Space Debris Removal: A Game Theoretic Analysis

Richard Klima[1] and Daan Bloembergen[1] and Rahul Savani[1] and Karl Tuyls[1] and Daniel Hennes[2] and Dario Izzo[3]

Abstract. We analyse active space debris removal efforts from a strategic, game-theoretic perspective. An active debris removal mission is a costly endeavour that has a positive effect (or risk reduction) for all satellites in the same orbital band. This leads to a dilemma: each actor (space agency, private stakeholder, etc.) has an incentive to delay its actions and wait for others to respond. The risk of the latter action is that, if everyone waits the joint outcome will be catastrophic leading to what in game theory is referred to as the 'tragedy of the commons'. We introduce and thoroughly analyse this dilemma using simulation and empirical game theory in a two player setting.

1 INTRODUCTION AND RELATED WORK

Since the late 1950s a number of public and private actors have launched a multitude of objects into Earth orbits with low or no incentive to remove them after their life span. As a consequence, there are now many inactive objects orbiting Earth, which pose a considerable risk to active spacecraft. By far, the highest spatial density of such objects is in the Low Earth Orbit (LEO) environment, defined as the region of space around Earth within an altitude of 160 km to 2,000 km. According to most simulations and forecast, the density of objects in LEO is destined to increase due to the rate of new launches, on-orbit explosions, and object collisions being higher than the capability of the LEO environment to clean itself using the natural orbital decay mechanism. The objective of this paper is to model this effect and understand its consequences. We thus introduce a non-cooperative game between self-interested agents in which the agents are the owners of space assets. Using a high-fidelity simulator we estimate payoffs to the agents for different combinations of actions taken, and analyse the resulting game in terms of best-response dynamics and (Nash) equilibria. Contrary to the urgency of the space debris dilemma there has not been much attention to this problem in scientific circles. To the best of our knowledge we are the first to consider this dilemma in the context of multi-agent strategic decision making using empirical game theoretic techniques.

Our study can be placed in the context of two different areas of related work. Firstly, from a simulation modelling perspective various attempts have been made to accurately predict the evolution of space debris and the resulting risk of collisions for active spacecraft. One of the earliest analyses of the projected evolution of space debris was done by Donald J. Kessler in 1978 [4]. This study led to the definition of the "Kessler Syndrome", a scenario where the density of objects in LEO becomes high enough to cause a cascade of collisions, each producing new debris and eventually saturating the environment, rendering future space missions virtually impossible. As a result, *active debris removal* (ADR) methods, in which spacecraft are deployed to capture and de-orbit larger pieces of debris and out-of-service satellites, are now considered by many as a necessary step to ensure sustainability of LEO [5]. Secondly, from a game theoretic perspective, researchers have utilised similar methods to study related problems of environmental pollution, and the shared exploitation of scarce resources. For example, carbon dioxide abatement modelled as a differential game [7].

We base our study on Liou and Johnson's single-agent approach [5] but, in contrast, consider a multi-agent scenario in which different space actors independently choose their removal strategy. In our model we implement individualised object removal criteria based on the potential risk to important assets of each of the actors. Our analysis is based on methods from empirical game theory [8] to convert empirical data to strategic (normal-form) games.

2 DEBRIS SIMULATION AND GAME MODEL

Our simulator builds on the Python scientific library PyKep [2], which provides basic tools for astrodynamics research such as satellite orbit propagators. To simulate the future development of space debris in Low Earth Orbit (LEO) we develop several sub-modules, including a collision model and a break-up model. To evaluate the probability of collision between objects we implement the *Cube* approach [6]. We follow NASA's standard breakup model [3] to generate the population of fragments resulting from a collision event. The initial input data to our model comes from the satellite catalogue SATCAT[4] and the TLE (two-line element set) database[5].

We model the space debris removal dilemma as a two-player game, with players being the United States (US) and the European Union (EU). The strategic interaction results from the fact that debris removal by one player may affect the collision risks to others as well. The players' actions are defined by the number of debris objects that will be removed, being either 0, 1, or 2 high risk objects every 2 years. We assume self-interested agents, meaning that each player first removes objects which directly threaten their active satellites, and only then consider objects which present a collision risk in general. The payoffs are based on risk of collision to each player's active satellites, multiplied by the cost of losing an asset C_l, and minus the costs of object removal C_r.

