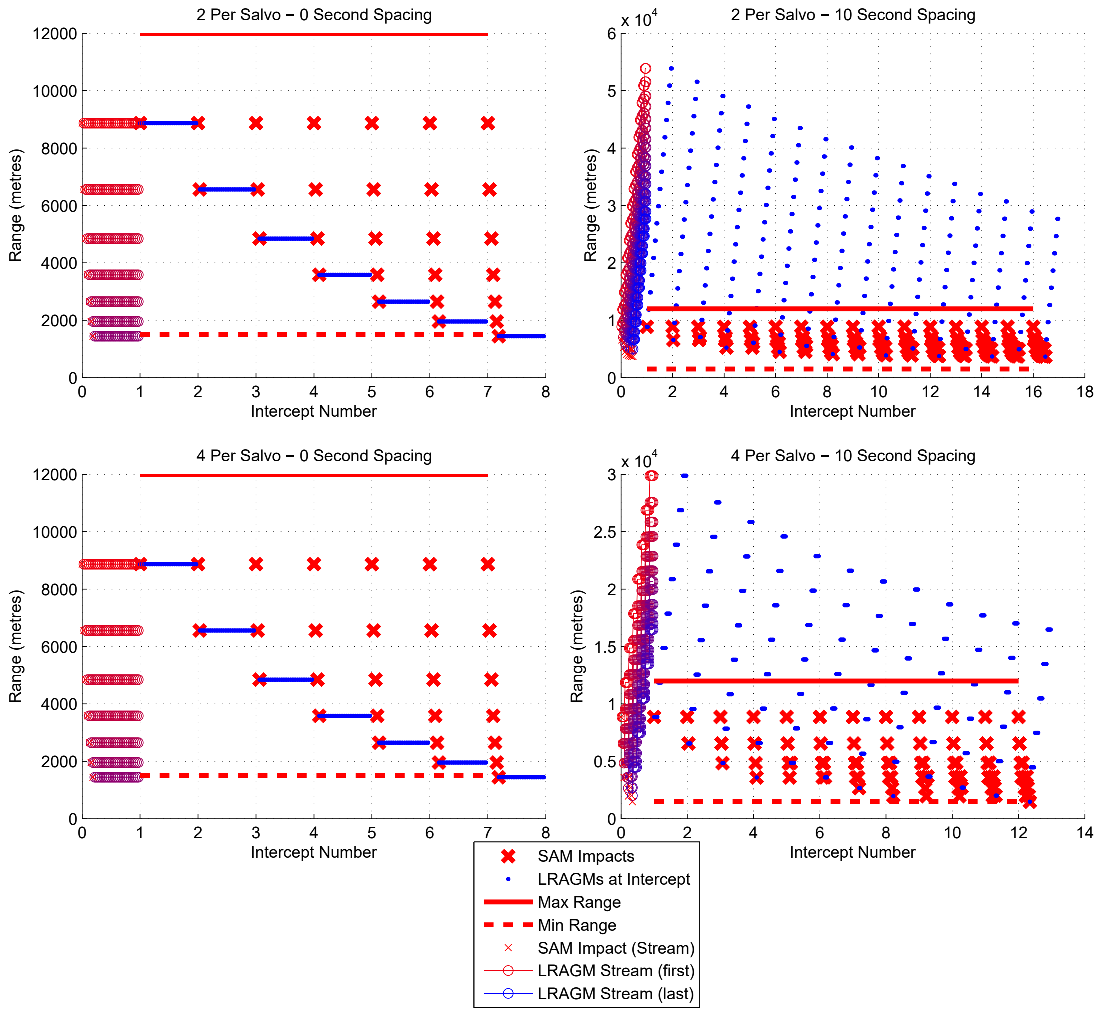

Figure 6.6: Estimates of Defending SAMs Intercept of Incoming LRAGM, by Iteration of Successful Intercept, and Range

6.2 Human Interface Design

The human operator is not just the user of a system designed to perform a particular job, they are part of the system as a whole. For the operator to be able to carry out their duties with ease, an interface must present information clearly and allow for interactions with the interface to be made in an understandable and logical way. To do this successfully a reasoned list of features and functions needed to be developed to initiate the design process.

6.2.1 Features and Functions

The interface's main function is to allow the operator to re-task or abort weapons during flight. The system must display information about these weapons and the status of targets to facilitate the decision making of the operator. Then, there must be a way of interfacing with the system to invoke the different types of action when required.

There is a requirement for a large number of weapons to be used against several targets, and the interactions will occur over time – i.e. the time at which different events will need to be monitored closely is normally sequential. This means that a large amount of information will need to be presented to operators.

Given the above set of functions and requirements, the first element of the user interface that is needed is a table that includes a list of weapons and columns that represent each target. This creates workable space within the interface to place information that is relevant to a particular weapon to target assignment and sets information out in a clear manner. It is also an established method of displaying information and has been used in similar systems for assigning tasks to different objects, from ATC, to TLAMs [36, 101, 104].

6.2.2 Task Allocation Table (TAT)

The operator will need both information related to the current weapon-target assignments and information about the ability to re-task a weapon to any other target. An overview of the layout of the grid (named the TAT) can be seen in Figure 6.7 with no information presented within the Weapon-Target Status Boxes.

WeaponID	Status	TGT 1,1	TGT 1,2	TGT 1,3	TGT 1,4
AGM011	Caged Est: 000s				
AGM012	Caged Est: 001s				
AGM013	Caged Est: 002s				
AGM014	Caged Est: 003s				
AGM021	Caged Est: 005s				
AGM022	Caged Est: 006s				
AGM023	Caged Est: 007s				
AGM024	Caged Est: 008s				

Figure 6.7: Task Allocation Table (TAT) Before Launching Weapons - Each Weapon to Target Status Box is Empty. Only the First Target Set and First Two Salvoes are Shown

There will be a potential of 32 LRAGMs and 8 SAM targets, needing up to 256 different Weapon-Target Status Boxes to be presented on the user interface at the same time. This raises an issue of salience. Important information needs to be highlighted in a way that allows the user attention to be focussed when it is necessary [151, 165]. There are specific times at which this is needed. Firstly, when a weapon is approaching the final 20 seconds of flight it will become critical for the operator to monitor it in case the weapon is intercepted and a re-task is needed. And secondly, when a re-tasking option is nearing the point at which it is no longer able to be made.

Further, when weapons are intercepted in flight, or have hit their targets, it is necessary for their salience on the interface to be reduced because the information they provide to the operator is no longer time dependent. This allows the operator to have a clearer picture of where attention is needed on the interface.

In practice, the availability of BDA is difficult to achieve in real-time. At best, the operator can be made aware of a weapon being destroyed in flight, due to the cease of data link messages received from the in-flight weapon (although this doesn't account for any system malfunction). The actual effectiveness that a weapon system has against a target can only be properly assessed based upon visual verification from a surveillance asset, which would need to be transmitted to the operator of the system. For the purposes of this trial, an operator was instructed that two missiles on target was sufficient that the TLAR could be considered destroyed, otherwise the trail would have become too complex to run in a laboratory condition. Further, the need for real-time BDA is not strictly necessary as a surveillance asset could begin assessing the damage once the primary target set were deemed destroyed and report their findings with only a short delay. The mission commander could then choose whether to re-engage any remaining TLARs or whether the mission was successful.

The Weapon-Target Status Boxes have four different primary conditions, and hence different levels of salience, these are:

- In flight towards target (Highest Salience).
- Possibility of re-task (High Salience).
- Hit target (Low Salience).
- Destroyed/intercepted by enemy (Lowest Salience).

WeaponID	Status	TGT 1,1	TGT 1,2	TGT 1,3	TGT 1,4
AGM011	Hit Tgt	Destroyed			
AGM012	Destroyed	Failed			

Figure 6.8: Elements of the Task Allocation Table and the Weapon-Target Status Boxes Showing AGM011 Hit Tgt status, and AGM012 Destroyed/Failed

Figure 6.8 shows the layout of the TAT with the various types of Weapon-Target Status Boxes shown. The different conditions are clearly distinguishable from one another. In addition to displaying key information within the TAT, operators must be able to interact with the different weapons to either abort or re-task them. There were several options that could be used to allow for this interaction.

- Drop-down list of weapons and a drop-down list of targets, followed by a button.
- Re-task button that creates a new window or panel that allows for re-tasking orders to be made.
- Placing a button in the TAT for each weapon-target re-tasking option and abort options.

To analyse these options a Cost-Benefit Analysis was carried out taking into account the following issues:

- Ease of Use Overall
- Clarity of System
- Feedback to User
- Ease of Multiple Re-tasks
- Speed of Re-task
- Likelihood of Mistake

A table was drawn up and the options given a relative score based upon rank in each category, 1 being best, 3 being the worst, with no two scores being the same in each category. As can been seen in Table 6.3 the best option is the individual button for each potential re-task or abort that might need to be made. It reduces the clarity of the TAT compared to the other two methods, however, it allows for easy and fast re-tasking, that only requires the operator to use a single button, rather than have to scroll through menus or occlude the main window by bringing up a second panel to carry out a weapon re-task or abort.

Table 6.3: Rating of Each Element in Cost Benefit Analysis

	Ease of Use Overall	Clarity of System	Feedback to User	Ease of Multiple Re-tasks	Speed of Re-task	Likelihood of Mistake	Total
Drop-down	2	2	2	2	2	3	13
Re-Task Window	3	1	3	3	3	1	14
Individual Button	1	3	1	1	1	2	9

Figure 6.9 shows the layout of the weapon-target status box based upon TTG and current targeting conditions. To minimise the risk of making a mistake, additional safety features have been implemented into the design. Upon pressing a button to make a re-task or abort request the operator is prompted to then confirm their command before any messages are sent to a weapon. This acknowledgement procedure is good practice in networked systems and was necessary for compliance with VMF type messaging architecture outlined in Chapter 3. Figure 6.10 shows the flow diagram of the change in button state when a command is issued.

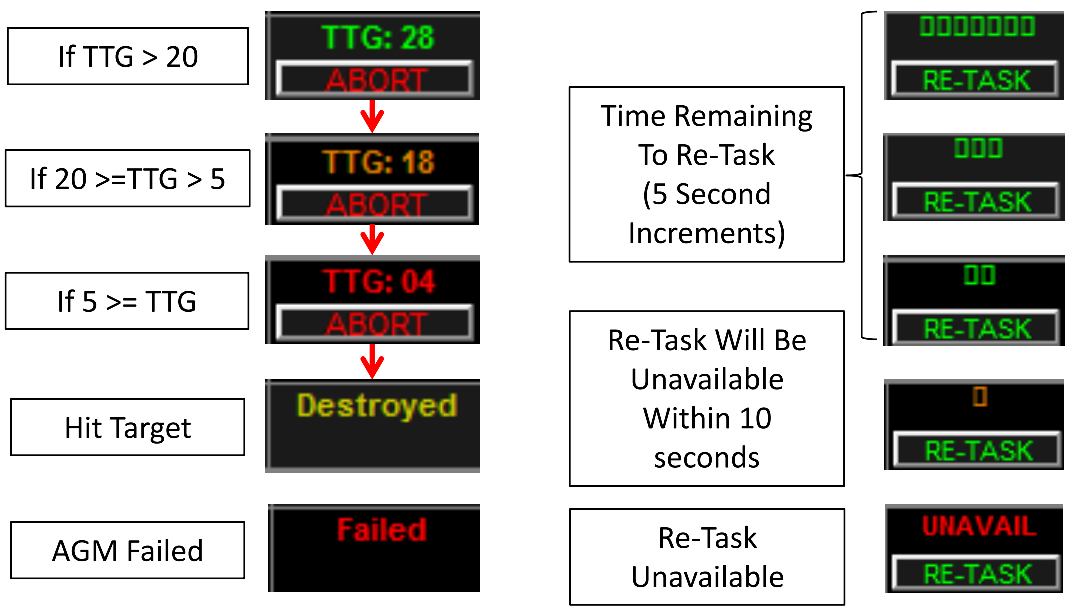

Figure 6.9: Weapon-Target Status Box Display, Left - Weapon Currently Assigned to This Column, Right - Weapon Not Currently Assigned to This Column

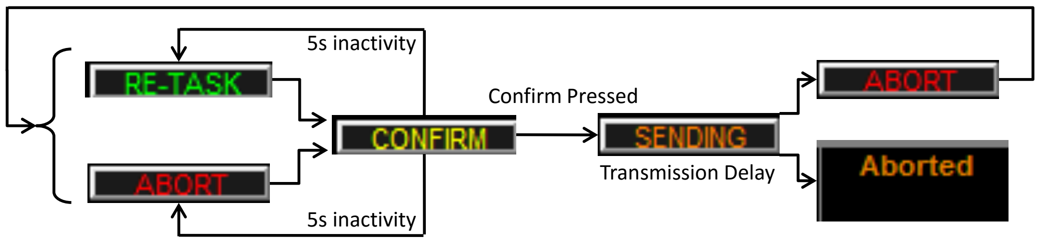

Figure 6.10: Re-Task/Abort Button Press Flow Diagram

In addition to the individual re-task and abort buttons for each Weapon-Target Status Box, an additional feature was developed for the interface. When the first SAM site has been successfully destroyed, there will be up to 16 LRAGM still in flight towards the primary target (assuming that 8 are intercepted and 8 hit their targets). To ease and simply the re-tasking of up to 16 missiles to the secondary SAM site a re-task salvo button was created. This button re-tasks an entire salvo from their current distribution against the primary SAM site, to the same distribution against the secondary SAM site. In scenarios with 4 weapons per salvo, this reduces the number of actions needed to re-task a salvo from the primary to secondary SAM site by 4 – significantly reducing the time to effect a decision once it has been made. Figure 6.11 highlights the Re-task Salvo button, which has the same two stage confirmation protocol as the standard re-task and abort buttons.

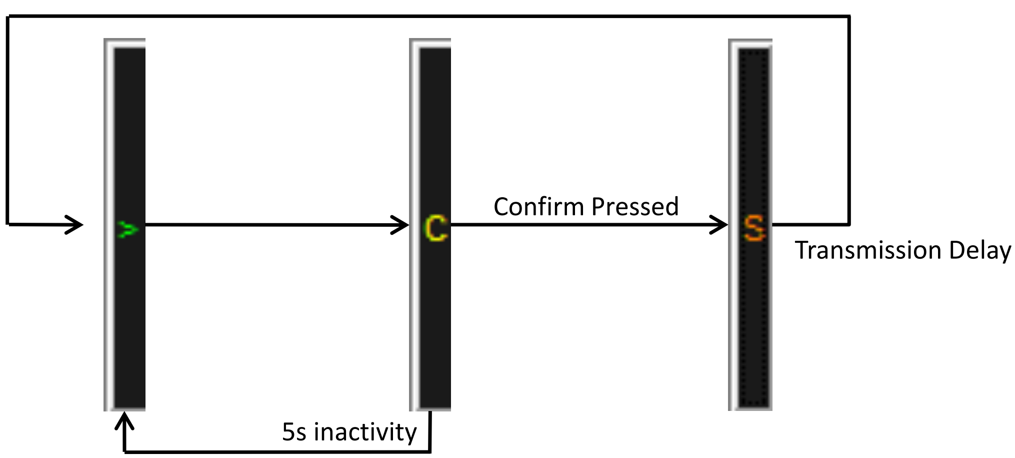

Figure 6.11: Re-Task Salvo Button Press Flow Diagram

6.2.3 Re-task Acceptability Region (RAR)

The RAR as seen in Chapters 3 & 5 was used in the TAT as a method of displaying the time available to re-task a weapon to a particular target. However, due to there being as many as 32 LRAGM in flight simultaneously, using a dynamic graphical overlay of the RAR on the map overview would be computationally demanding as well as overwhelming for operators. Instead a system must be used that provides the operator the same level of information but in an easily interpretable format. As shown in the previous chapter, a numerical representation provides a useful way of representing the data that improves the accuracy of decision makers in time critical situations, whilst maintaining a comparable reaction time.

In the previous study the numerical data was presented as two numbers – the range to the target from the zero controls free-fall trajectory of the GBU, and the maximum possible range that the trajectory could be shifted in the direction of the new target. As shown this works sufficiently well for free-fall type weapons. However, the LRAGM is a powered missile, capable of cruising at a constant altitude whilst there is sufficient fuel to do so. This creates extra complexity in the method used to calculate the weapon's ability to be re-tasked to different locations. Chapter 3 contains more detail about how the RAR is calculated for the LRAGM. The output of the calculations is the route and time it would take to reach the target, as well as the time spent in straight and level cruising flight.

This flight phase is important for predicting the time at which it will no longer be possible to reach a target. Figures 6.12, 6.13 and 6.14 show a number of approaches to a single target. The different flight phases are shown in different colours. For any flight, the optimum – minimum distance route to a target will be a combination of one or two turns, a section of gliding flight, a section of cruising flight, and the terminal phase. A normal weapon release from high altitude will typically have a glide, with or without a turn, followed by cruise. Then there will be a final turn towards the target (given the desired attack heading) followed by the terminal phase of flight to intercept it.

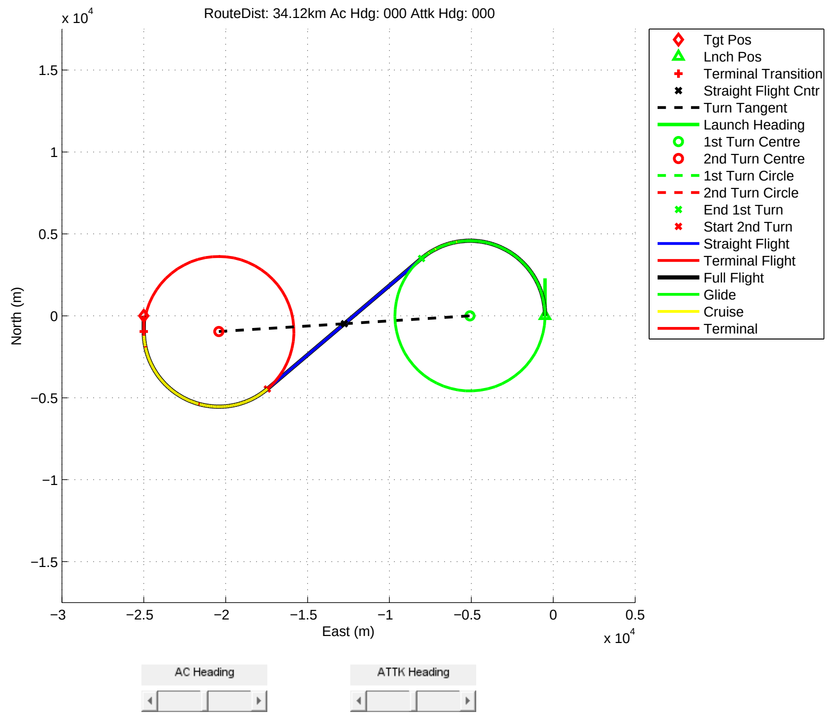

Figure 6.12: Approach Paths of Air-to-Surface LRAGM Given Launch and Approach Headings (North,North)

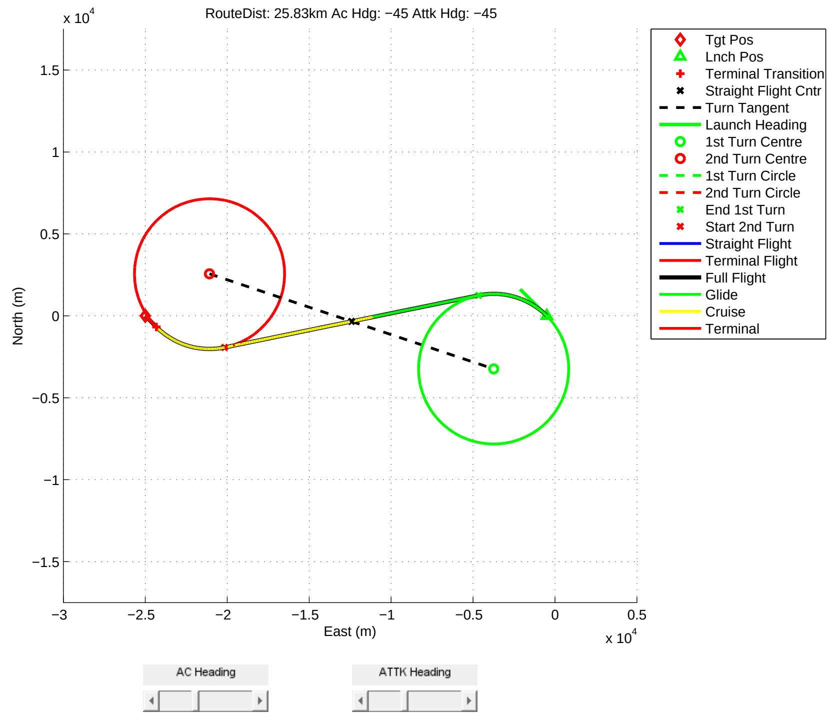

Figure 6.13: Approach Paths of Air-to-Surface LRAGM Given Launch and Approach Headings (North-West,North-West)

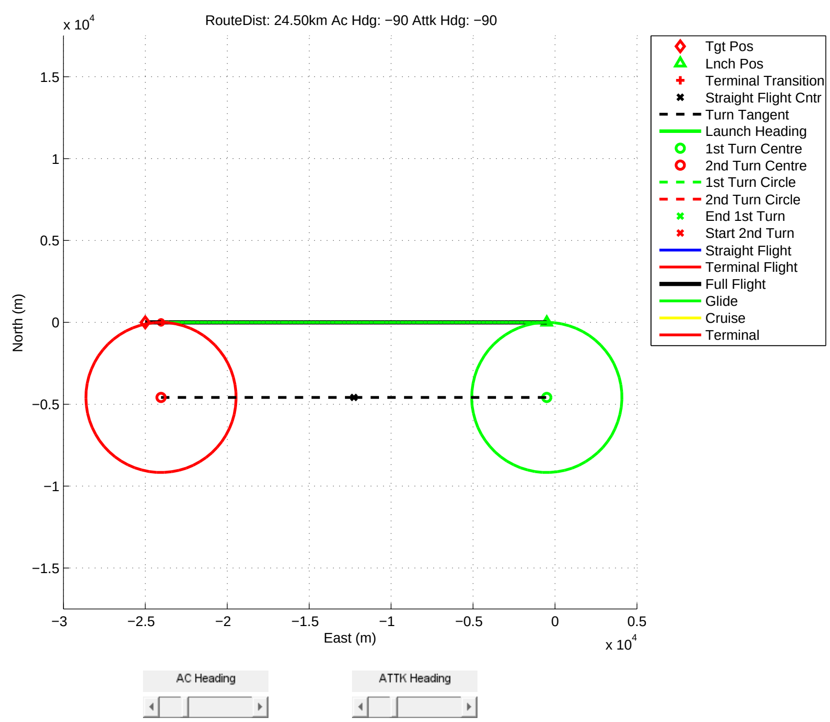

Figure 6.14: Approach Paths of Air-to-Surface LRAGM Given Launch and Approach Headings (West,West)

The routes to each different target are calculated every time step for each different weapon, based upon the flight properties calculated from the Monte-Carlo simulations run in the LRAGM design phase to find the RAR of the weapon. A number of these flight properties are constant values, such as turn rate and cruise speed, which allows a simple routing solution to be generated, rather than running a complex, time-consuming Monte-Carlo analysis of the route for each potential weapon-target assignment. Given the turn rates and velocities, constant radius curved trajectories can be calculated for the flight path of the LRAGM during turning flight. This leads to a simplification of the route, and way-points, that are to be generated for the LRAGM. From each initial condition of the weapon, there are four possible trajectories to the target. A combination of two turns, either left - left, left - right, right - left, or right - right, will bring the LRAGM to the target on the desired attack heading. Of these routes some may be impossible – i.e. the distance between the target and the missile may not provide sufficient distance to carry out the required turns – others will be too long, with cruise distances required that are beyond the range capability of the weapon.

From the four potential routes, the shortest achievable route to each target is found. This route can then be used to calculate the time until this route is no longer possible. The amount of TTG remaining in only the cruise phase of flight can be used to estimate the distance remaining until the LRAGM is too close to the target and needs to 'Go Around'. A 'Go Around' occurs when the LRAGM can no longer make the necessary final approach turn to enter terminal guidance and hit the target. The estimation of the distance remaining can be used, along with the weapon's velocity, to indicate to a Remote Operator how much time remains until they can no longer re-task a weapon to a target.

Preliminary prototyping of the interface found that the display would not be clear enough if the value presented in the re-task status boxes was a time value similar to the TTG displayed in the currently assigned status box for each weapon. Moreover, the operator needs to be able to quickly assess the available weapon-target pairings. For this reason, the time values were represented by a number of blocks each representing 5 second increments of time remaining until the re-task will no longer be available.

Colour coding was also used to infer the successful outcome of the re-tasking request. Green indicated that the re-tasking request will be successfully received by the weapon in time. Orange indicated that the re-tasking request would have a chance to be successfully received by the weapon before reaching the last point at which it could turn to the new target. Red indicates that the re-task request is unavailable and will not be received by the weapon, and hence will not be sent. The text 'UNAVAILABLE' is also printed instead of the blocks to indicate this to the Remote Operator. Figure 6.9 shows the different forms of the RAR information as time progresses in a scenario.

6.2.4 Map Overview

In addition to the TAT, a map display was included in the interface (shown in Figure 6.1). This map display is used primarily for displaying positional information to the operators. The icons used, and the sizing of text and graphical objects, were based upon the standardised mapping and symbology set out the APP-6A and MIL-STD-2525D documents used by NATO members for map generation [20, 143]. Further the formatting, size, colour and additional textual information represented around these icons is specified in these documents and adhered to in the GUI. The maximum and minimum ranges of the SA-15 TLAR are also shown on the Map Overview to show the user where they should expect the LRAGM to be vulnerable to the enemy's SAMs.

Additional textual information is applied to some of the icons displayed on the screen. The ASM icons used for the LRAGM have the Salvo and Missile ID number appended to the icon. The TLAR icons on the map represent a group of SA-15 TLARs due to the scale of the map, and to prevent unnecessary overlapping of multiple icons. For this reason the number of sites is appended above the TLAR icon. Further, an estimation of the number of missiles remaining is included. The maximum load-out is known (8 missiles per launcher) and as weapons are launched from the SAM sites an estimation of the remaining missiles can be presented to the operator.

6.3 Scenario

A generic SEAD scenario was developed around the strategic deployment of a layered air defence network. This is when several SAM sites are positioned in concentric circles around a protected asset of high value – for example a large military base or weapons store. For the purpose of this trial there are two layers of defence (see Figure 6.1). For friendly aircraft to be able to prosecute the protected asset they would have to fly through the first SAM site's coverage, then through the second, putting the aircraft and crew at significant risk.

In this fictitious scenario a SEAD mission was drafted to clear a corridor for friendly aircraft to fly safely through hostile territory. A large number of LRAGMs will be launched from outside of the range of the defending SAM sites to prosecute the targets. Due to the ability of the SAM sites to defend against incoming missile attack, weapons will need to be re-tasked so that they are evenly distributed across the targets at a SAM site.

The scenario is configured as follows:

- An aircraft begins launching salvoes of weapons at the primary SAM site, with equal distribution across the targets.
- Once launched, authority of the weapon is handed over and it appears active on the Remote Operator Terminal.
- Remote Operator is responsible for managing the distribution of the weapons across the targets at the first SAM site.
- The Remote Operator must manage the weapon distribution, and re-task weapons when appropriate, such that each target is hit twice.
- Any remaining weapons are re-tasked to the secondary SAM site, and distributed evenly across the targets.
- Any surplus weapons, that cannot be safely re-tasked, are aborted such that they self destruct in flight and do not hit their target.

6.3.1 Summary of Trial

A total of 30 participants were recruited for the trial from Science and Engineering courses of study at the University of Liverpool. This was to ensure that participants had a moderate understanding, and were familiar with, computer systems. Test subjects were asked to participate in a simulated Remote Operator trial. They were informed that they are responsible for NEC missiles that have been launched from a delivery aircraft towards an enemy SAM site. The enemy's anti-air defence network consists of two SAM batteries/sites in a layered deployment. For an acceptable assumption that the target has been destroyed before making any BDA, each individual target must be hit twice. It is also undesirable to waste LRAGM by 'overkill' (hitting a target more times than necessary). The following objectives were given to the participant:

- Primary Objective: Destroy ALL targets at the first SAM site.
- Secondary Objective: Use any remaining weapons to destroy as many targets at the second SAM site as possible.
- Rules to Observe: Each target must be hit TWICE to be considered destroyed.
- Rules to Observe: Abort any surplus weapons that cannot be safely re-tasked to prevent 'overkill'.

The participants were presented three training scenarios, followed by the main set of 8 randomly ordered scenarios. Performance measures were taken, including the NASA Task Load Index (TLX) assessment tool [159] and a detailed feedback questionnaire. This information was then analysed post trial to find the limits of operator performance, and look for recommendations into improving the display system.

6.4 Study Aims and Methodology

The principal study aim was to establish the limit of operator capacity in managing multiple remote weapons in a SEAD scenario. Of particular interest was the operators' ability to complete the task, given a set of objectives, the outcome being that each target at both SAM sites were hit twice, and thus all targets were neutralised. Analysis of the data generated by the participants was aimed at finding the limit of operator performance and sources of error when performing the task, and to make comparisons between human operators and an automated system for re-tasking.

6.4.1 Independent Variables

Two independent variables were manipulated to generate 8 different scenario conditions for testing. The Independent Variables were Number of LRAGM in each Salvo, and the Time Delay Between Salvoes being launched. The Number of LRAGM in each Salvo was varied between 2 and 4, and the Time Delay Between Salvoes was varied between 5, 10, 15 and 20 seconds. These independent variables were consistent for the duration of each individual scenario, i.e. within one scenario there will not be a mix of the size of salvoes or the time delay between salvo launches. Each participant was trained in how to use the remote operator terminal through a presentation and then provided 3 training scenarios for practice to improve competency using the system. Following the training, participants were asked to complete 8 different scenarios. Each participant saw each scenario once, in a random order. This was to reduce the learning and session effects across the sample size. Table 6.4 shows the different scenario configurations and their associated difficulty level.

Table 6.4: Scenario Difficulty Level Configurations

Difficulty Level	Number of Weapons Per Salvo	Time Interval Between Salvoes
1	2	20
2	4	20
3	2	15
4	4	15
5	2	10
6	4	10
7	2	5
8	4	5

6.4.2 Performance Measures

Several measures were recorded that relate to performance of participants during the trial. The main performance indicator was the number of, and which, targets are destroyed by the participant. In order the get these data, the operator system was designed to log each event that occurred during the scenarios, such as a missile hitting its target, or being intercepted. It also logged each user interaction with the interface. Performance measures include both positive indicators, such as the number of successfully hit targets, and error indicators, such as the number of overkills against a target, or number of re-tasks that occur late into the scenario.

6.4.3 NASA TLX

The NASA TLX procedure was followed to record participants' perceived workload throughout the trial [159]. After each scenario was completed (including the training scenarios) the participant noted their workload rating across six different measures; Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration. These were photographed and recorded on a spreadsheet (an online version is available but was not used so as not to interrupt the interface during the session). Once all 3 training and 8 trial scenarios were completed, the participant was asked to complete a NASA TLX 'Sources of Workload' task where they were presented fifteen different cards each with two of the six workload rating measures listed previously. No combination of measures appeared twice. Participants were asked to circle the more important contributor to workload for the whole trial from the two measures shown on each card. Then the number of each measure circled across all 15 cards was used to weight the score on each NASA TLX Workload Rating Scale completed to find a single score for each trial completed per participant. Although the order of the trial seen was randomised, the resulting order was recorded so as to match the workload ratings taken during the trial to each distinct scenario configuration.

6.4.4 Additional Measures

A detailed feedback questionnaire was created to record non identifiable participant data such as age-group, gender, course of study and military experience. Further, a set of questions was generated to obtain detailed feedback about the interface. The questions were as follows:

- Please describe, step by step, the thought process you progressed through when deciding how to allocate the ASMs in flight, and how you chose whether to re-task or abort a weapon.
- Did you use any type of strategy in completing the scenarios? Did your methods differ between the scenarios?
- At any point during the scenarios did you miss the opportunity to re-task the missile?
  a) What thoughts did you have that you believe caused you to do this?
  b) What feelings did you have that you believe caused you to do this?
- At any point during the scenarios did you make any mistakes?
- Were any elements of the display confusing? Please explain.
- How would you suggest improving the Task Allocation Table?
- How would you suggest improving any other elements of the display?

Within this questionnaire, a shortened 'Need for Closure' questionnaire was included [166].

6.4.5 Invoking a Re-task and Scenario Repeatability

The Scenario Outcome Estimation calculations made earlier focus on the kill probability of the SAMs against an incoming missile threat, and assume that 1 in four missiles hits the target. If the actual Hit/Miss event is calculated by using a random number generator then the outcome of each individual intercept will not be known. This is problematic for running an operator trial, as scenarios of the same difficulty level must be repeatable. Further, the number of forced re-tasks affects the difficulty level itself and must be maintained.

Based on the p_{kill} of 0.25, the SAM sites are guaranteed to hit eight of the incoming missile threats. It would be expected that the missiles lost to the enemy SAMs would be the first eight as it is expected the enemy doctrine is to shoot the closest threats first. This means that the second set of 8 missiles are guaranteed to hit, and that no re-tasks are actually needed. For this reason, a reference array was built containing true/false values that are used by the SAMs when they reach the intercept event to decide whether they've hit their target or not. These reference arrays are configured so that there is one partial hit in the first 8 missiles. This creates a situation where one target is under-assigned in the early salvo, or over-assigned in following salvoes. This situation invokes a re-task or abort procedure by the operator, as the target either needs another assignment in the early part of the scenario, or a re-task away from the target in the following salvo aimed at the target. The decision that is made by the participant will then potentially change the way in which the later events occur, however, the repeatability of the trial as a whole is maintained.

6.4.6 Equipment

The Remote Operator Terminal was displayed on a 1920x1080 pixel computer screen, and the participant provided a mouse to interact with the display. The NASA TLX form was laminated so that a dry-wipe marker could be used by participants when completing the forms for each scenario. This was done, as recommended in the NASA TLX instructions, to reduce paper usage. A photo was taken of each completed form, and the answers were transcribed to a master spreadsheet. The feedback questionnaires were provided on paper.

6.5 Automated Control System Solution

Although the need for a WO in the context of remote weapon re-tasking is extremely important, there may be benefits to using an automated process to manage the way in which the weapons are distributed across their target sets. Logic statements can be written that include the rules set out for operators, and then an Automated Control System (ACS) can monitor the situation in real time and make re-tasking decisions based upon the inputs received, much like a human operator. The ACS is a closed loop system that has been written in MATLAB. The function requires the following information to generate sets of re-tasking commands that are sent to in-flight missiles:

- Target States
- LRAGM States
- Launch Configuration

Figure 6.15 shows the flow diagram of the ACS. The inputs are passed to functions that generate vectors including the remaining TTG for each LRAGM, the number of assignments that each target has, as well as the required number of hits each target needs to be considered destroyed. Then the ACS calculates the LRAGMs that are available to be re-tasked, i.e. those weapons that can be re-tasked without removing an assignment that is needed. A cost matrix is then generated using the remaining TTG of each available LRAGM and their ability to be re-tasked to each target within the target set currently being targeted (primary/secondary). The available LRAGMs are then distributed if necessary to the targets that need them. This process repeats each time-step of the simulation as the scenarios evolve to ensure that re-tasking occurs when necessary.

The performance measurements taken from the ACS will be the same as that generated for the participant study so that direct comparisons can be made between the two control methods. These comparisons will be made in the results and discussion sections later in this chapter.

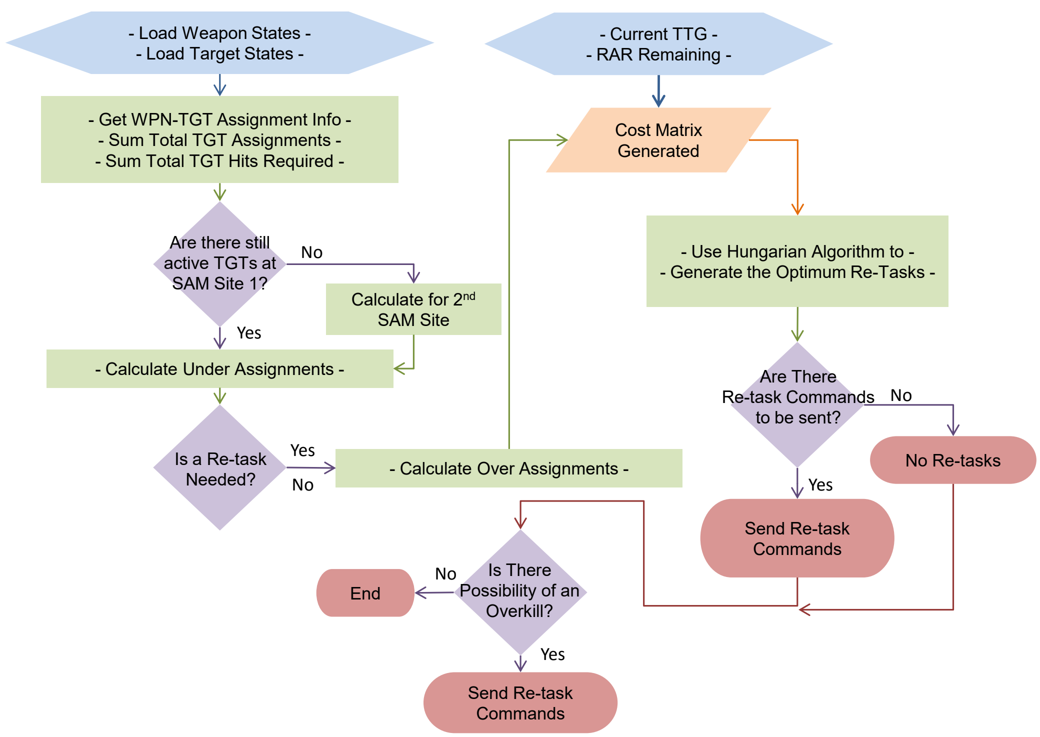

Figure 6.15: Automatic Control System Decision Making Flow Diagram

6.6 Results

Several different sources of data were produced from this study. The primary source of data is the event and actions log recorded from the operator terminal which monitored all of the button presses made by participants, including any cancellations of a request. This data can be used to generate several metrics of performance:

- Overall Performance (Number of Successfully Destroyed/Missed/Overkilled SAM Sites)
- Primary Objective Performance (Number of Successfully Destroyed/Missed/Overkilled Primary Targets)
- Secondary Objective Performance (Number of Successfully Destroyed/Missed/Overkilled Secondary Targets)
- Number of Re-Task Commands (20/20-10/<10 seconds remaining)
- Number of Abort Commands

The secondary source of data is the participants' self reported workload scores. These were generated using the NATA TLX method [159]. This data is useful to support the outcomes achieved by participants from the primary data. Worse outcomes should correlate with higher workload.

Lastly, the questionnaire responses provide several pieces of useful data:

- Participant Information (Age Range, Gender, Course and Previous Military Experience)
- Overall Rating of Aspects of Trial (Difficulty, Stress etc.)
- Reduced Need for Closure Scale (Personality Traits)
- Qualitative Written Feedback

Qualitative analysis was carried out on the written feedback to find common positive and negative themes about the trial and the operator interface used.

Each of these data will be discussed herein:

6.6.1 Operator Terminal Logged Data

The first set of data produced from the data logging is the overall performance of participants. Successfully hitting all 8 targets twice is considered a perfect score. This task was achievable if the operator made their decisions quickly and effectively. The results for scenario vs. overall performance are presented in Table 6.5 and shown in Figure 6.16. Note: in the following abbreviations are used in tables – Standard Error (SErr), Variance (Var), Significance/p-value (sig).

Table 6.5: Participant Average Overall Score, Number of Missed Targets and Number of Overkills

Difficulty	Overall				Miss				Overkill			
	Mean	SD	SErr	Var	Mean	SD	SErr	Var	Mean	SD	SErr	Var
1	7.500	1.009	0.184	1.017	0.133	0.434	0.194	0.189	0.000	0.000	0.000	0.000
2	6.900	1.185	0.216	1.403	0.500	1.075	0.295	1.155	0.100	0.403	0.074	0.074
3	7.700	0.837	0.153	0.700	0.100	0.403	0.063	0.162	0.000	0.000	0.000	0.000
4	7.033	0.964	0.176	0.930	0.400	0.675	0.267	0.455	0.033	0.183	0.033	0.033
5	7.367	0.890	0.162	0.792	0.200	0.610	0.166	0.372	0.067	0.254	0.046	0.046
6	6.400	1.248	0.228	1.559	0.633	1.129	0.313	1.275	0.200	0.407	0.074	0.074
7	5.800	0.997	0.182	0.993	1.100	0.923	0.385	0.852	0.200	0.551	0.101	0.101
8	4.833	1.177	0.215	1.385	1.700	1.442	0.823	2.079	0.400	0.814	0.149	0.149

It is necessary to look individually at primary and secondary objective completion. The participants were primed to perform the primary objective and do as best they could at the secondary objective. Tables 6.6 and 6.7, and Figure 6.17, show the results of scenario vs. primary and secondary objective performance respectively. Due to the nature of the task given to the operators, it is expected that the primary objective should always be completed and that the level to which the secondary objective is completed will indicate the drop in performance.