3 SIMULATION RESULTS AND PROJECTIONS

We use our simulator to project the evolution of debris and collision risks with a time horizon of 150 years, i.e. the period 2016-2165, while repeating the launch history of 2006-2015 with a 0.5%

[1]University of Liverpool, UK, email: {richard.klima, d.bloembergen, rahul.savani, k.tuyls}@liverpool.ac.uk [2]DFKI, Bremen, Germany, email: daniel.hennes@dfki.de [3]European Space Agency, Noordwijk, NL, email: dario.izzo@esa.int

[4] https://celestrak.com [5] https://www.space-track.org/

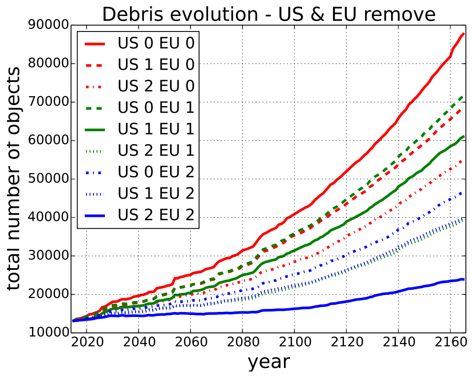

Figure 1. Debris evolution in LEO for next 150 years

yearly increase. For each combination of actions we average over 160 Monte-Carlo runs to account for randomness in the collision and break-up modules. Figure 1 shows the evolution of objects in LEO for different numbers of objects removed by the US and the EU. We observe an exponential growth trend without mitigation, in line with previous findings [5]. One can clearly see that removing high risk objects leads to reduced growth in the total number of objects in LEO. The cumulative risks to both players resulting from the debris evolution in Figure 1 are given in the following table:

	EU 2	*EU 1*	*EU 0*
US 2	$0.03413, \mathit{0.03733}$	$0.05247, \mathit{0.07108}$	$0.07704, \mathit{0.27474}$
US 1	$0.06073, \mathit{0.06352}$	$0.09499, \mathit{0.10405}$	$0.10885, \mathit{0.31401}$
US 0	$0.25022, \mathit{0.07368}$	$0.28848, \mathit{0.12447}$	$0.34261, \mathit{0.36385}$

4 GAME THEORETIC ANALYSIS

We derive the payoff matrix for the two players (US and EU) from the risks given above for varying levels of cost of removal C_r (assuming w.l.g. $C_l = 1$), and find the Nash equilibria. We identify two interesting regions in the range of costs C_r. For very low costs, removing 0 will never be a best response for either player. Similarly, for high costs, removing 2 will never be a best response. Therefore we can focus on two sub-games defined by the action-pairs $\{0, 1\}$ and $\{1, 2\}$. We compute Nash equilibria for a range of C_r, and visualise the results in Figure 2 for the sub-game $\{0, 1\}$ (we observe similar results for the sub-game $\{1, 2\}$). On the y-axis we have the probability of playing the first action in each sub-game (which equals 1 minus the probability of the second action) for US (top) and EU (bottom). The colours/line styles indicate the action pairs that make up the equilibria, e.g. the solid lines in Figure 2 correspond to the pure Nash equilibria $(0, 0)$ (black) and $(1, 1)$ (red). In the figure we see transitions from the single Nash equilibrium at $(0, 0)$, to a situation where three equilibria exist (at $(0, 1)$, $(1, 0)$, and one mixed), and finally back to a single pure equilibrium at $(1, 1)$. These transition phases also include a stage in which only one of the asymmetric pure equilibria at $(1, 0)$ or $(0, 1)$ exists. These result from the asymmetry that is inherent in the risk matrix due to players having different numbers of assets in different orbits.

In general, ADR has a positive effect not only for the instigator of the removal but also for other players, and this is the cause of the dilemma that we are studying. In game-theoretic terminology, this suggests that we have games with a *weak strategic substitutes property*. Any two-player game that has this property admits a pure equilibrium, which is important for many practical purposes [1].

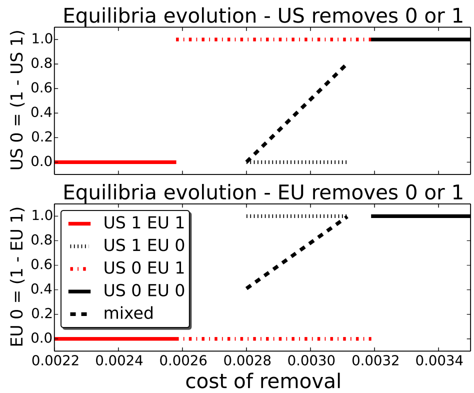

Figure 2. Equilibrium strategies for the sub-game $\{0, 1\}$ for a range of C_r.

5 CONCLUSIONS AND FUTURE WORK

We have introduced a multi-player non-cooperative game named the *Space Debris Removal Dilemma* based on prediction data from our space debris and satellite simulator. The game highlights how the rational behaviour of players varies depending on the cost of active debris removal versus the value of active satellites. In our game-theoretic analysis we identified which removal strategies for the different actors are in equilibrium with each other, i.e. which strategies purely rational actors are expected to decide on. We demonstrated the sensitivity of these equilibrium strategies to the ratio between cost of debris removal and the value of the active satellites. Although the costs of active debris removal are still prohibitively high at the moment they are expected to decrease with future technological developments while the value of orbiting assets may increase. The results of this work help to better understand the debris removal problem and its short and long term consequences.

In future work we aim to move from a one-shot normal-form game to a stochastic or extensive-form game, where the agents can decide on their strategy based on the history of past play. In addition, we will consider a larger set of players, representing e.g. the main space agencies and commercial stakeholders that are currently active.

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