Table 6.6: Participant Average Primary Objective Score, Number of Missed Targets and Number of Overkills

Difficulty	Primary Partial				Primary Miss				Primary Overkill			
	Mean	SD	SErr	Var	Mean	SD	SErr	Var	Mean	SD	SErr	Var
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.300	0.988	0.180	0.976
2	0.100	0.403	0.074	0.162	0.033	0.183	0.033	0.033	0.867	1.306	0.238	1.706
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.305	0.056	0.093
4	0.033	0.183	0.033	0.033	0.000	0.000	0.000	0.000	0.733	1.285	0.235	1.651
5	0.067	0.254	0.046	0.064	0.000	0.000	0.000	0.000	0.633	0.615	0.112	0.378
6	0.200	0.407	0.074	0.166	0.067	0.254	0.046	0.064	1.233	1.736	0.317	3.013
7	0.200	0.551	0.101	0.303	0.000	0.000	0.000	0.000	2.567	2.144	0.392	4.599
8	0.400	0.814	0.149	0.662	0.000	0.000	0.000	0.000	5.100	4.649	0.849	21.610

Table 6.7: Participant Average Secondary Objective Score, Number of Missed Targets and Number of Overkills

Difficulty	Secondary Partial				Secondary Miss				Secondary Overkill			
	Mean	SD	SErr	Var	Mean	SD	SErr	Var	Mean	SD	SErr	Var
1	0.367	0.718	0.131	0.516	0.133	0.434	0.079	0.189	0.033	0.183	0.033	0.033
2	0.500	0.630	0.115	0.397	0.467	1.008	0.184	1.016	0.267	0.583	0.106	0.340
3	0.200	0.484	0.088	0.234	0.100	0.403	0.074	0.162	0.033	0.183	0.033	0.033
4	0.533	0.629	0.115	0.395	0.400	0.675	0.123	0.455	0.267	0.785	0.143	0.616
5	0.367	0.556	0.102	0.309	0.200	0.610	0.111	0.372	0.367	0.718	0.131	0.516
6	0.767	0.774	0.141	0.599	0.567	1.073	0.196	1.151	0.167	0.379	0.069	0.144
7	0.900	0.712	0.130	0.507	1.100	0.923	0.168	0.852	0.233	0.430	0.079	0.185
8	1.067	0.944	0.172	0.892	1.700	1.442	0.263	2.079	0.233	0.430	0.079	0.185

Both the number and the frequency of re-task commands are good indicators of workload. Tables 6.8 and 6.9, and Figure 6.18 show the relationship between scenario and the number of re-task commands overall, and based on the TTG remaining on the LRAGM. The re-tasks based on TTG are grouped into decisions made with more than 20 seconds remaining, between 20 and 10 seconds remaining, and less than 10 seconds remaining of flight time before impact. Table 6.10, and Figure 6.19 also shows the average frequency of re-tasks in each scenario and Table 6.11 shows the average NASA TLX score recorded by participants across the difficulty levels. These workload scores are included in Figure 6.16.

The NASA TLX score is based upon weighting applied across the six different scores provided by participants. Table 6.12 shows the average scores for the sources of workload. Mental and Temporal demand are the highest rated contributing sources, with physical having almost no weighting on the overall workload scored.

Table 6.8: Average Total Scenario Re-Tasks (All TTGs)

Difficulty	Re-Task Total			
	Mean	SD	SErr	Var
1	23.867	14.012	2.558	196.326
2	29.567	12.805	2.338	163.978
3	23.400	12.974	2.369	168.317
4	25.767	10.085	1.841	101.702
5	26.267	12.597	2.300	158.685
6	24.300	11.136	2.033	124.010
7	20.633	9.212	1.682	84.861
8	17.433	10.371	1.894	107.564

Table 6.9: Average Scenario Re-Tasks Grouped by TTG

Difficulty	Re-Task TTG>20s				Re-Task 20s >TTG >10s				Re-Task 10s >TTG			
	Mean	SD	SErr	Var	Mean	SD	SErr	Var	Mean	SD	SErr	Var
1	22.833	12.562	2.293	157.799	0.800	1.769	0.323	3.131	0.233	0.774	0.141	0.599
2	26.667	11.926	2.177	142.230	2.400	2.621	0.479	6.869	0.500	0.731	0.133	0.534
3	22.433	11.933	2.179	142.392	0.933	1.701	0.310	2.892	0.033	0.183	0.033	0.033
4	21.833	9.596	1.752	92.075	3.400	3.318	0.606	11.007	0.533	1.196	0.218	1.430
5	24.267	11.543	2.107	133.237	1.567	1.813	0.331	3.289	0.433	0.898	0.164	0.806
6	16.500	11.942	2.180	142.603	6.000	2.704	0.494	7.310	1.800	1.901	0.347	3.614
7	14.233	9.971	1.820	99.426	4.967	3.045	0.556	9.275	1.433	2.285	0.417	5.220
8	12.567	9.926	1.812	98.530	2.667	3.575	0.653	12.782	2.200	2.469	0.451	6.097

Table 6.10: Average Frequency of Actions (Num Actions Per Second)

Difficulty	Frequency of Actions			
	Mean	SD	SErr	Var
1	0.148	0.072	0.013	0.005
2	0.253	0.127	0.023	0.016
3	0.212	0.130	0.024	0.017
4	0.249	0.108	0.020	0.012
5	0.238	0.093	0.017	0.009
6	0.288	0.154	0.028	0.024
7	0.345	0.220	0.040	0.049
8	0.361	0.248	0.045	0.061

Table 6.11: Average NASA TLX Workload

Difficulty	NASA TLX Workload			
	Mean	SD	SErr	Var
1	7.011	3.570	0.652	12.743
2	10.146	3.727	0.680	13.888
3	7.980	3.559	0.650	12.663
4	9.811	4.330	0.791	18.749
5	9.383	3.812	0.696	14.528
6	11.179	3.379	0.617	11.419
7	12.609	3.583	0.654	12.840
8	14.202	3.335	0.609	11.125

Table 6.12: NASA TLX Sources of Workload Breakdown

Source	Mean	SD
Mental Demand	4.07	0.74
Physical Demand	0.47	0.82
Temporal Demand	4.07	1.05
Performance	2.37	1.16
Effort	2.10	1.24
Frustration	1.93	1.46

The difficulty level of the scenarios ranks from 1 (easiest) to 8 (hardest) with the scenarios with two missiles per salvo being easier than those with four missiles per salvo with the same separation between salvoes. A simple Linear Regression analysis was carried out using SPSS in order to establish whether a linear trend could be found between the difficulty level and the various metrics collected, the main interest being in the performance of participants, and the performance indicators.

There are data that record the actual outcomes, such as number of primary targets destroyed, that describe the performance of participants and data such as number of re-tasks, or frequency of button clicks, that instead are latent variables that could be useful indicators of the causes of different levels of performance. Table 6.13 shows the Linear Regression output, the relevant significance values and the equation of the linear function that represents the data.

Table 6.13: Linear Regression Analysis Results (* indicates statistical significance, green indicates increasing with difficulty, red indicates decreasing with difficulty)

	Correlations		ANOVA		Coefficients			R^2
Factor	Pearson's	Sig	F	Sig	Const	Grad (B)	Std Err	(Adjusted)
Workload*	0.463	0.000	65.076	0.000	6.443	.855	.106	0.211
Overall*	-0.551	0.000	103.497	0.000	8.177	-.330	.032	0.300
Miss*	0.408	0.000	47.421	0.000	-0.227	.183	.027	0.163
Overkill*	0.497	0.000	78.257	0.000	-0.883	.561	.063	0.244
Pri Partial*	0.250	0.000	15.849	0.000	-0.086	.047	.012	0.058
Pri Miss	0.008	0.450	0.016	0.900	0.011	.000	.003	-0.004
Pri Over*	0.485	0.000	73.175	0.000	-0.99	.540	.063	0.232
Sec Partial*	0.312	0.000	25.733	0.000	0.136	.100	.020	0.094
Sec Miss*	0.413	0.000	48.898	0.000	-0.238	.183	.026	0.167
Sec Over	0.093	0.076	2.064	0.125	0	N/A	N/A	0.004
Abort Conf	0.109	0.046	2.854	0.092	0.36	.068	.040	0.008
Re-Task >20*	-0.339	0.000	30.93	0.000	28.17	-1.779	.320	0.111
Re-Task 20>n>10*	0.341	0.000	31.225	0.000	0.738	.467	.084	0.112
Re-Task <10*	0.387	0.000	41.891	0.000	-0.37	.281	.043	0.146
Re-Task Total*	-0.196	0.001	9.480	0.002	28.538	-.037	.012	0.034
Frequency*	-0.456	0.000	62.48	0.000	0.146	.026	.004	0.012

Thirteen of the sixteen metrics investigated show a statistically significant correlation between difficulty and the output value of the metric. Both direct measures of performance and latent indicator variables of performance correlate with the difficulty level of the scenario seen. From these data the following statements can be made: Workload increases linearly with difficulty, overall performance reduces with increasing difficulty. The number of missed targets increases with increased difficulty, as does the number of overkills logged on targets.

However, the R2 values (which measure goodness of fit to a regression line) are low in all cases and there is potential to improve the relationships found by applying more complex curves to the data. An investigation into curve fitting using the SPSS statistical analysis software found increases in the R2 for the following cases shown in Table 6.14. The increase in R2 values ranges from small increases of around 2%, to larger increases of 13%. The average increase amongst these factors is 6%. Whilst the R2 values achieved through both linear regression and curve fitting are all below 0.5 and average around 0.21 (21%), it still shows that there is a relevant goodness of fit within the model.

Table 6.14: Curved Regression Analysis Results (green indicates increasing with difficulty, red indicates decreasing with difficulty

Factor	Linear R2	Curve R2	Type	sig	constant	X	x2	x3
Workload	0.211	0.235	Cubic	.000	5.918	2.101	-0.471	0.043
Overall	0.300	0.401	Cubic	.000	7.448	-0.171	0.082	-0.013
Miss	0.163	0.237	Cubic	.000	-0.007	0.317	-0.110	0.012
Overkill	0.244	0.364	Cubic	.000	-0.519	1.322	-0.434	0.045
Pri Partial	0.058	0.080	Cubic	.000	-0.007	0.044	-0.015	0.002
Pri Over	0.232	0.363	Cubic	.000	-0.460	1.183	-0.415	0.044
Sec Partial	0.094	0.120	Quad	.000	0.496	-0.116	0.024	/
Sec Miss	0.167	0.247	Cubic	.000	-0.040	0.347	-0.119	0.013
Re-Task >20	0.111	0.135	Cubic	.000	19.871	4.551	-1.185	0.062
Re-Task 20>n>10	0.112	0.173	Cubic	.000	3.205	-2.649	0.930	-0.075
Re-Task <10	0.146	0.171	Cubic	.000	0.771	-0.567	0.153	-0.007
Re-Task Total	0.034	0.059	Cubic	.000	23.848	1.335	-0.102	-0.021
Frequency	0.124	0.185	Inverse.	.000	0.146	0.098	/	/

Figure 6.16 show the best fit curved regression lines and the corresponding mean values. It can be clearly seen that the workload increases continually as task difficulty increases, with an exponential increase occurring towards the higher levels of difficulty. In tandem with this, the overall score based upon the number of targets successfully destroyed across both SAM sites (batteries) reduces in an exponential shape as difficulty level increases. For the easier levels (1-4) the performance is relatively similar with a visible inverse exponential drop off in performance occurring in the more difficult scenarios. Two variables that show the causes of lower performance can be seen increasing in the opposite trend. These are the number of missed targets, and the number of overkills.

Overall these remain at similar levels for difficulties 1-4 and then increase exponentially from levels 5 to 8.

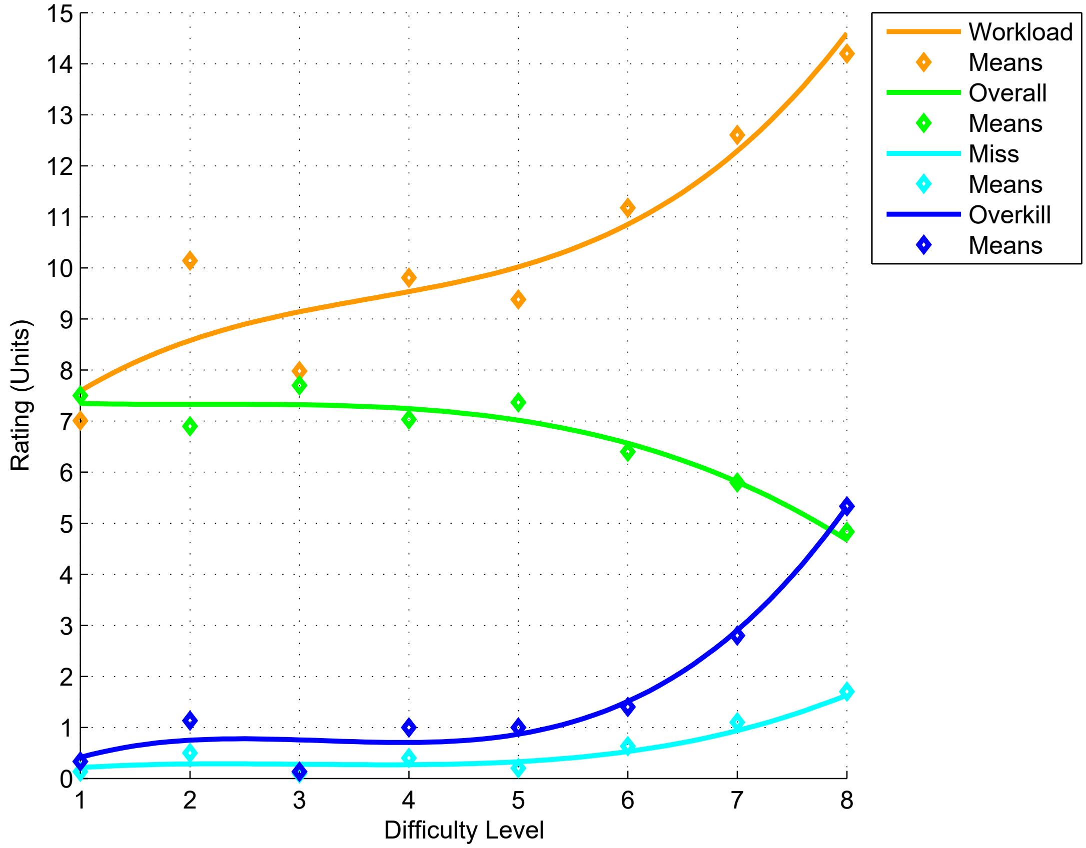

Figure 6.16: Workload and Overall Hit Targets, Missed Targets and Overkills vs. Difficulty (Curved Regression Fit)

However, when breaking down misses, partial hits against targets and the number of overkills between the primary and secondary SAM batteries, there is a clear difference between the two. Figure 6.17 shows the regression lines/curves for the primary and secondary partial hits, complete misses and overkills. It can be seen that the number of complete misses of primary targets is generally zero; this shows that the primary target set is almost always completely destroyed in all difficulty levels. What is more striking though is the significant number of overkills on primary targets when the difficulty level increases. After level 5, the average number of overkills increases from below 1, to more than 5 at difficulty level 8. This means that, on average, 5 missiles are being wasted. There is a slight increase in primary partial hits as difficulty level increases, however, the average at the most difficult level is still below 1. Secondary target overkills remains low with varying difficulty, however, both partial and complete missed targets increase with increasing difficulty. This is a latent effect of overkill on the primary targets. As the number of overkills increases, the available missiles for the second SAM battery is reduced to a point where there are no longer enough missiles to completely destroy it.

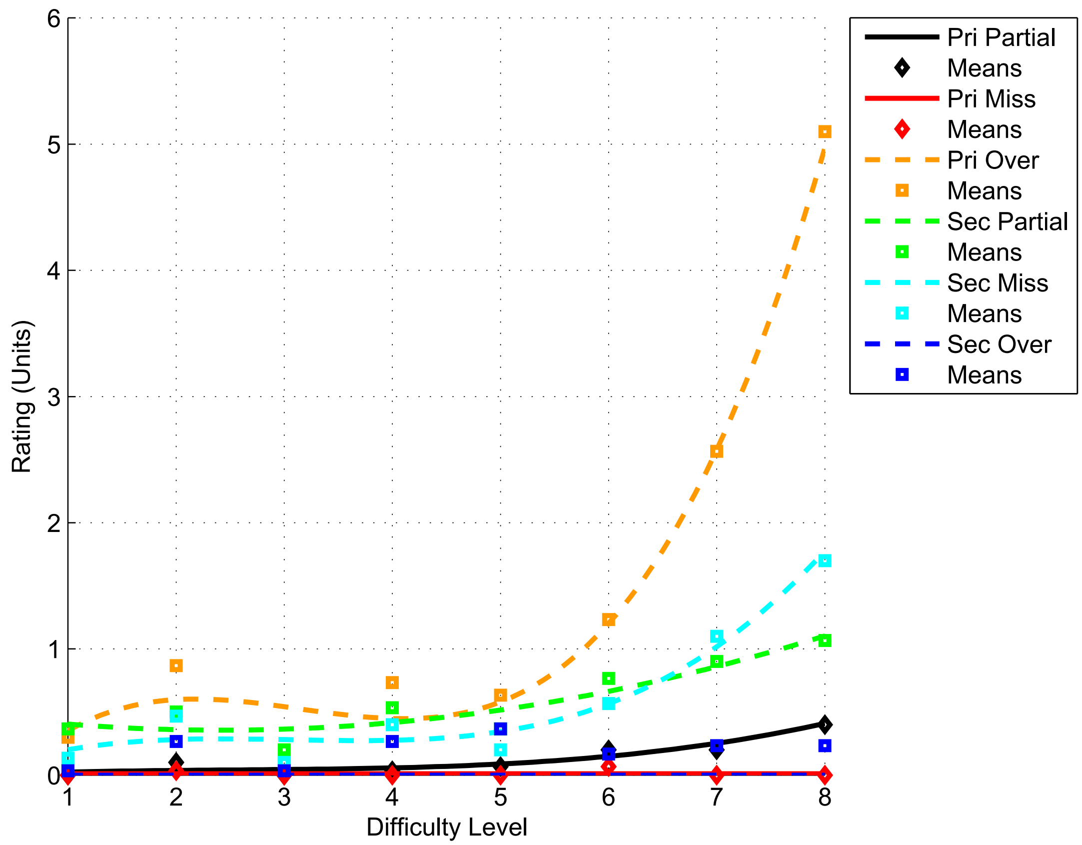

Figure 6.17: Primary and Secondary Partial Hits, Missed Targets and Overkills vs. Difficulty

A useful indicator of performance can be found in the number of re-tasks and the time at which participants make their re-tasking decisions. Figure 6.18 shows that overall, as the difficulty increases, the number of re-tasks decreases. This data can be grouped based upon the missile's TTG at point of re-task, as specified with the colour coding of the interface. There are three groups; TTG greater than 20 seconds, TTG between 20 and 10 seconds, TTG less than 10 seconds. From Figure 6.18 it can be seen that as the mean re-tasks when TTG is greater than 20 seconds falls with increasing difficulty, the number of re-tasks in the 10-20 seconds and below 10 seconds groups increase. These trends imply that as the difficulty level increases, participants become less able to re-task the missiles between targets, and have less time to make their decisions. It further suggests that participants' ability to correctly predict the behaviour of the weapons in flight is reduced as the difficulty increases.

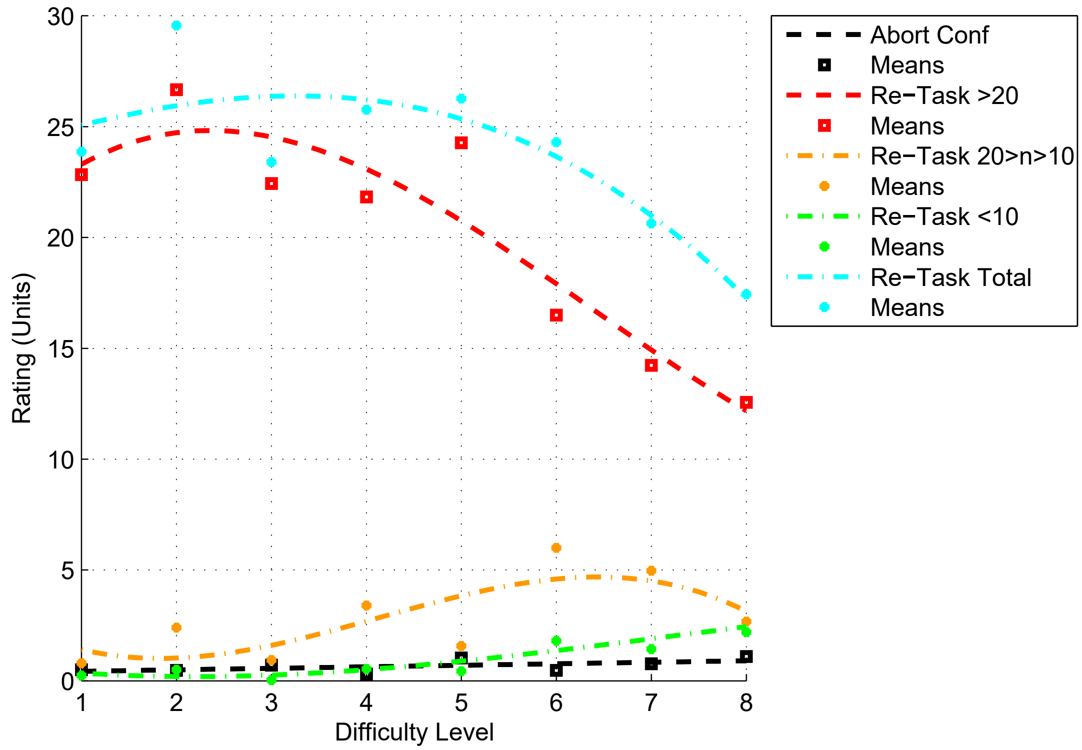

Figure 6.18: Number of Re-Task and Abort Commands vs. Difficulty

Lastly, the frequency of button presses is an interesting performance indicator. It can be seen in Figure 6.19 that as the difficulty increases, the average number of re-tasks per second also increases. This correlates well with the decrease in time available as the scenario difficulty increases. However, the number of re-tasking decisions made overall also decreases as difficulty increases meaning that the reduction in time available for re-tasking has a larger effect on the frequency of re-tasks than the decrease in re-tasks overall. The point of overall performance drop off, and its corresponding frequency of actions may be a good indicator of the upper threshold to the limit of human operator capacity as indicated in a Cummings study that highlighted a possible optimum percentage busy time of 70% [36].

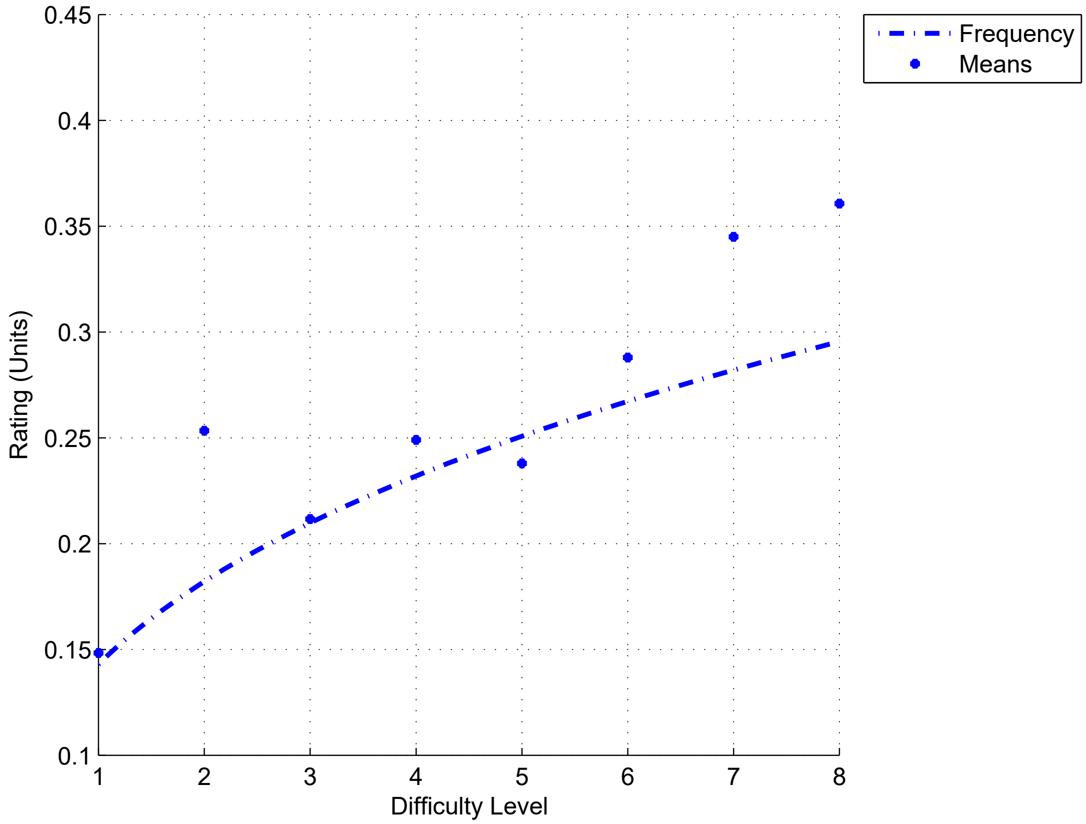

Figure 6.19: Frequency of Actions vs. Difficulty

6.6.2 Heat Maps

Human Factors studies are often exploratory and contain data that can often best be understood when presented graphically. The methods of participants when completing the different scenarios can be analysed by looking at heat maps that depict the concentration of the participants' activity with relation to the TAT. The heat maps are laid out as a grid representation of the TAT, with Rows indicating the different weapons and Columns indicating the targets. Four heat maps were generated for each scenario showing:

- LRAGMs destroyed by the SAM sites
- Valid LRAGM hits on SAM sites (non-overkill)
- Invalid LRAGM hits on SAM sites (overkills)
- Aborted LRAGMs

The colour intensity of the grid boxes corresponds to the frequency of events occurring across the population of participants. These heat maps provide a useful insight, particularly when the method that participants can use to complete the task is unbounded.

Figure 6.20 to Figure 6.27 show the heat maps generated (from difficulty level 1 to 8) of the frequency of the four main events that occur during the scenarios. There is a clear difference between scenarios in the overkill frequency (confirmed statistically by the regression results) as well as the in the other performance metrics. The heat maps show where the increase in the overkill frequency occurs in each scenario. As the scenarios become more difficult, the number of overkills on primary targets increases, particularly in LRAGMs that immediately follow the successfully hit primary targets.

Another interesting artefact from the data is the distribution of LRAGM to target assignments aimed at the Secondary SAM battery. In the easier scenarios there is a more varied distribution of the LRAGM amongst the four secondary targets, however, when the scenarios become more difficult there is far less variation in the distribution of LRAGMs. This corresponds well with the regression trends of decreasing re-tasking as difficulty levels increase. Operators are less likely to manipulate the method of prosecuting the SAM batteries if they are not confident that there is enough time to do so.

Whilst observing participants, an interesting behaviour was witnessed. Instead of re-tasking missiles in order to recover an even distribution when having lost an in-flight missile, this participant deliberately re-tasked all missiles evenly across the secondary set of targets as soon as they were able to do so. Then when the primary SAM site had expended its ammunition the participant would re-task eight missiles back to the primary targets in an even distribution, with plenty of time to do so in each difficulty level. In some cases early salvoes had already passed the primary targets, and in these cases the participant would re-task the first safe to re-task missiles that had not yet passed the primary targets. This method allowed the participant to achieve both the primary and secondary objectives at all difficulty levels.

This method was trialled offline in the development research laboratory with researchers who were involved in running the trials. Although of no scientific merit, the method did provide operators the ability to complete the primary and secondary tasks in all difficulty levels. The method allows for the operator to spend less time dynamically responding to the loss of own assets, and instead observe the system and the SAM intercepts and then re-task the appropriate number of missiles to complete the task with confidence that they will hit their target. Whilst this strategy works for the primary target, the operator must still be reactive in the prosecution of the secondary objectives. Interestingly though, from a weapon conservation perspective. If any missiles successfully pass through the engagement zone of the primary targets, their utility at wasting the enemy's ammunition is increased and could reduce the overall missiles needed to complete this type of SEAD scenario.

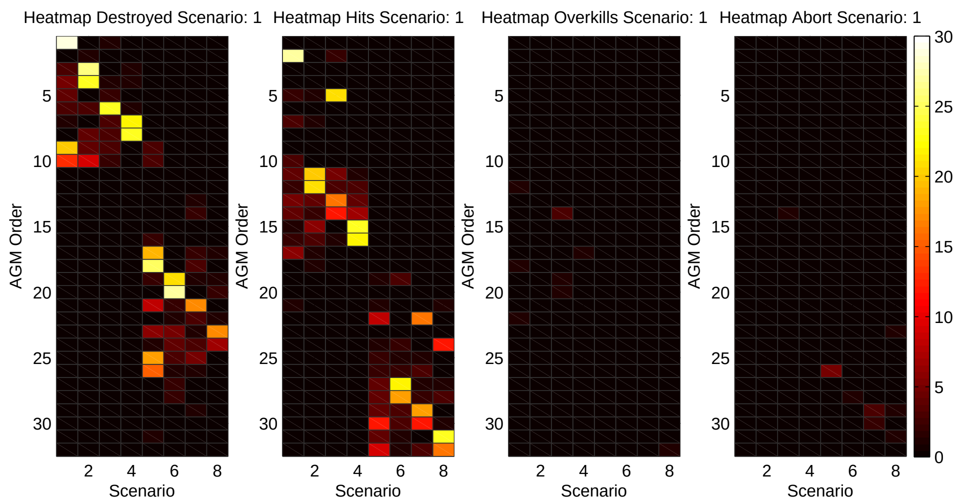

Figure 6.20: Participant Scenario 1 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

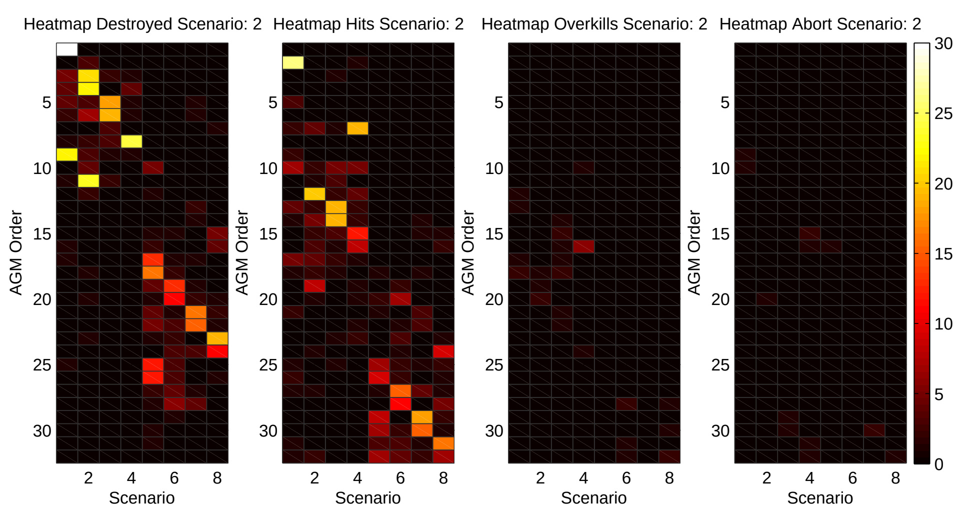

Figure 6.21: Participant Scenario 2 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

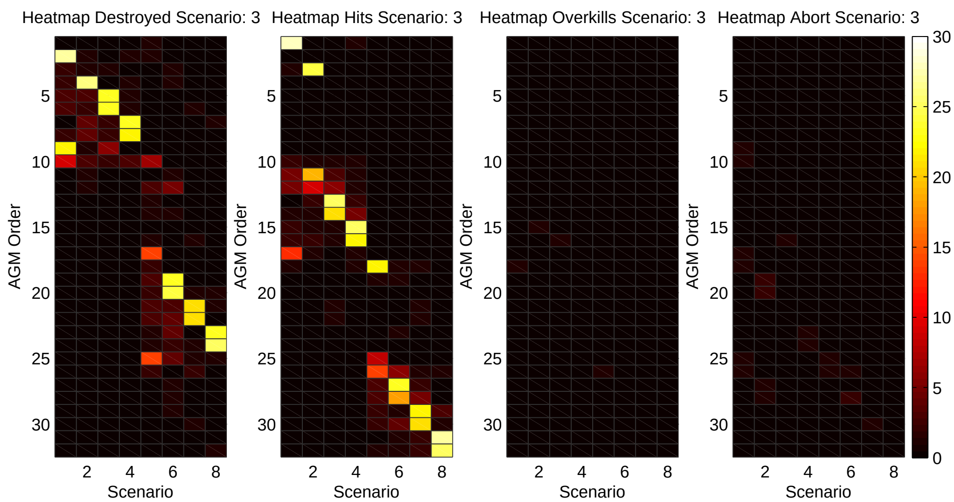

Figure 6.22: Participant Scenario 3 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

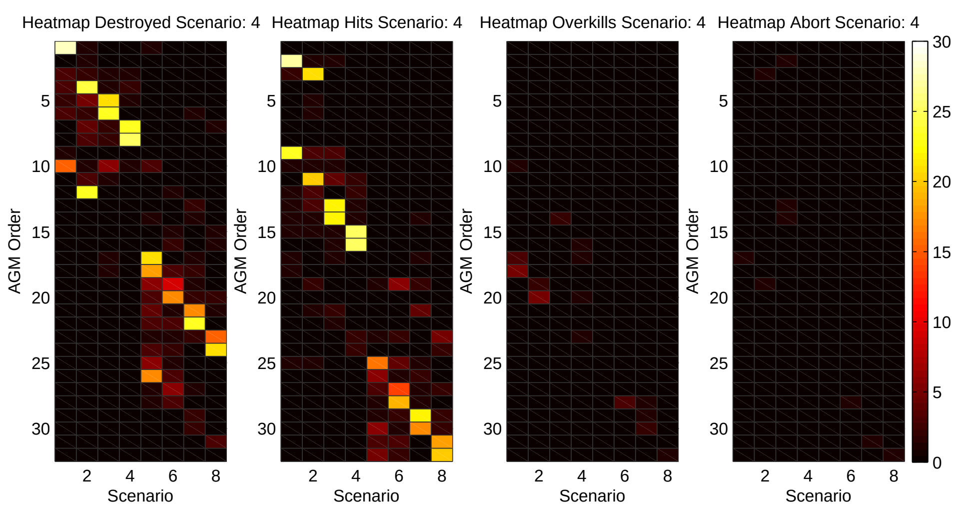

Figure 6.23: Participant Scenario 4 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

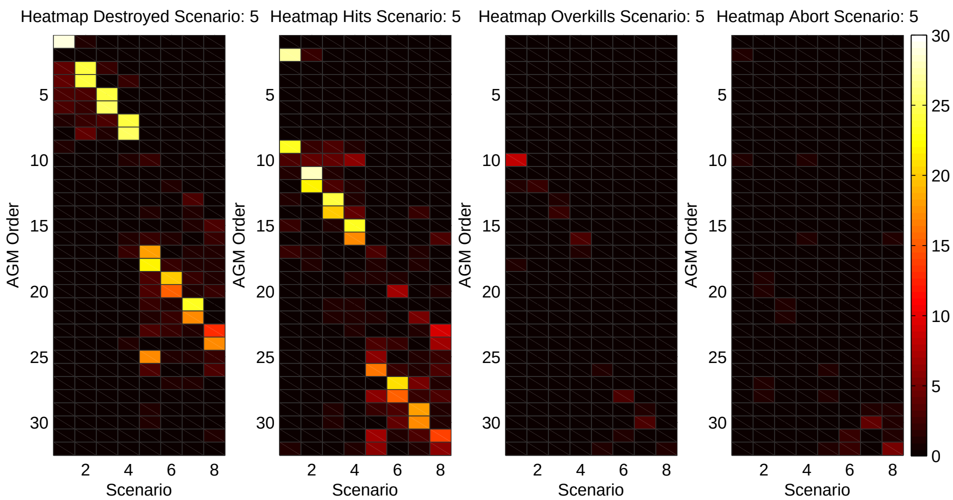

Figure 6.24: Participant Scenario 5 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

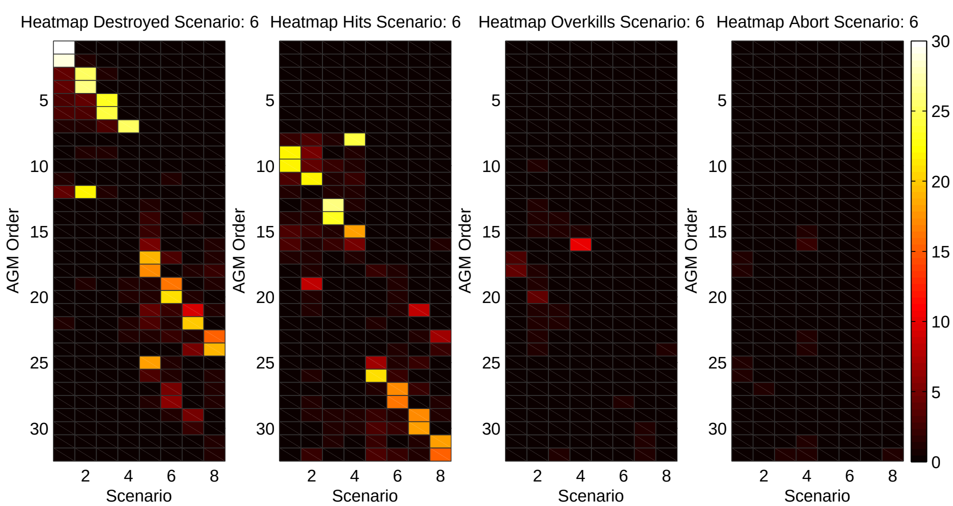

Figure 6.25: Participant Scenario 6 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

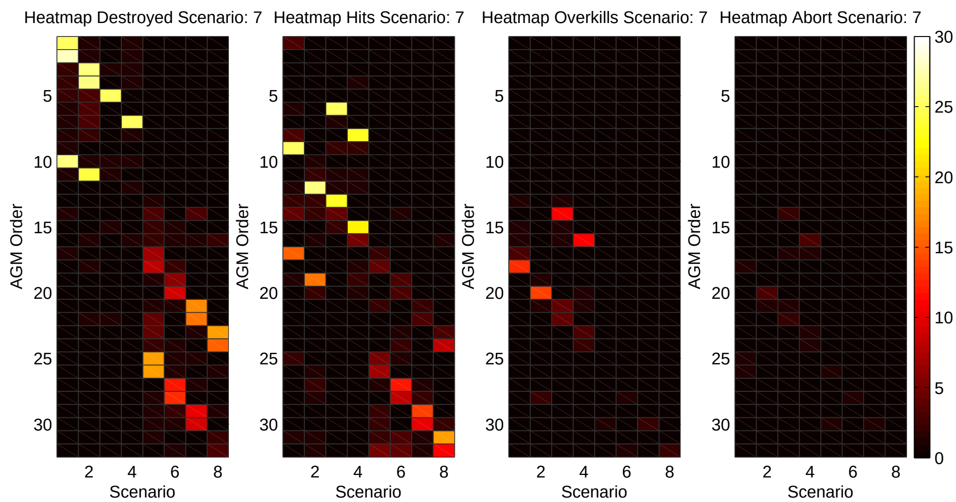

Figure 6.26: Participant Scenario 7 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

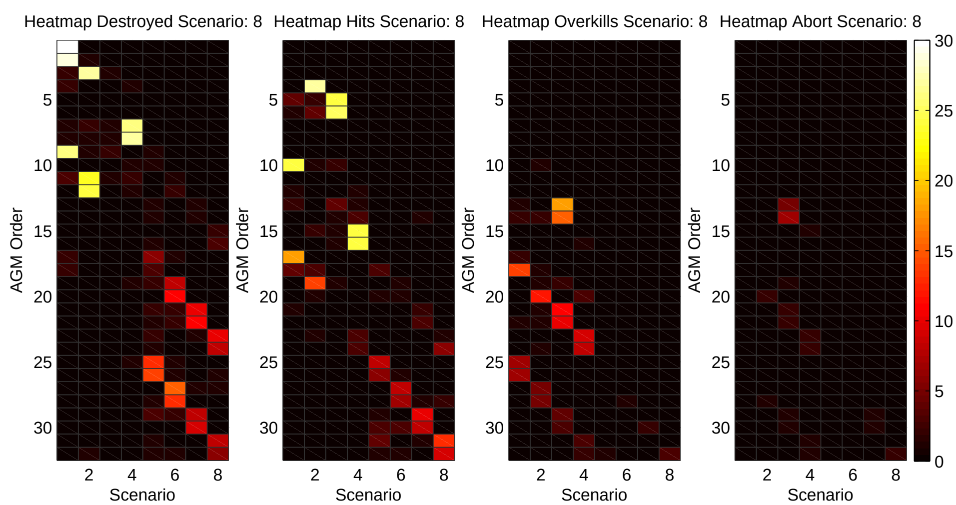

Figure 6.27: Participant Scenario 8 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

6.6.3 Automated System Data

Action and event data was logged from the ACS when completing the 8 different scenarios. The benefit of using an ACS that makes clear, logical decisions is that actions and events that occur in each difficulty level do not differ between independent runs. This means that the results for each difficulty level are repeatable, and that the decisions made by the ACS are traceable. The ACS totals in four categories: Hits, Destroyed, Misses and Overkills can be seen in Figure 6.28. As the difficulty level increases, the ACS's performance metrics remain the same. Total hits on targets are the same across difficulty levels at 16, two hits per target. The number of destroyed targets is also the same across all levels at 8. Both miss, and overkill numbers are zero across all the difficulty levels.

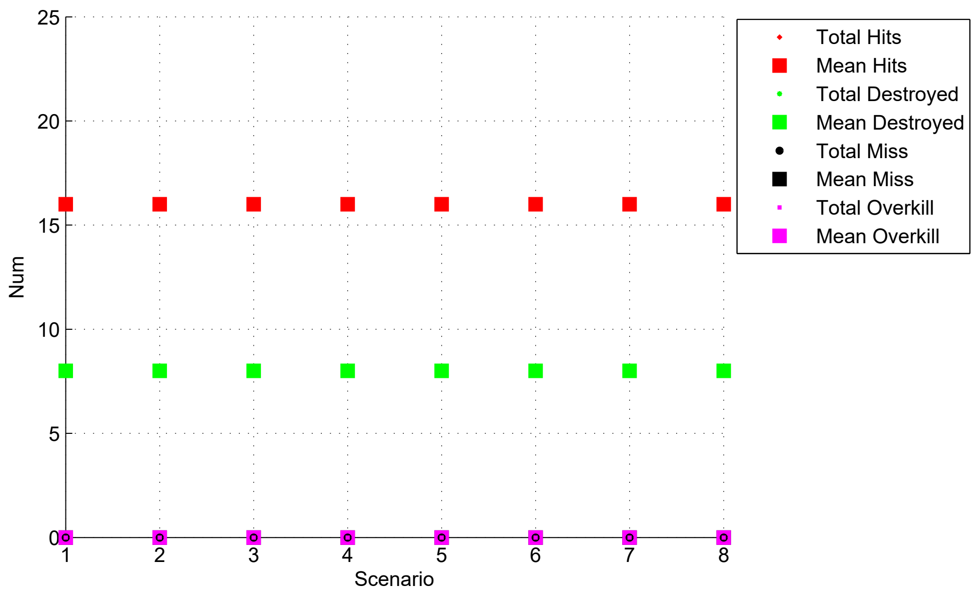

Figure 6.28: ACS Total Hits, Destroyed Targets, Misses and Overkills vs. Difficulty

Figure 6.29 shows the number of actions carried out by the ACS in each scenario. The mean number of re-tasks is relatively similar with one clear outlier. When looking at the heat maps it can be seen that for scenario 3 the ACS managed to re-task a missile on to the secondary target set early. This has the knock on effect of requiring re-tasks of missiles 17, 18, and 23 back to the primary targets, increasing the number of re-tasks. It is worth noting that the ACS completed this scenario with one spare missile at the end that was aborted.

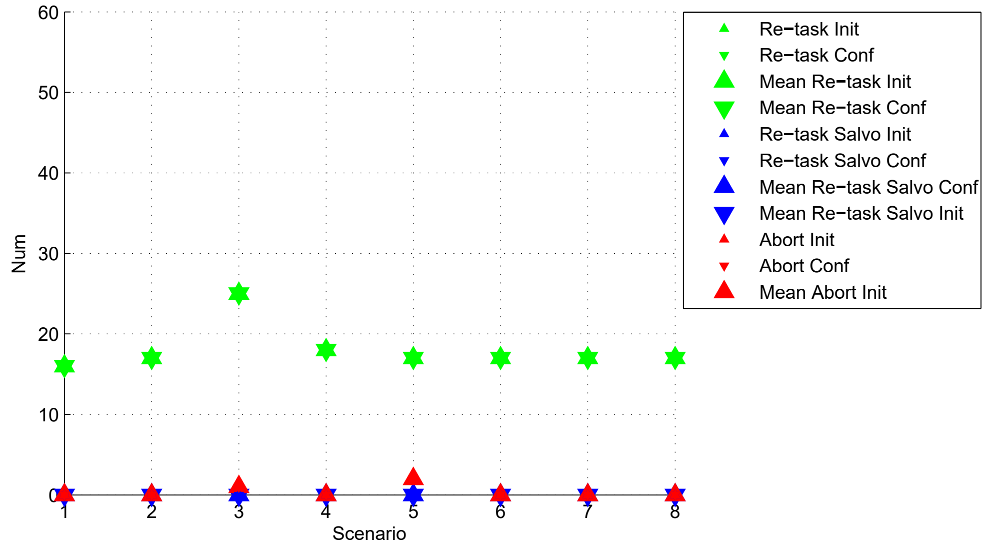

Figure 6.29: ACS Number of Re-Task, Re-Task Salvo, and Abort Actions vs. Difficulty

Figure 6.30 shows that the frequency of decision making by the ACS follows the same trend as participant data, with an increase in difficulty increasing the frequency of decisions made. Direct comparison the participant data frequency graph, Figure 6.19, shows that the ACS makes more re-tasking commands than the operators. This includes an adjustment made for the number of re-task salvo confirmations that effectively re-tasks 2/4 missiles rather than just one. The lower than expected frequency seen in Figure 6.30 (based on the trend seen in the figure) is a result of fewer re-tasks being needed to complete the task due to the missiles that are lost through being intercepted by the enemy's SAMs.

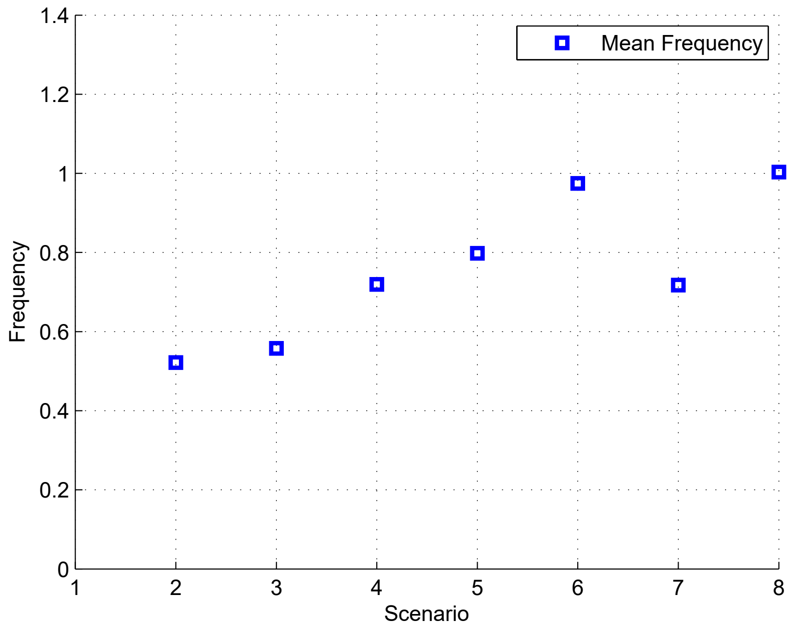

Figure 6.30: ACS Frequency of Actions vs. Difficulty

Heat maps were also generated to show the ACS method for completing each difficulty level. The heat maps are shown in Figure 6.31 (difficulty level 1) to Figure 6.38 (difficulty level 8). The method of completing each difficulty level is the same. The LRAGM are not re-tasked unless they have to be, allowing for the staggered paired targeting of the SAM batteries to continue as intended when the weapons are launched. Following the successful destruction of the primary target, or the acknowledgement that the SAM battery has been depleted of weapons, all remaining LRAGM are re-tasked across to the second SAM battery. What is also clear from these Figures is that there are no overkills made against targets regardless of the difficulty level, and that there are two scenarios in which aborts occur – to prevent overkill on a target at the second SAM site after completing all the objectives.

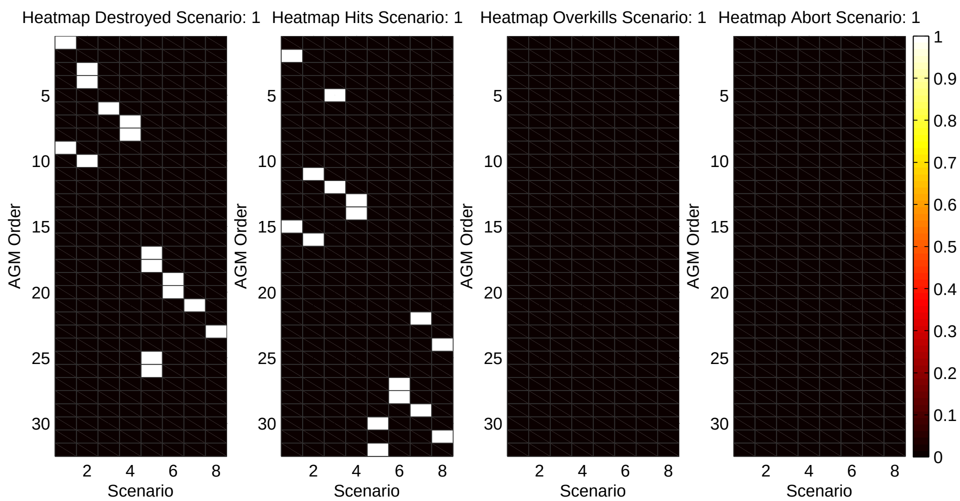

Figure 6.31: ACS Scenario 1 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

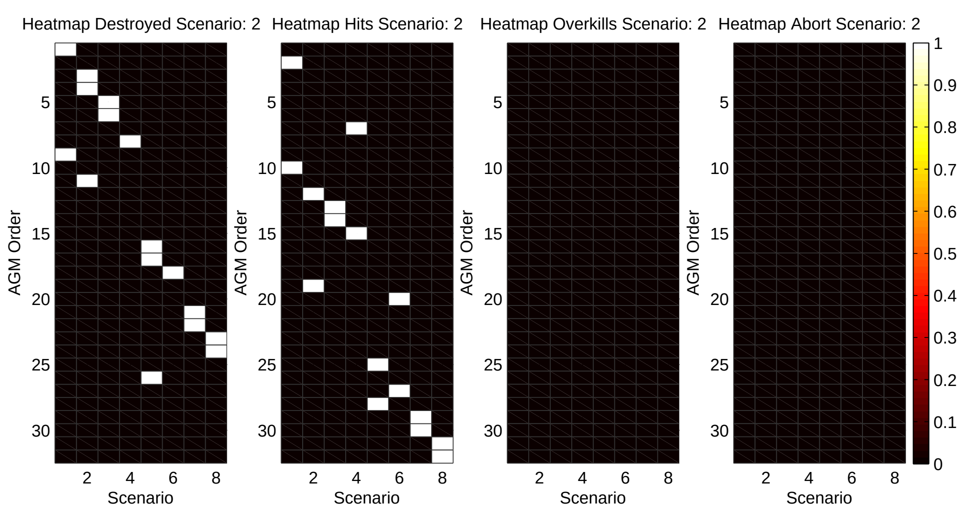

Figure 6.32: ACS Scenario 2 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

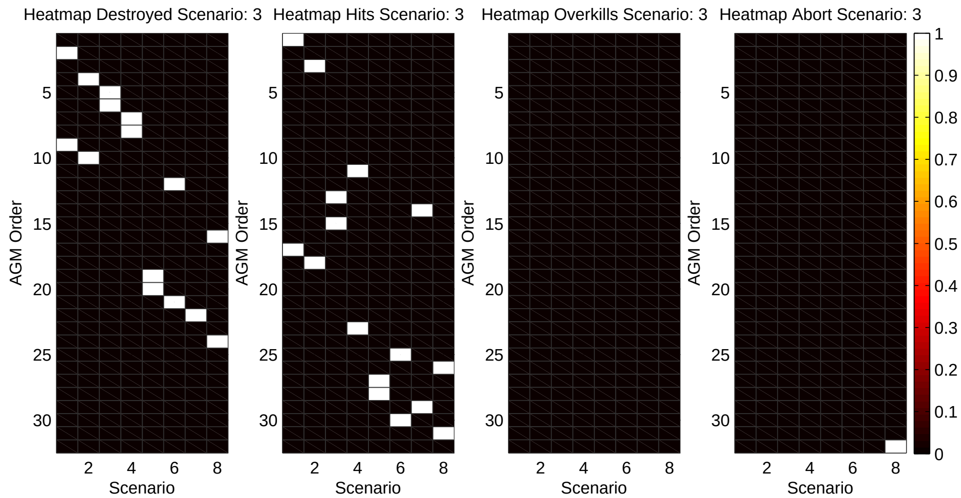

Figure 6.33: ACS Scenario 3 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

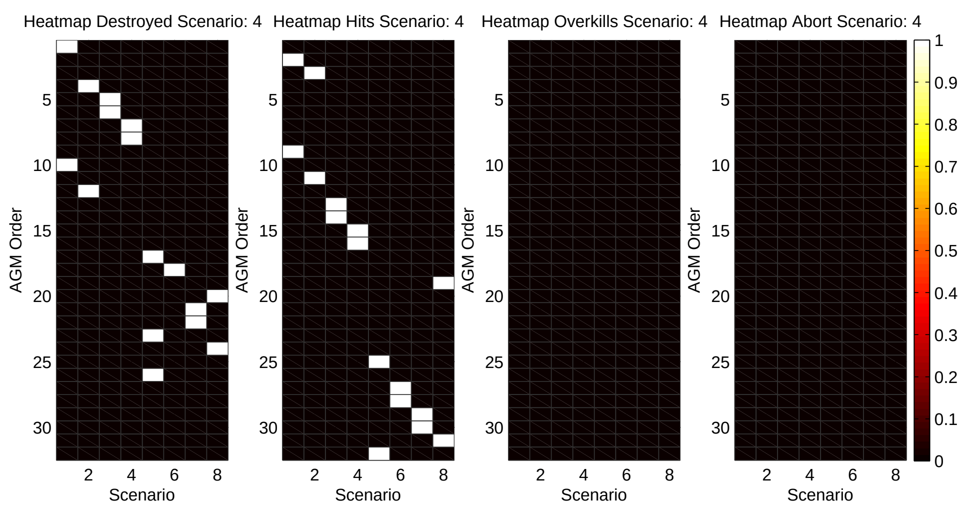

Figure 6.34: ACS Scenario 4 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

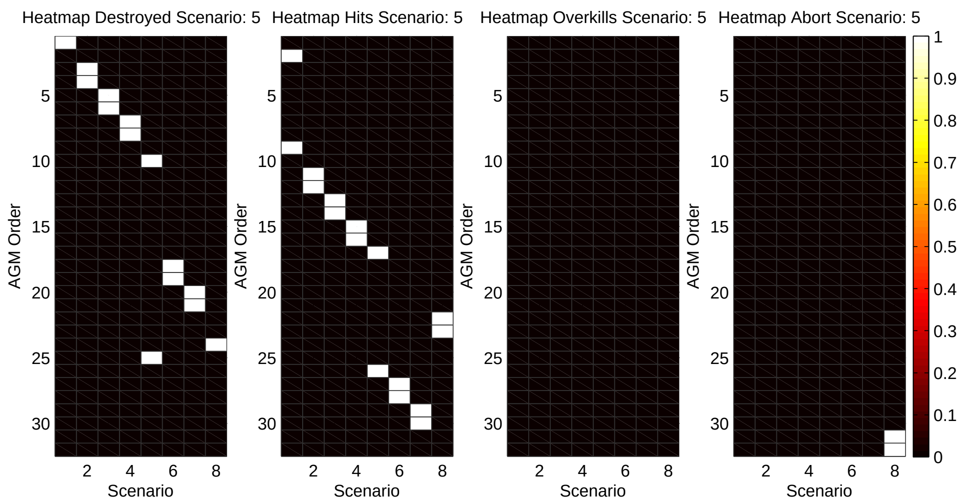

Figure 6.35: ACS Scenario 5 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

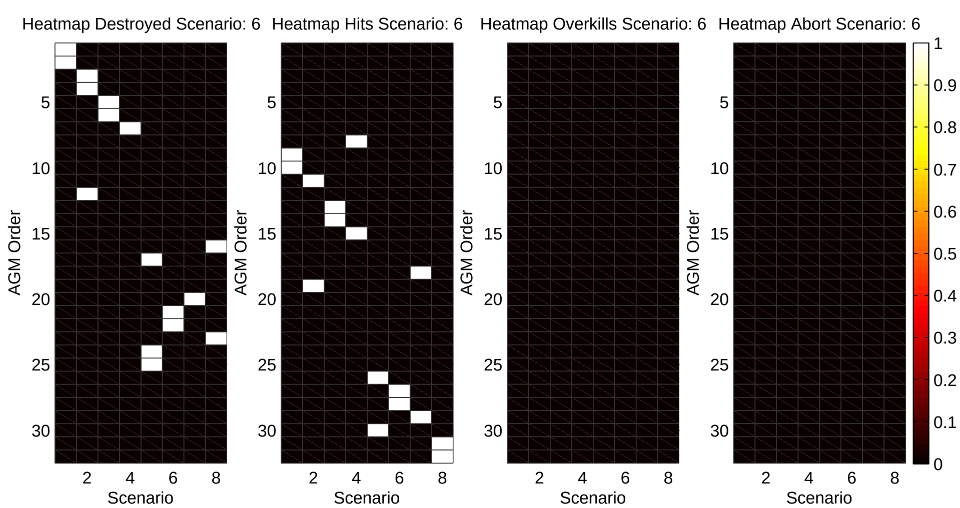

Figure 6.36: ACS Scenario 6 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

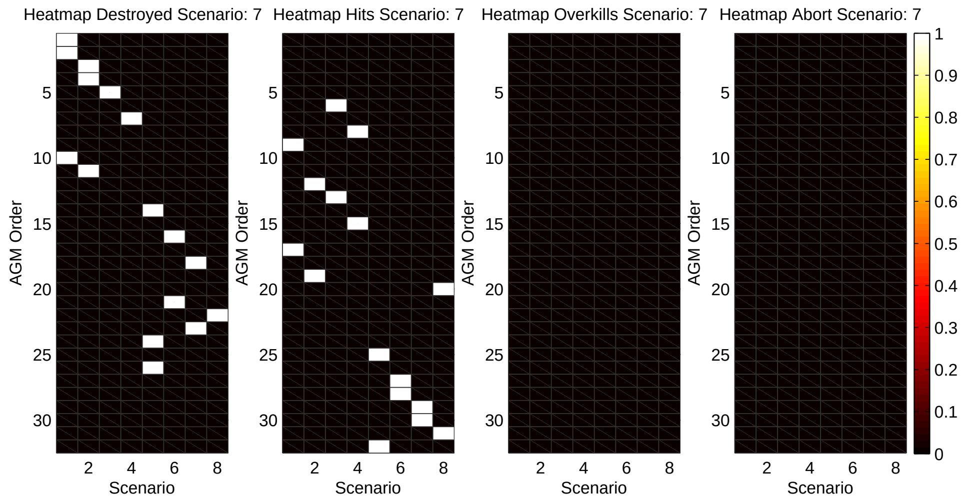

Figure 6.37: ACS Scenario 7 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

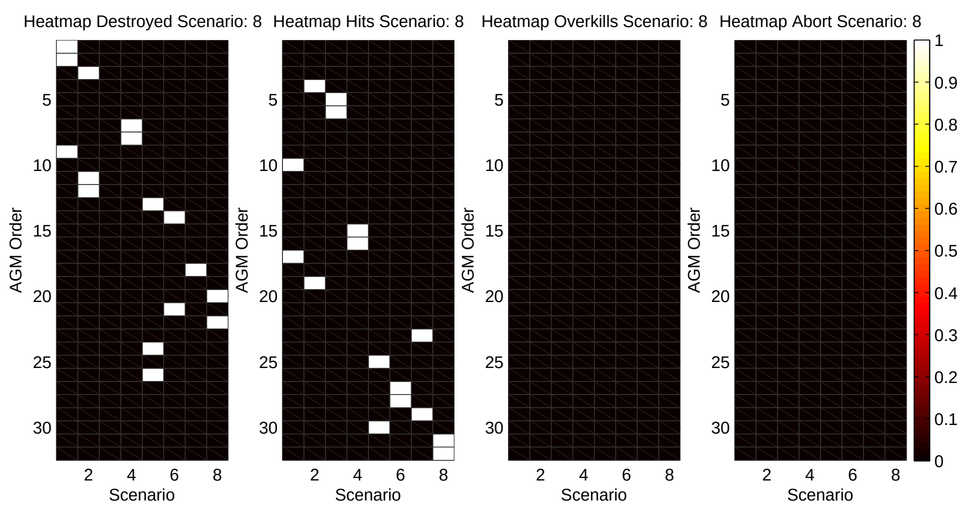

Figure 6.38: ACS Scenario 8 Heat Maps of Intercepted (Destroyed) LRAGM, LRAGM Hits on Target, LRAGM Overkills on Target, LRAGM Abort from Target

In order to directly compare these heat maps, the information was collated between both sets and the ratio between ACS to Participant frequency was used to create a third set of heat maps showing the differences [167]. Figure 6.39 to Figure 6.46 show these relationships (for difficulty level 1 through to difficulty level 8), with no difference between ACS or Participant data shown at white. A higher occurrence of Participants shown in red, and a higher occurrence of ACS shown as blue. With the ACS never overkilling a target, the overkill ratio always shows elements of red where participants make mistakes. These patches of red are faded for the easy scenarios, but as the scenarios become more difficult (and in line with the regression trends shown previously) the intensity of red and the size of the patches increases. For the highest difficulty it can be seen that overkills occur not only on the next wave of ASM following destruction of the first SAM battery, but also on the wave following that. This is indicative of the participants becoming so overwhelmed that are unable to make any further useful decisions once the primary SAM battery is destroyed.

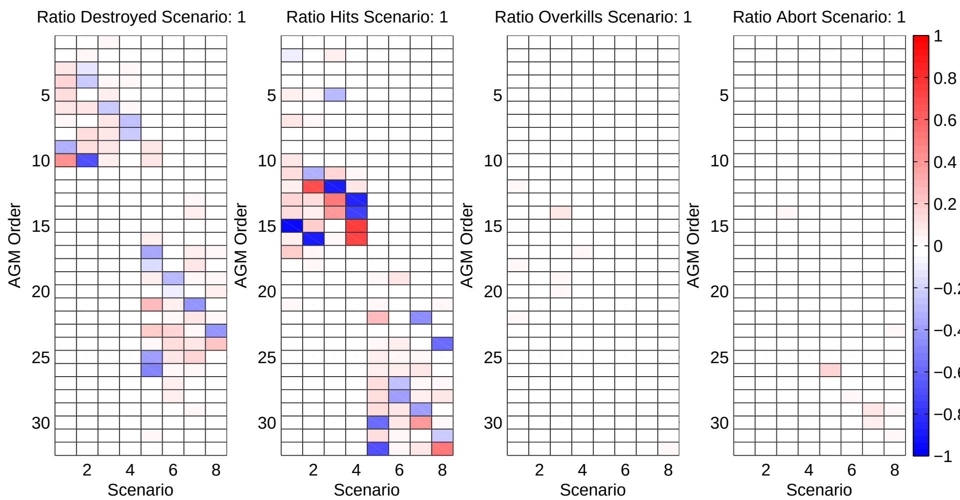

Figure 6.39: Ratio of Difference between ACS and Participants for Scenario 1. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

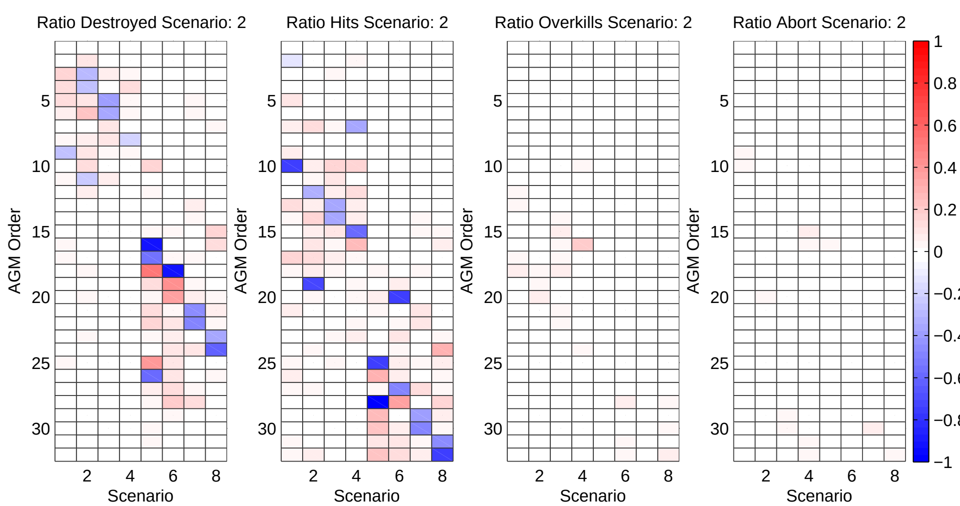

Figure 6.40: Ratio of Difference between ACS and Participants for Scenario 2. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

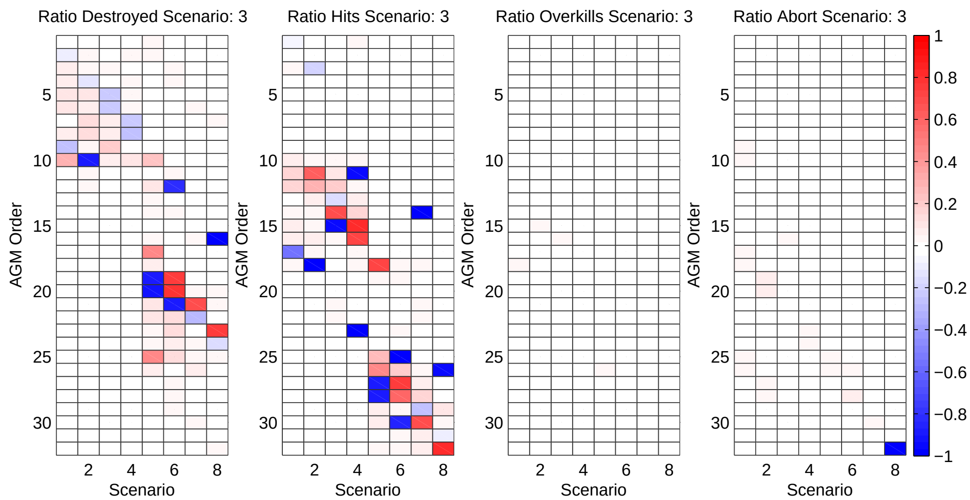

Figure 6.41: Ratio of Difference between ACS and Participants for Scenario 3. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

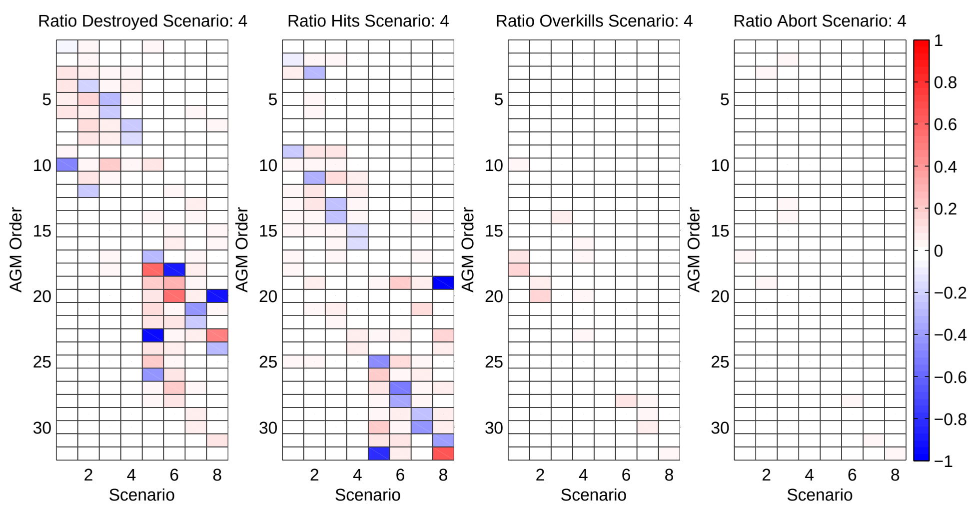

Figure 6.42: Ratio of Difference between ACS and Participants for Scenario 4. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

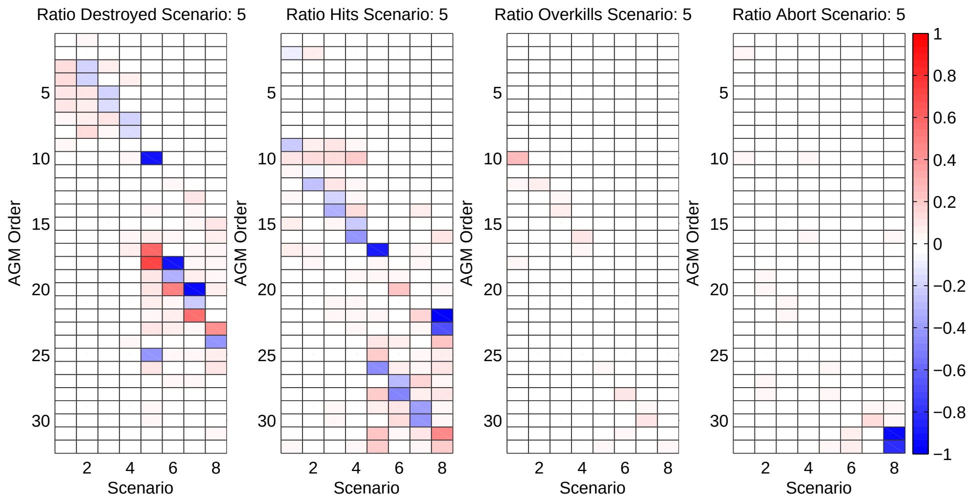

Figure 6.43: Ratio of Difference between ACS and Participants for Scenario 5. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

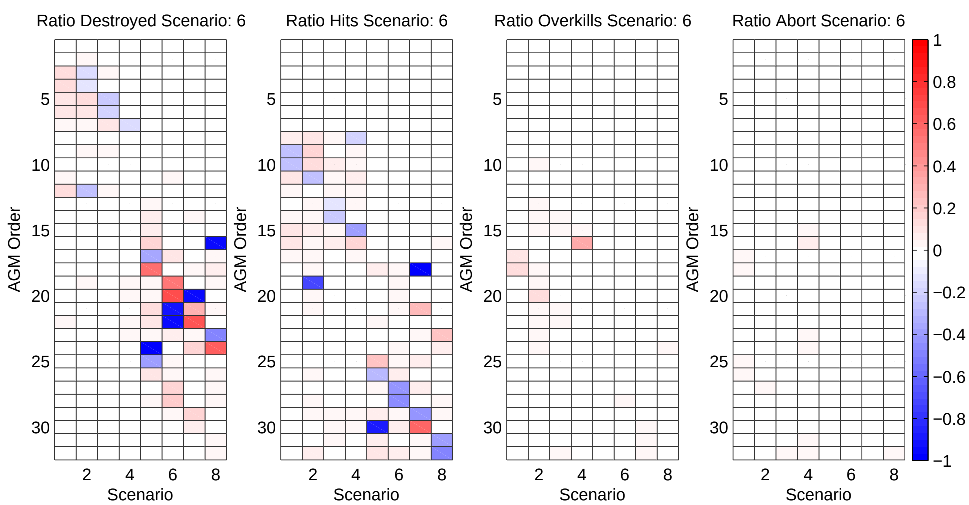

Figure 6.44: Ratio of Difference between ACS and Participants for Scenario 6. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

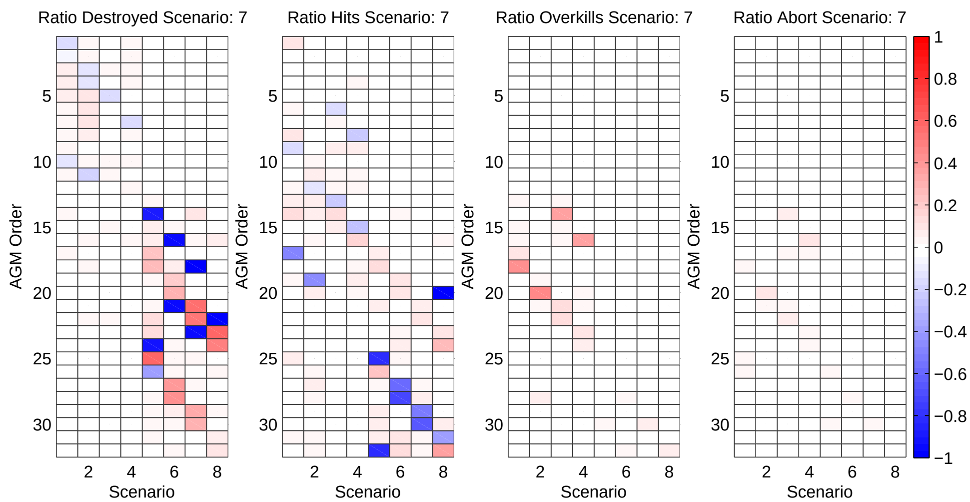

Figure 6.45: Ratio of Difference between ACS and Participants for Scenario 7. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

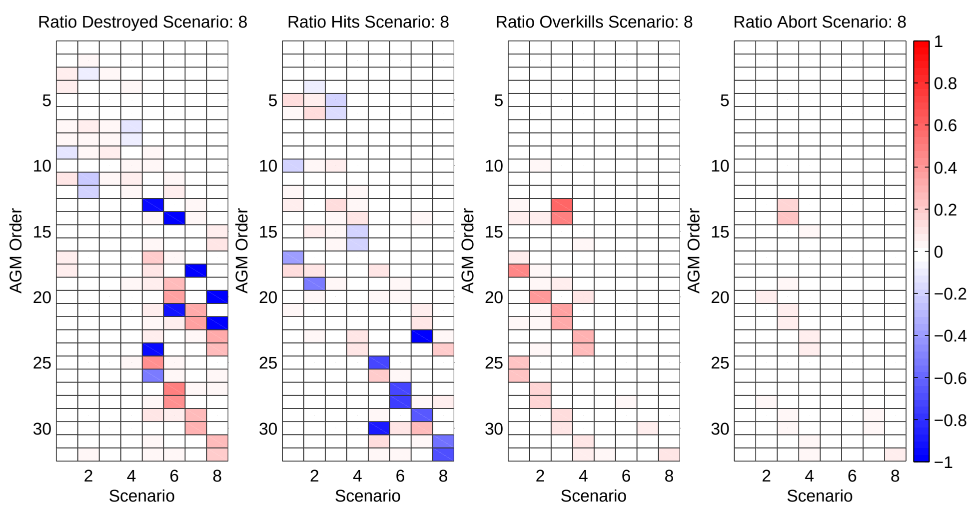

Figure 6.46: Ratio of Difference between ACS and Participants for Scenario 8. Red is higher frequency of Participants than ACS actions, Blue is higher frequency of ACS than Participants actions

6.6.4 Qualitative Analysis

The feedback questionnaires were investigated using thematic analysis techniques and the OSR NVivo 10 software package. The information gathered was retrospective and varying in both quality and quantity, with some participants giving the questionnaire a lot of thought, whilst others writing single sentence or word answers. The qualitative analysis is useful as it provides context to the raw data collected from the performance metrics and is supportive of a mixed methods approach – necessary for Human Factors and Psychology research. Key themes from the written responses to the questionnaire were identified and were split into four main categories of nodes with various sub-nodes as follows:

- Cause of Errors
- Cognitive Processes
  - Positive Comments
  - Negative Comments
- Display
  - Positive Comments
  - Negative Comments
  - Suggestions
    - Colour Changes
    - Map Comments
    - Request for Automation
    - Size of TAT Elements
- Strategies

The nodes were developed as coding took place to allow for dynamic generation of the above model. The Cause of Errors node is used to code any feedback that relates to any indication of a cause of error. This is when a participant volunteers information relating to either a display element or some method that the participant is using, causing a perceived error. The Cognitive Processes node is used to code any effect highlighted as a cognitive process, and these were split between general comments, positive comments and negative comments. The Display node was used to code any information relating to the display. As the display is the main interface for users, there was a wealth of information to code. In the feedback questionnaire there is a section specifically for participants to make suggestions for improving elements of the display. Therefore, in this node, there are the following sub nodes, Positive Comments and Negative Comments for general feedback, and a Suggestions node for recommendations. Further, within the coded information for Suggestions there were three main themes found. These related to Colour Changes, Map Changes and Size changes for TAT Elements. Lastly, a Strategies node allowed coding of any information related to the strategy used by participants.

Sources and References are useful indicators of the themes model. Table 6.15 shows the model in more detail, Figure 6.47 shows a tree map of the number of items coded to each node, and Figure 6.48 shows the number of items coded in from each source.

Table 6.15: Node Coding Model

Nodes	Number of coding references	Number of items coded	% of participants
Nodes Cause of Errors	106	30	100
Nodes Cognitive Processes	15	11	37
Nodes Cognitive Processes Negative Comments	39	22	73
Nodes Cognitive Processes Positive Comments	20	12	40
Nodes Display	1	1	3
Nodes Display Negative Comments	32	20	67
Nodes Display Positive Comments	14	10	33
Nodes Display Suggestions	19	15	50
Nodes Display Suggestions Colour Changes	22	17	57
Nodes Display Suggestions Map Comments	12	8	27
Nodes Display Suggestions Request for Automation	3	1	3
Nodes Display Suggestions Size of TAT Elements	11	8	27

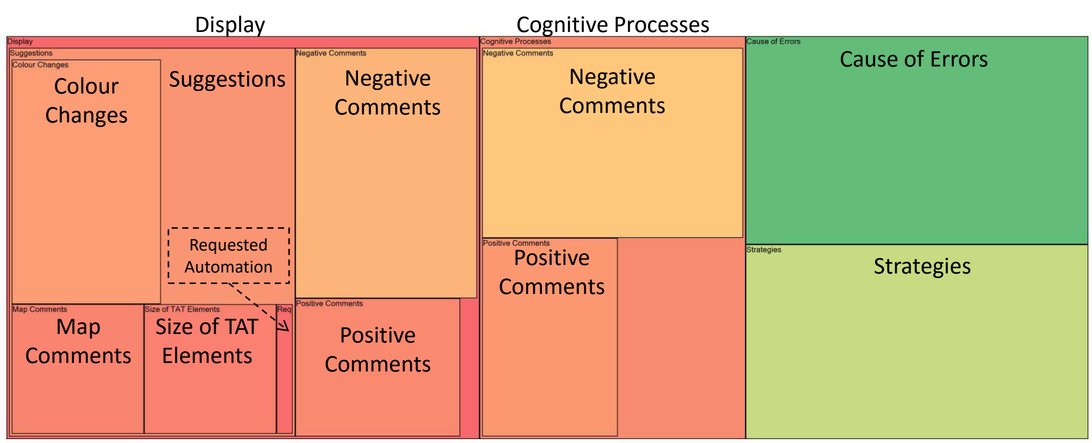

Figure 6.47: Tree Diagram of Number of Items Coded for Each Node - Area Depicts Number of Coded Items

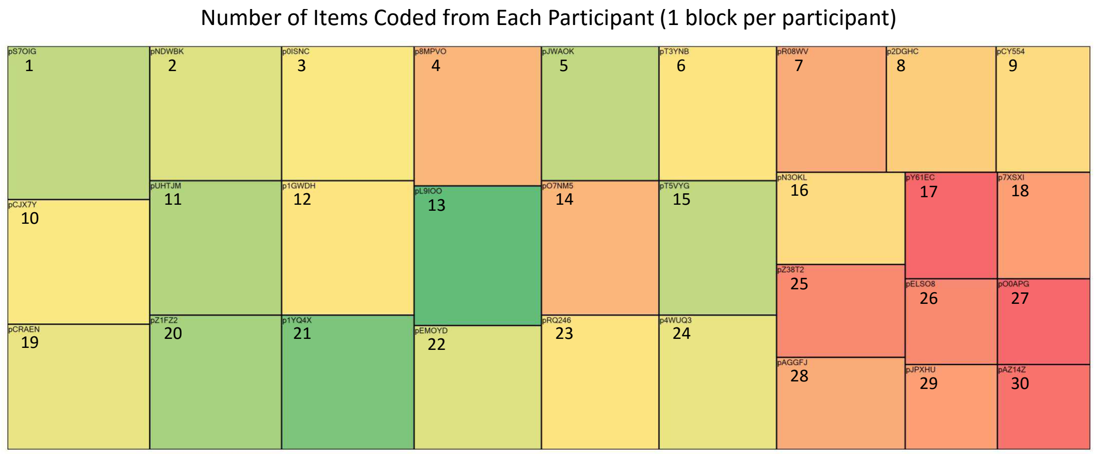

Figure 6.48: Tree Diagram of Number of Items Coded from Each Participant - Area Depicts Number of Coded Items

There was feedback coded from all 30 participants in the *Cause of Errors* nodes. All but two participants commented on using some sort of strategy. Under the *Display* node the number of *Negative Comments* nodes is 20, to only 10 *Positive Comments*. Further the number of actual coded references shows the same approximate ratio of 2:1 with 32 coding references from all sources for *Negative Comments* and only 14 for *Positive Comments*. The same relationship is present in the *Cognitive Processes* node where a ratio of approximately 2:1 exists between negative and positive comments. The *Display<Suggestions* nodes provide interesting feedback into where the visual system needs improvement. Slightly more than half (57%) of participants commented on making colour changes to the display – although these are occasionally conflicting between participants. A smaller percentage of participants suggested changes to *Map* elements and the sizing of objects within the TAT (27% in both cases). Interestingly only one participant requested more automation for overall task allocation between missiles, and automatic re-tasking. Specifically, the automatic re-tasking of weapons from first SAM site targets to second SAM site targets when the first SAM site was destroyed. Lastly Figure 6.48 shows that in all participants provided responses to code from in their questionnaire responses. The average number of items coded per participant was 16.3, with a standard deviation of 6.0. The maximum number of coded items was 30, and the minimum was 6.

6.7 Discussion

The participant data shows that there are clear correlations between difficulty and reported workload. This is as expected and provides evidence that the difficulty settings selected are appropriate with even spacing between the difficulty levels during initial trial coding. Further it provides credibility that the self reported data gathered from the NASA TLX Workload Scales were being used appropriately by participants and that it is a valuable tool for measuring workload.

The performance of participants reduces as the scenarios increase in difficulty and the trend from the NASA TLX workload suggest that the drop off in performance should be somewhat linear in the lower difficulty scenarios, with an exponential decrease in performance from scenario 5 onwards. The initial hypothesis was that, as difficulty increases, there will be a clear drop off point in performance. This drop off point can be clearly seen in the performance data plots, where participant performance is comparable with the automated system (with some small variance) until the operators become overwhelmed and their ability to complete the task reduces. This point is at difficulty level 6 – when missiles are launched in salvoes of 4 and at an interval of 10s. This is an effective rate of 1 missile every 2.5 seconds and a time between salvoes missiles of 6 seconds. The performance drop off is such that on average, at difficulty level 8, the participants are only able to complete the primary objective.

The source of the errors that occur in re-tasking, and missing targets, is the overkill on primary targets. This can be seen increasing as difficulty level increases in Figures 6.20 to 6.27. In scenarios 1-4, the overkills and subsequent misses are very low. Then as difficulty level increases, the number of overkills increases in an exponential shape, with the number of missed targets also increasing with the same shape but at half the magnitude (due to the two missiles to one target rule). The significant rise in overkill occurrences causes there to be insufficient missiles being available to prosecute the second SAM battery. As explained in section 6.1.3 the minimum number of LRAGM needed to prosecute a single SAM battery is 16. If more than 16 of the available 32 missiles are used to complete the primary objective there is a significant chance that the secondary objective will not be completed.

The behaviour of re-task quantity as difficulty is particularly interesting. As difficulty increases, it would be expected that decisions are made closer to the point when the LRAGM can no longer be re-tasked. What is significant however, is that even though participants are informed explicitly that they should not attempt re-tasks when the TTG value is below 5 seconds, they still attempt to do so. What was less expected was the number of re-tasks overall dropping by 30% from the easier to more difficult scenarios, and how much the fall in re-tasks where there is greater than 20 seconds remaining accounts for this. Further it is interesting that the number of abort decisions made is very low across all scenarios even though there was clearly an issue with overkills, and that participants were specifically instructed to abort rather than allow overkill events to occur. There is a very small increase in the mean number of aborts as difficulty increases, but this is negligible compared to the mean number of overkills.

6.8 Chapter Summary

This chapter has detailed the background, development and findings of a human factors trial on a remote operator station designed with the express purpose of aiding decision making, using a SEAD mission as the basis for testing. Relevant background literature relating to previous studies into both re-tasking, and interface design, as well as the theory and implementation of ecological interface design have been examined. The development of the overall system, both from the point of view of generating representative models of weapon systems, and air defence systems, as well as from the perspective of developing the operators' GUI were discussed.

A psychological human factors study was outlined and the results were explained in detail. The findings of the trial, in which human participants were tasked to re-task weapons to effectively carry out a successful SEAD mission, were also compared to an ACS. Human performance when using the DSS was found to be within reasonable performance levels at the easy and moderate difficulty scenario levels when compared to the 'perfect' ACS. As the scenarios became more difficult, the participants' performance dropped off quickly and only partial completion of the mission was achievable.

There were a number of specific indicators of errors made by participants, and the source of the error. For example, the error that caused the performance drop off was overkill events occurring on the primary SAM battery targets, which led to insufficient missiles being available to successfully prosecute the second SAM battery. After difficulty level 5 (10 seconds between salvoes, 2 missiles per salvo), the number of overkills against primary targets increases quickly from a mean of 0.63, to mean of 5.10 at level 8 (5 seconds between salvoes, 4 missiles per salvo). The data corresponds well with NASA TLX workload ratings and qualitative thematic analysis, the latter suggests that some slight changes in colour and salience of elements of the display could help to improve the overall SA and increase operator performance.

Overall this chapter has concluded that complex and time-limited decision making can be achieved at effective levels by human operators from a lay but computer skilled background. It has found that even when comparing performance against a perfect automated process, it may not be necessary to remove the human operator from being 'in the loop'. Instead it would be prevalent to focus research and development towards improving the interface and systems that the human is interacting with to improve performance in 'worst case' scenarios.

Chapter 7

Summary and Conclusions

7.1 Summary

This thesis focused on the area of NEW in a data-linked military as part of NEC and highlights the need for an in depth understanding of the Human Factors issues pertaining to its use. New capabilities that are developed through application of networking to the operation of weapon systems will always need human factors research to underpin systems design. This thesis investigates the process of designing a novel interface for use in a new domain and presents findings of two participant studies to support its conclusions. The context of the thesis is introduced in Chapter 1.

In Chapter 2 the research area and technical need for the research was highlighted, followed by critiques of related psychological research into interface design in related contexts. Further, the use of remote systems by human operators, the related SA and decision making theory was also discussed.

Chapter 3 expands on the background literature and describes the tools developed to allow for the following studies into the applicability of NEC in three different cases that represent different levels of C2 systems. To support this research, two air-to-surface weapons were modelled using MATLAB. These were then integrated into a distributed simulation environment where pilots and remote operators could interface with the weapons simulations. This chapter also discussed the method of communicating information, based upon a number of military standards, and describes the implementation of the front end operator interface used by participants in the human factors trials conducted.

Chapter 4 presents an investigation into the real-time application of an automated task allocation algorithm for a remote operator terminal. The automated task allocation algorithm allocates mixed aircraft formations amongst mixed and unknown target types. The system made use of the networking and simulation environment as a proof of concept exercise before developing human factors trials. A simulated annealing optimisation process was applied to distribute weapon allocations across target set such that a cost function was minimised. The cost function takes into account the correct matching of weapon effect to target type, as well as aiming to reduce the time taken to complete the overall tasks. Further, conditions were included for CAS priority missions. Solutions generated by the algorithm were incorporated into the operator terminal to support their decision making.

Chapter 5 then set out to establish a base line standard for remote operator terminals for the purpose of re-tasking NEW in a real-time distributed simulation environment. A human factors participant trial was carried out in a single weapon re-tasking scenario to investigate the advantages and disadvantages associated with two common types of information representation that had not been previously applied in this context. The advantages and disadvantages of each type of display are discussed in the literature, however, in general terms there are still conflicting opinions about which is more suitable. The trial found that the RAR of a weapon should be displayed numerically rather than as a graphical overlay on the map – as operators are more likely to make errors when using the graphical overlay. This finding differs from the more established practice of showing the full graphical overlay to weapons operators on-board aircraft.

Chapter 6 takes the findings from the study in Chapter 5 and expands the use of the remote operator system to handling multiple re-tasking of multiple in-flight weapons against multiple targets – the highest complexity level at which such a re-tasking system may need to be used. The findings from Chapter 5 were adapted into a large scale operator system that facilitated operator decision making. A human factors participant trial was then conducted to investigate the limits of operators ability to make effective decisions and complete a set of mission objectives. A computer automated re-tasking process was also developed such that human performance could be compared to an ideal case solution where the automated system always follows the same, logical decision making process set out based upon the same mission goals. When compared directly, it was found that human operators are able to carry out re-tasking duties in complex scenarios using the DSS developed at moderate levels of difficulty. A threshold was discovered beyond which human operator performance reduces quickly below the constant level of the automated system.

Overall this thesis has demonstrated that firstly, the development of distributed simulation networks and modelling of appropriate network architectures can be used to conduct very meaningful research into the use of NEWs by remote operators. Secondly it has provided a novel insight into the way in which re-tasking DSS should be developed, using the findings herein to shape the way in which key decision making information is displayed to operators when carrying out complex tasks in time limited situations. Further, comparison with idealised decision making has demonstrated that human operators are capable of carrying out such tasks, even at moderate levels of pace, and thus should be kept in the loop. The upper frequency limit was found to be one missile every 2.5 seconds, and that once this limit is passed, performance drops off exponentially. As technology develops, it is increasingly important that the capabilities that have become technically possible are also sufficiently presented to a human operator such that they can carry out their duties effectively. The way in which information such as the RAR and the pace at which operations are carried out in complex environments must be done with the knowledge of the way in which their use will affect operators.

7.2 Limitations

One limitation of the overall system design used for this research was the way in which the messaging structure was established. Unfortunately, due to the inability to access and/or disseminate classified information, the MIL-STD-6017 VMF was unable to be fully implemented. The VMF K-Series document contains the specific format of all data packets that can be sent using VMF. As access to this document is classified, the system developed was unable to include a direct reproduction of this message structure. Instead, a few resources (as discussed in Chapter 3) discussed partial message structures that allowed for the inclusion of a representative network architecture that would facilitate the expansion of the K-Series message structure should it be declassified in the future.

Another limitation involves the use of university students as participants. Initially the research was intending to use participants from military establishments, with additional insight from the military and the defence industry. Unfortunately, access to military personnel as participants was not achievable. Instead, contact with military establishments (DSTL) and industry (MBDA) provided useful input to the research project. As discussed in Chapter 2, useful insight can still be drawn from university students in the participant trials that were carried out. The operator performance limits found may well improve when testing military personnel although there is no guarantee or knowledge of how much performance will improve.

The final limitation that needs referring to is the time allocated to this research, and as such the number of trials that were conducted. The pace of this type of human factors research is limited by the time it takes to carry out such studies; several stages are involved, from initial conception to the generation of final results; development of the system, testing and debugging of software, finalising designs, ethics approval process, recruiting of participants, training, running trials, data collection and processing, data analysis, and generation of final results. Each section can take anywhere from one to three or more months.

7.3 Recommendations for Future Work

Moving forward with the research findings in this thesis, one study that would be of great interest would be to repeat the SEAD trial with the use of military personnel with specific experience in operating similar remote systems (such as UAVs). Such a study would be able to provide direct comparisons between lay participants and service personnel. Whilst it might be expected that service personnel would have better performance overall, and that this would result in a higher difficulty level being achievable before drop off in performance, they would be equally inexperienced using the specific DSS and as such may have similar performance levels. The direct input from military operators would no doubt offer up adaptations to the system that might facilitate the way in which SME operators would use the system. A study into the differences between lay and military operators would prove very useful in this research area.

Additional research trials would be useful for establishing the impact of making the changes set out by participants in feedback. A number of key areas were highlighted by participants about the display, particularly colour and salience of the current assignment of missiles to their targets in the second participant trial. Incremental improvements based upon this feedback could be conducted that would help to confirm whether the feedback provided proved useful. Although results found in the first participant trial indicate that participants may be underestimating their performance and changing the colour and salience of individual elements in the display may not impact on their performance at all.

Lastly, a full demonstration of the distributed simulation using trained military personnel would prove to be very useful in highlighting further decision making and C2 issues that may arise in carrying out complex remote weapon re-tasking missions. SA can be both supplemented or confused when operators have both audio and visual cues – and it would be of great interest to investigate the change in performance levels when operators are connected via verbal communication with other elements in the simulated environment.

Bibliography

[1] Ministry of Defence, *Network Enabled Capability, JSP 777*. U.K. Ministy of Defence, 1st ed., 2005.

[2] I. Burch, "Complex Weapons and DEW," in *Defence Research 2009*, (Birmingham), pp. 34–46, 2009.

[3] Jane's Defence Weekly, "Aimpoint Selection: The UK's SPEAR Cap 3 Air-to-Surface Weapon." `http://www.janes360.com/images/assets/853/47853/the_UK_s_SPEAR_Cap_3_air-to-surface_weapon.pdf`. Accessed: 01-09-2015.

[4] MBDA Systems, "SPEAR Network Enabled Precision Surface Attack," tech. rep., MBDA Systems, 2015.

[5] Jane's, *MBDA Fire Shadow (United Kingdom), Unmanned aerial vehicles*. Jane's Publishing Group, Unmanned Aerial Vehicles, 2011.

[6] G. J. Holzmann and B. Pehrson, *The Early History of Data Networks*. London: IEEE Computer Society Press, 1994.

[7] A. Cebrowski and J. Garstka, "Network Centric Warfare: It's Origins and Future," in *U.S. Naval Institute 124*, 1998.

[8] K. Edwards, S. Lloyd, and J. Ralph, "Air to Ground Weapon Aiming - A Brief Synopsis to Data and a Look to the Future," *Aeronautical Journal*, vol. 105, no. 1044, pp. 53–62, 2001.

[9] K. Edwards and S. Lloyd, "The Use of Third Party Targeting in Precision Air-to-Ground Operations," *Journal of Defence Science*, vol. 7, no. 1, 2002.

[10] K. Edwards, "Air-To-Ground Targeting - UAVs, Data Links and Interoperability (Project Extendor)," *Aeronautical Journal*, vol. 108, no. 1088, pp. 493–504, 2004.

[11] K. Edwards, "The Development of a UK Tactical Datalink for Time-Sensitive Targeting with Maximum Interoperability," in *Military Communications RTO-MP-IST-054*, pp. 4.1–4.14, 2006.

[12] R. A. Monetti, "NATO Time Sensitive Targeting - A Strong Beginning, Now What?," in *NATO School POLARIS Quarterly, NATO Network Enabled Capability Conference Report*, pp. 3–13, 2004.

[13] J. F. Ralph and D. M. Jones, "Automatic Task Assignment for Mixed Aircraft Formations," in *Proc. SPIE*, vol. 7307, pp. 73070N–73070N–9, 2009.

[14] Harris Press Release, "Harris Corporation's Low-Cost Weapon Data Link Used In Successful JDAM Moving Target Demonstration." http://harris.com/print_pressrelease.asp?act=lookup&pr_id=1677. Accessed: 01-09-2015.

[15] A. Sparkes, "Complex Weapons - Delivering Affordable Capability," in *RUSI Land Warfare*, (London), 2011.

[16] Air Land Sea Application Center, "Multi-Service Tactics, Techniques, and Procedures for the Joint Application of Firepower," tech. rep., Langley AFB: Air Land Sea Application Center, 2007.

[17] J. Gadsden and C. Outteridge, "What Value Analysis? The Historical Record of Fratricide," in *23 rd International Symposium on Military Operational Research*, 2006.

[18] C. M. Webb and K. J. Hewett, "An Analysis of U.S. Army Fratricide Incidents During the Global War on Terror (11th September 2001 to 31 March 2008) (USAARL Report No. 2010-14)," tech. rep., U.S. Army Aeromedical Research Laboratory, Wright Patterson AFB, OH, 2010.

[19] Department of the Navy, "Marine Corps Warfighting Publication 3-23.1 , Close Air Support," tech. rep., Department of the Navy, Washington DC, 1998.

[20] Department of Defense, "Interface Standard 2525D Joint Military Symbology," tech. rep., US Department of Defense, 2014.

[21] H. Hart, "FBCB2 Overview," in *IEEE 14th Annual Software Technology Conference*, (Salt Lake City, Utah), 2002.

[22] E. Macy, *Hellfire*. London: Harper Collins Press, 2009.

[23] Royal Air Force Crown Copyright, "Close Air Support for Troops in Afghanistan." http://www.raf.mod.uk/news/archive/close-air-support-for-troops-in-afghanistan-26062013. Published: 26-06-2013, Accessed: 01-09-2015.

[24] Royal Air Force Crown Copyright, "Harrier GR9/9A." http://www.raf.mod.uk/history/harriergr9.cfm. Accessed: 01-09-2015.

[25] M. Veth, J. Busque, D. Heesch, T. Burgess, F. Douglas, and B. Kish, "Affordable Moving Surface Target Engagement," in *Aerospace Conference Proceedings, 2002. IEEE*, vol. 5, pp. 5–2545–5–2551 vol.5, 2002.

[26] Jane's, *QinetiQ Shows Mid-Course Moves with GPS.* Jane's Information Group, 2006.

[27] Jane's, *QinetiQ Wraps Up First Phase of ISE trials.* Jane's Information Group, 2007.

[28] C. McDermott, B. Kelly, and K. Neace, "Net-Enabled Weapons (NEW) Support to ASuW," in *Naval Precision Weapons Session. PMA-201/OPNAV N98/JHUAPL*, PSA Annual Review, 2012.

[29] D. Clark, A. Faust, and A. Jones, "Common Launch Acceptability Region Task Group," Tech. Rep. 2001-01-2953, Socity of Automotive Engineers (SAE), 2001.

[30] The Boeing Company, "B-1B Avionics Flight Software (AFS) Software Design Description," Tech. Rep. MIL-STD 1760 Weapons, Block 7.1. Vol. 1, rev. A, Boeing, 2002.

[31] Society of Automotive Engineers, "Common Launch Acceptability Region Truth Data Generator Interface Control Document for the CLAR Approach," Tech. Rep. AIR 5788 Rev. A., Socity of Automotive Engineers (SAE), Warrendale, 2012.

[32] Society of Automotive Engineers, "Common Launch Acceptability Region Approach Interface Control Document," Tech. Rep. AIR 5682 Rev. A., Socity of Automotive Engineers (SAE), Warrendale, 2012.

[33] Society of Automotive Engineers, "Common Launch Acceptability Region Approach Rationale Document," Tech. Rep. AIR 5712 Rev. A., Socity of Automotive Engineers (SAE), Warrendale, 2012.

[34] W. G. Kalman, J. M. Kline, S. Provost, B. A. Gable, and C. R. Taylor, "B-1B Human Factors Baseline Study Report (ASC-TR-1999-5007)," tech. rep., Wright-Patterson AFB, OH: Air Force Crew Station Evaluation Facility, 1999.

[35] S. Provost, W. G. Kalman, J. M. Kline, C. R. Taylor, B. A. Gable, and M. Angesart, "B-1B Alternative Launch Acceptability Region (ALT LAR) Study (ASC-TR-2000-5009)," tech. rep., Wright-Patterson AFB, OH: Air Force Crew Station Evaluation Facility, 2000.

[36] M. Cummings and S. Guerlain, "Developing Operator Capacity Estimates for Supervisory Control of Autonomous Vehicles," *Human Factors Journal*, vol. 49, no. 1, pp. 1–15, 2007.

[37] I. Mitchell, A. Bayen, and C. J. Tomlin, "A Time-Dependant Hamilton-Jacobi Formulation of Reachable Sets for Continuous Dynamic Games," *IEEE Transactions on Automatic Control*, vol. 50, no. 7, pp. 947–957, 2005.

[38] N. A. Shneydor, *Missile Guidance and Pursuit*. Westergate U.K.: Horwood, 1998.

[39] United Nations, "Somalia - UNOSOM I. UN Department of Public Information.." `http://www.un.org/Depts/DPKO/Missions/unosomi.htm`, 1997. Accessed: 01-09-2015.

[40] United Nations, "Somalia - UNOSOM I Background. UN Department of Public Information." `http://www.un.org/en/peacekeeping/missions/past/unosom1backgr2.html`, 2003. Accessed: 01-09-2015.

[41] D. Cernis, "The B of the Bang: TARVIEW Lethality Modelling and Warhead Concepting," in *Proceedings of RAeS conference 'Trials, Modelling & Validation of Weapon Systems & Technologies: Supporting Development to Operations'*, (London), 2012.

[42] J. F. Ralph, M. I. Smith, M. Bernhardt, C. E. West, C. R. Angell, and S. W. Sims, "Distributed Air-to-Ground Targeting," in *SPIE Sensor Fusion: Architectures, Algorithms, and Applications VI*, vol. 4731, pp. 216–226, 2002.

[43] J. F. Ralph, K. L. Edwards, and S. W. Sims, "Contextual Targeting," in *SPIE Signal Processing, Sensor Fusion, and Target Recognition XIV*, vol. 5809, (Orlando, FL), pp. 176–185, 2005.

[44] B. Lambert, J. F. Ralph, L. Wren, D. Dwyer, and J. Dale, "Harmonisation and Alignment of Multiple Camera Imagery," in *SPIE Signal Processing, Sensor Fusion, and Target Recognition XIV*, vol. 5809, (Orlando, Florida), pp. 453–463, 2005.

[45] J. Wang, J. F. Ralph, and J. Y. Goulermas, "High-Resolution Reconstruction of Objects from Cloud-Covered Infrared Images," in *SPIE Signal Processing, Sensor Fusion, and Target Recognition XVIII*, vol. 7336, pp. 1–10, 2009.

[46] J. F. Ralph, S. W. Sims, and K. L. Edwards, "Scene-Referenced Object Localisation," in *SPIE Signal Processing, Sensor Fusion, and Target Recognition XIII*, (Orlando, FL), pp. 200–209, 2004.

[47] J. M. Davies, J. F. Ralph, and N. P. Oxtoby, "Tracking System to Maximise the Engagement Envelope of a Data Linked Weapon," in *Proceedings of SPIE conference 'Signal Processing, Sensor Fusion, and Target Recognition XX*, vol. 8050, (Orlando, Florida), pp. 1–9, 2011.

[48] J. F. Ralph and J. M. Davies, "Semi-Active Guidance Using Event Driven Tracking," in *IEEE Information Fusion XIV*, (Chicago, IL), pp. 1–7, 2011.

[49] J. K. Davis, E. Griffith, and J. F. Ralph, "Real-Time Task Allocation for Remote Weapon Operators," in *IEEE Infirmation Fusion ISIF 16*, (Istanbul, Turkey), pp. 1841,1848, 2013.

[50] K. J. Vicente and J. Rasmussen, "Ecological Interface Design: Theoretical Foundations," *Systems, Man and Cybernetics, IEEE Transactions on*, vol. 22, no. 4, pp. 589–606, 1992.

[51] The Economist, "Out of the Blue: A Growing Controversy Over the Use of Unmanned Aerial Strikes," in *The Economist*, vol. 399, pp. 36–37, 2011.

[52] J. Rogers, "The Public View: British Attitudes to Drone Warfare and Targeted Killing," in *Royal United Services Institute Whitehall Report 2-13 'Hitting the Target? How New Capabilities are Shaping International Intervention'* (M. Aaronson and A. Johnson, eds.), pp. 7–17, RUSI, 2013.

[53] National Audit Office, "Ministry of Defence - The Major Projects Report 2012," tech. rep., National Audit Office, 2012.

[54] M. R. Endsley, "Design and Evaluation for Situation Awareness Enhancement," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 32, pp. 97–101, SAGE Publications, 1988.

[55] M. R. Endsley, "Theoretical Underpinnings of Situation Awareness: A Critical Review," *Situation Awareness Analysis and Measurement*, pp. 3–32, 2000.

[56] M. R. Endsley, "A Taxonomy of Situation Awareness Errors," in *Human Factors in Aviation Operations* (R. Fuller, N. Johnston, and N. McDonald, eds.), pp. 287–292, Aldershot, England: Avebury Aviation, Ashgate Publishing Ltd, 1995.

[57] M. R. Endsley, "Toward a Theory of Situation Awareness," *Human Factors*, vol. 37, no. 1, pp. 32–64, 1995.

[58] M. R. Endsley, "SAGAT: A Methodology for the Measurement of Situation Awareness (NOR DOC 87-83)," tech. rep., Northrop Corporation, 1987.

[59] N. Cowan, "What are the Differences Between Long-term, Short-term, and Working Memory?," *Progress in Brain Research*, vol. 169, pp. 323–338, 2008.

[60] G. A. Miller, E. Galanter, and K. H. Pribram, "Plans and the Structure of Behaviour," in *American Anthropologist* (A. F. C. Wallace, ed.), vol. 62, pp. 1065–1067, Blackwell Publishing Ltd, 1960.

[61] R. W. Engle, "Working Memory Capacity as Executive Attention," *Current Directions in Psychological Science*, vol. 11, no. 1, pp. 19–23, 2002.

[62] D. G. Jones and M. R. Endsley, "Sources of Situation Awareness Errors in Aviation," *Aviation, Space, and Environmental Medicine*, 1996.

[63] G. A. Klein, *A Recognition-Primed Decision (RPD) Model of Rapid Decision Making*. Ablex Publishing Corporation, 1993.

[64] M. L. Fracker, "A Theory of Situation Assessment: Implications for Measuring Situation Awareness," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 32, pp. 102–106, SAGE Publications, 1988.

[65] G. Klein, "The Recognition-Primed Decision (RPD) Model: Looking Back, Looking Forward," in *Naturalistic Decision Making* (C. Zsambok and G. Klein, eds.), pp. 285–292, Mahwah, NJ: Psychology Press, 1997.

[66] L. Rothrock and A. Kirlik, "Inferring Rule-Based Strategies in Dynamic Judgement Tasks: Toward a Non-Compensatory Formulation of the Lens Model.," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 33, no. 1, pp. 58–72, 2003.

[67] H. Simon, "Rational Choice and the Structure of the Environment," *Psychology Review*, vol. 63, pp. 129–138, 1956.

[68] A. Tversky and D. Kahneman, "Judgement under Uncertainty: Heuristics and Biases," *Science*, vol. 185, no. 4157, pp. 1124–1131, 1974.

[69] G. Klein, *Sources of Power: How People Make Decisions*. Cambridge, MA: MIT Press, 1998.

[70] Z. Chua and K. Feigh, "Pilot Decision Making During Landing Point Designation," *Cognition, Technology & Work*, vol. 15, pp. 297–311, 2013.

[71] J. Boyd, "A Discourse on Winning and Losing," tech. rep., Maxwell Air Force Base, AL: Air University Library Document No. M-U 43947 (Briefing slides), 1987.

[72] J. J. Gibson, *The Ecological Approach to Visual Perception*. Boston, MA.: Houghtin-Mifflin, 1979.

[73] J. Flach, K. Vicente, F. Tanabe, K. Monta, and J. Ramussen, "An Ecological Approach to Interface Design," in *Proc. Human Factors and Ergonomics Society 42nd Annual Meeting*, (Santa Monica, CA), pp. 295–299, HFES, 1998.

[74] R. E. Nisbett and Y. Miyamoto, "The Influence of Culture: Holistic Versus Analytic Perception," *Trends in cognitive sciences*, vol. 9, no. 10, pp. 467–473, 2005.

[75] I. Vessey, "The Effect of Information Presentation on Decision Making: A Cost-benefit Analysis," *Inf. Manage.*, vol. 27, pp. 103–119, Aug. 1994.

[76] C. Speier, "The Influence of Information Presentation Formats on Complex Task Decision-Making Performance," *Int. J. Hum.-Comput. Stud.*, vol. 64, pp. 1115–1131, Nov. 2006.

[77] Y. Cao, M. Theune, and A. Nijholt, "Modality Effects on Cognitive Load and Performance in High Load Information Presentation," in *Proc. of the 14th International Conference on Intelligent User Interfaces*, (New York, NY), pp. 335–344, 2009.

[78] C. Gonzalez and J. Golenbock, "Impact of Numerical and Graphical Formats on Dynamic Decision Making Performance: An Eye-Tracking Study," in *Proc. of the Latin American Conference on Human-Computer Interaction*, (New York, NY), pp. 231–234, 2003.

[79] D. Kahneman, *Attention and Effort*. Englewood Cliffs, New Jersey: Prentice-Hall, 1973.

[80] D. Kahneman, "Remarks on Attention Control," in *Acta Psychologica, Attention and performance III* (A. F. Sanders, ed.), ch. 33, pp. 118–131, 1970.

[81] D. Kahneman, J. Beatty, and I. Pollack, "Perceptual Deficit During a Mental Task," *Science*, vol. 157, pp. 218–219, 1967.

[82] M. L. Posner and S. J. Boies, "Components of Attention," *Psychological Review*, vol. 78, pp. 391–408, 1971.

[83] M. L. Posner and S. W. Keele, "Attention Demands of Movements," in *Sixteenth International Congress of Applied Psychology, Symposium on Work and Fatigue*, (Amsterdam), 1969.

[84] M. L. Posner and R. M. Klein, "On the Functions of Consciousness," in *Attention and performance IV* (S. Kornblum, ed.), 1972.

[85] H. G. Shulman and S. N. Greenburg, "Perceptual Deficit due to Division of Attention Between Memory and Perception," *Journal of Experimental Psychology*, vol. 88,, pp. 171–176, 1971.

[86] W. Gaissmaier, O. Wegwarth, D. Skopec, A. Muller, S. Broschiniski, and M. Politi, "Numbers Can Be Worth a Thousand Pictures: Individual Differences

in Understanding Graphical and Numerical Representations of Health-Related Information," *Health Psychology*, vol. 31, no. 3, pp. 286–296, 2012.

[87] D. Mayer and R. Schvaneveldt, "Facilitation in Recognising Pairs of Words: Evidence of a Dependece Between Retrieval Operations, journal = Journal of Experimental Psychology," vol. 90, no. 2, pp. 227–234, 1971.

[88] E. Harmon-Jones, C. Harmon-Jones, and T. F. Price, "What is Approach Motivation?," *Emotion Review*, vol. 5, no. 3, pp. 291–295, 2013.

[89] A. J. Elliot, A. B. Eder, and E. Harmon-Jones, "ApproachAvoidance Motivation and Emotion: Convergence and Divergence," *Emotion Review*, vol. 5, no. 3, pp. 308–311, 2013.

[90] A. J. Elliot, "The Hierarchical Model of Approach-Avoidance Motivation," *Motivation and Emotion*, vol. 30, no. 2, pp. 111–116, 2006.

[91] A. Elliot and T. Thrash, "Achievement Goals and the Hierarchical Model of Achievement Motivation," *Educational Psychology Review*, vol. 13, no. 2, pp. 139–156, 2001.

[92] T. Thrash and A. Elliot, "Delimiting and Integrating Achievement Motive and Goal Constructs," in *Trends and Prospects in Motivation Research* (A. Efklides, J. Kuhl, and R. Sorrentino, eds.), pp. 3–21, Springer Netherlands, 2001.

[93] A. J. Elliot and K. M. Sheldon, "Avoidance Achievement Motivation: A Personal Goals Analysis," *Journal of Personality and Social Psychology*, vol. 73, no. 1, pp. 171–185, 1997.

[94] A. J. Elliot and K. M. Sheldon, "Avoidance Personal Goals and the Personality-Illness Relationship," *Journal of Personality and Social Psychology*, vol. 75, no. 5, pp. 1282–1299, 1998.

[95] planecrashinfo.com, "Causes of Fatal Accidents by Decade (percentage)." `http://www.planecrashinfo.com/cause.htm`. Accessed: 01-09-2015.

[96] Z. Chua, L. Major, and K. Feigh, "Modelling Cockpit Interface Usage During Lunar Landing Redesignation," in *In Proc. of the 15th International Symposium on Aviation Psychology.*, (Dayton, OH), 2009.

[97] Z. Chua, K. Feigh, and R. Braun, "Examination of Human Performance During Lunar Landing," in *Aerospace Conference, 2010 IEEE*, pp. 1–11, March 2010.

[98] E. Weiner and R. Curry, "Flight-Deck Automation: Promises and Problems," *Ergonomics*, vol. 23, no. 10, pp. 995–1011, 1980.

[99] D. B. Kaber and M. R. Endsley, "Out-of-the-Loop Performance Problems and the Use of Intermediate Levels of Automation for Improved Control System Functioning and Safety," *Process Safety Progress*, vol. 16, no. 3, pp. 126–131, 1997.

[100] P. Smith, C. McCoy, and C. Layton, "Brittleness in the Design of Cooperative Problem-Solving Systems: The Effects on User Performance," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 27, pp. 360–371, May 1997.

[101] B. Hilburn, M. Bakker, W. Pekela, and R. Parasuraman, "The Effect of Free Flight on Air Traffic Controller Mental Workload, Monitoring and System Performance," in *Proc of the 10th International Conference of European Aerospace Societies.*, vol. 14, (Amsterdam, NED), pp. 1–12, 1997.

[102] F. Zijlstra and L. van Doorn, "The Construction of a Scale to Measure Subjective Effort," tech. rep., Delft University of Technology, 1985.

[103] B. Hilburn, P. Jorna, and R. Parasuraman, "The Effect of Advanced ATC Strategic Decision Aiding Automation on Mental Workload and Monitoring Performance: An Empirical Investigation in Simulated Dutch Airspace," in *Proceedings of the Eighth International Symposium on Aviation Psychology*, (Columbus, Ohio USA), pp. 387–391, April 1995.

[104] M. Cummings and S. Guerlain, "The Tactical Tomahawk Conundrum: Designing Decision Support Systems for Revolutionary Domains," in *Systems, Man and Cybernetics, 2003. IEEE International Conference on*, vol. 2, pp. 1583–1588 vol.2, Oct 2003.

[105] H. Ruff, S. Narayanan, and M. Draper, "Human Interaction with Levels of Automation and Decision Aid Fidelity in the Supervisory Control of Multiple Simulated Unmanned Air Vehicles," *Presence*, vol. 11, no. 4, pp. 335–351, 2002.

[106] W. B. Rouse and S. H. Rouse, "A Framework for Research on Adaptive Decision Aids (Technical Report AFAMRL-TR-83-082)," tech. rep., Air Force Aerospace Medical Research Laboratory, Wright Patterson AFB, OH, 1983.

[107] K. Johnson, J. Kuchar, and C. Oman, "Experimental study of automation to support time-critical replanning decisions,"

[108] K. A. Rigby, *Aircraft Systems Integration of Air-Launched Weapons*, p. 8. West Susex, United Kingdom: John Wiley and Sons Ltd., 2013.

[109] R. Brochu and R. Lestage, "Three-Degree-of-Freedom (DOF) Missile Trajectory Simulation Model and Comparative Study with a High Fidelity 6DOF Model,"

tech. rep., Defence R and D Canada - Valcartier - Technical Memorandum DRDC Valcartier TM 2003-056, 2003.

[110] R. M. Gorecki, "A Baseline 6 Degree of Freedom (DOF) Mathematical Model of a Generic Missile (DSTO-TR-0931)," tech. rep., DSTO Systens Sciences Laboratory, 2003.

[111] S. M. Murman, M. J. Aftosmis, and M. J. Berger, "Simulations of 6-DOF motion with a Cartesian method," *AIAA 41st Aerospace Sciences Meeting and Exhibit*, 2003.

[112] R. E. Kalman, "A New Approach to Linear Filtering and Prediction Problems," *Journal of Fluids Engineering*, vol. 82, no. 1, pp. 35–45, 1960.

[113] D. Perh, "A Study into Advanced Guidance Laws using Computational Methods," tech. rep., DTIC Document, 2011.

[114] P. Zarchan, *Tactical and Strategic Missile Guidance*. Reston, VA: AAIA, 6th ed., 2012.

[115] Y.-C. Chiou and C.-Y. Kuo, "Geometric Approach to Three-Dimensional Missile Guidance Problem," *Journal of Guidance, Control, and Dynamics*, vol. 21, no. 2, pp. 335–341, 1998.

[116] J. A. Lukacs and O. A. Yakimenko, "Trajectory-Shape-Varying Missile Guidance for Interception of Ballistic Missiles During the Boost Phase," in *AIAA Guidance, Navigation and Control Conference and Exhibit*, pp. 20–23, 2007.

[117] J. Z. Ben-Asher and I. Yaesh, *Advances in Missile Guidance Theory*, vol. 180. Reston, VA: American Institute of Aeronautics & Astronautics, 1998.

[118] N. F. Palumbo, R. A. Blauwkamp, and J. M. Lloyd, "Modern Homing Missile Guidance Theory and Techniques," *Johns Hopkins APL Tech. Dig*, vol. 29, no. 1, pp. 42–59, 2010.

[119] I. H. Abbott and A. E. Von Doenhoff, *Theory of wing sections, including a summary of airfoil data*. Courier Corporation, 1959.

[120] US Department of Transport, "Traffic Analysis Toolbox Vol III: Guidelines for Applying Traffic Microsimulation Modeling Software." `http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol3/Vol3_Guidelines.pdf`, 2004. Accessed: 13-05-2014.

[121] National Cooperative Highway Research Program, "NCHRP Report 348 Access Management Guidelines for Activity Centres," tech. rep., Transportation Research Board: National Research Council, Washington D.C., 1992.

[122] I. Filippidis, “Matlab Central File Exchange: OpenStreetMap Functions.” http://www.mathworks.co.uk/matlabcentral/fileexchange/35819-openstreetmap-functions. Accessed: 22-03-2012.

[123] E. Dijkstra, “A Note on Two Problems in Connexion with Graphs,” *Numerische Mathematik*, vol. 1, no. 1, pp. 269–271, 1959.

[124] G. Priestnall, “Tutorial: Introduction to Variable Message Format (VMF),” in *MilCIS*, (Canberra, AUS), 2010.

[125] A. Shegog, “Variable Message Format (VMF),” tech. rep., Tactical Information Exchange Integration Office (TIE IO) Defence Material Organisation - Australian Department of Defence, 2008.

[126] Department of Defense Interface Standard, “MIL-STD-2045-47001D (w.Change 1) Connectionless Data Transfer Application Layer Standard,” tech. rep., US Department of Defense, 2008.

[127] B. Supnik, “Open Street Map and X-Plane 10, X-Plane Developer.” http://developer.x-plane.com/2011/04/openstreetmap-and-x-plane-10/. Published: 17-04-2011, Accessed: 01-09-2015.

[128] S. M. McGovern and S. B. Cohen, “Survey of Contemporary Aircraft Flight Dynamics Models for use in Airspace Simulation,” in *Defense and Security Symposium*, pp. 65640V–65640V, International Society for Optics and Photonics, 2007.

[129] W. Z. Stepniewski, *Rotary-Wing Aerodynamics: Volume 1: Basic Theory of Rotor Aerodynamics*. New York: Dover Publications Inc, 1984.

[130] A. Meyer, “How X-Plane Works.” http://www.x-plane.com/desktop/how-x-plane-works/. Published: 02-02-2012, Accessed: 01-09-2015.

[131] FSDeveloper.com, “SDK Toolset (FSX).” http://www.fsdeveloper.com/wiki/index.php?title=SDK_Toolset_%28FSX%29. Published: 27-06-2010, Accessed: 01-09-2015.

[132] xsquawkbox.net, “X-Plane Plugin SDK User’s Manual.” http://www.xsquawkbox.net/xpsdk/mediawiki/Documentation. Accessed: 01-02-2012.

[133] xsquawkbox.net, “Datarefs for X-Plane 1040.” http://www.xsquawkbox.net/xpsdk/docs/DataRefs.html. Published: 18-06-2015, Accessed: 01-09-2015.

[134] US Department of Defense, “Unmanned Systems Integrated Roadmap: FY2011-2036,” tech. rep., US Department of Defense, 2011.

[135] UK Ministry of Defence, "RAF Announces New Reaper Squadron," tech. rep., Ministry of Defence, 2011.

[136] R. Sparrow, "Building a Better WarBot: Ethical Issues in the Design of Unmanned Systems for Military Applications," *Science and Engineering Ethics*, vol. 15, no. 2, pp. 169–187, 2009.

[137] L. Royakkers and R. van Est, "The Cubicle Warrior: The Marionette of Digitalized Warfare," *Ethics in Information Technology*, vol. 12, pp. 289–296, 2010.

[138] N. Power, L. Alison, and J. Ralph, "Unmanned Weapons Systems and Just Wars: The Psychological Dimension," in *Precision Strike Warfare and International Intervention: Strategic, Ethico-Legal and Decisional Implications* (M. Aaronson, W. Aslam, T. Dyson, and R. Rauxloh, eds.), Oxon: Routledge, 2015.

[139] J. Cruz, G. Chen, D. Garagic, X. Tan, D. Li, D. Shen, M. Wei, and X. Wang, "Team Dynamics and Tactics for Mission Planning," in *Decision and Control, 2003. Proceedings. 42nd IEEE Conference on*, vol. 4, pp. 3579–3584 vol.4, Dec 2003.

[140] G. Lamont, J. Slear, and K. Melendez, "UAV Swarm Mission Planning and Routing using Multi-Objective Evolutionary Algorithms," in *Computational Intelligence in Multicriteria Decision Making, IEEE Symposium on*, pp. 10–20, April 2007.

[141] P. Moss, B. Baker, D. Khosla, and A. Dow, "Multi-Mission Prioritization Using Cost Based Mission Scheduling," in *11th International Command and Control Research and Technology Symposium (ICCRTS)*, pp. 1–18, 2006.

[142] W. Press, A. Teukolsky, W. Vetterling, and B. Flannery, *Numerical Recipes in C, 2nd Ed*, ch. 10. Cambridge: Cambridge University Press, 1999.

[143] Ministry of Defence, "Land Component Handbook," tech. rep., Ministry of Defence, 2001.

[144] Air Land Sea Application Centre, "J-FIRE Multiservice Procedures for the Joint Application of Firepower," tech. rep., Air Force Doctrine Center, Langley AFB, VA., 1997.

[145] Department of Defence, "MIL-STD-6107A: Interoperability Standard - Variable Message Format (VMF) Message Standard (U)," tech. rep., US DoD, 2006.

[146] J. Groh, *Army War College Guide to National Security Issues, Vol. 1*, ch. 21, pp. 323–338. Carlisle, US: Strategic Studies Institute of the US Army War College (SSI), 2008.

[147] D. Murphey and J. Groh, "Landpower and Network-Centric Operations: How Information in Today's Battlespace can be Exploited," in *Proceedings Network-Centric Warfare Europe*, (London, UK), pp. 1–10, 2006.

[148] D. Woods, J. Wise, and L. Hanes, "An Evaluation of Nuclear Power Plant Safety Parameter Display Systems," in *Human Factors Society 25th Annual Meeting*, (Santa Monica, CA), pp. 110–114, 1981.

[149] M. Jessa and C. M. Burns, "Visual Sensitivities of Dynamic Graphical Displays," *Int. J. Hum.-Comput. Stud.*, vol. 65, pp. 206–222, Mar. 2007.

[150] C. Wickens and C. Carswell, "The Proximity Capability Principle: Its Psychological Functions and its Relevance to Display Design," *Human Factors*, vol. 37, pp. 473–494, 1995.

[151] K. B. Bennett, M. L. Toms, and D. D. Woods, "Emergent Features and Graphical Elements: Designing More Effective Configural Displays," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 35, no. 1, pp. 71–97, 1993.

[152] J. Pomerantz, "Visual Form Perception: An Overview," in *Pattern Recognition by Humans and Machines: Vol 2* (H.C.Nusbaum and E. Schwab, eds.), pp. 1–30, Orlando, FL: Academic, 1986.

[153] C. Wickens and A. Andre, "Proximity Compatibility and the Object Display," in *Human Factors Society 32nd Annual Meeting*, (Santa Monica, CA.), pp. 1335–1339, 1988.

[154] E. Hoadley, "Investigating the Effects of Color," *Commun. ACM*, vol. 33, pp. 120–125, Feb. 1990.

[155] C. Gonzalez, "Does Animation in User Interfaces Improve Decision Making?," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '96, (New York, NY, USA), pp. 27–34, ACM, 1996.

[156] E. Fleeman, *Tactical Missile Design*. Reston, VA: AAIA, 2th ed., 2006.

[157] R. W. Engle, S. W. Tuholski, J. Laughlin, and A. R. A. Conway, "Working Memory, Short-Term Memory and General Fluid Intelligence: A Latent-Variable Approach," *Journal of Experimental Psychology: General*, vol. 128, pp. 972–992, 1999.

[158] R. W. Engle, "What is Working Memory Capacity?," in *The nature of remembering: Essays in honour of Robert G. Crowder* (H. K. Roediger, J. S. Nairne,

I. Neath, and A. M. Suprenant, eds.), pp. 297–314, Washington, DC: American Psychological Association, 2000.

[159] S. Hart and L. Staveland, "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," in *Human Mental Workload* (P. Hancock and N. Meshkati, eds.), p. North Holland Press, 1988.

[160] IBM, "Statistical Package for the Social Sciences (SPSS)." `http://www-01.ibm.com/software/uk/analytics/spss/`. Accessed: 22-12-2015.

[161] R. W. Schmell and N. S. Umanath, "An Experimental Evaluation of the Impact of Data Display Format on Recall Performance," *Commun. ACM*, vol. 31, pp. 562–570, May 1988.

[162] O. Ulgen, "UAVs and Removal of Central Thinking Activities: Implications for Principles of Legitimate Targeting, Proportionality and Unnecessary Suffering," in *RAeS Weapon Systems and Technology Group Conference on Delivering Weapon System Effects: The Contrast Between Piloted and Remotely-Piloted Platforms*, (RAeS QinetiQ Malvern), 2015.

[163] V. V. Kuzmin, "Tor-M1 SAM (2)." `https://commons.wikimedia.org/wiki/File:Tor-M1_SAM_(2).jpg#/media/File:Tor-M1_SAM_(2).jpg`, 2010. Licensed under CC BY-SA 3.0.

[164] C. Kopp, "Technical Report APA-TR-2009-0707 - APA 9K331 Tor," tech. rep., Air Power Australia, 2009.

[165] E. R. Stone, W. R. Sieck, B. E. Bull, J. F. Yates, S. C. Parks, and C. J. Rush, "Foreground:Background Salience: Explaining the Effects of Graphical Displays on Risk Avoidance," *Organizational Behavior and Human Decision Processes*, vol. 90, no. 1, pp. 19 – 36, 2003.

[166] A. Roets and A. Van Hiel, "Item Selection and Validation of a Brief, 15-Item Version of the Need for Closure Scale," *Personality and Individual Differences*, vol. 50, no. 1, pp. 90–94, 2011.

[167] D. Krakov and D. G. Feitelson, "Comparing Performance Heatmaps," in *Job Scheduling Strategies for Parallel Processing*, pp. 42–61, Springer, 2014.