Game theoretic analysis of the space debris removal dilemma

Study reference number: 15-8401
Type of activity: Standard study (25k€)

Project Summary

Objective
Study active space debris removal activities from a strategic, game-theoretical perspective

Target university partner competences
Algorithmic game theory, mechanism design

ACT provided competences
Orbital debris modelling, game theory, multi-agent systems

Keywords
Space debris, dynamic games, algorithmic game theory, mechanism design, CleanSpace

Study Objective

This study aims to analyse space debris removal activities from a strategic, game-theoretical perspective. The objective is three-fold, one, to model debris accumulation and active removal efforts as a dynamic game, two, to determine the optimal time-dependent policies or behaviour assuming both cooperative and self-interested players, and three, to propose a mechanism to steer the dynamics of the game to a desirable outcome. It is expected that such a study will provide a deeper understanding of the space debris problem and its potential (economic) ramifications, and will provide an outlook on potential game-theoretic solution strategies.

Background and Study Motivation

Space debris is defined as non-manoeuvrable, human-made objects orbiting Earth. In some orbits, space debris poses a significant collision risk for an operational spacecraft, especially in low-Earth orbit (LEO). At typical relative velocities of 10km/s, a collision with a piece of space debris of about 10cm in diameter is expected to cause a disintegration of the spacecraft. This breakup causes a large number of fragments and the higher density of debris increases the risk of collision further. The build-up of space debris eventually results in a catastrophic cascade of collisions, also called the *Kessler syndrome*. Currently, there are more than 23,000 objects larger than 5-10cm in Earth orbit (see Figure 1). For further information we refer to [1].

Within the *Clean Space* initiative ESA is investigating active debris removal in addition to mitigation measures to keep the growth of space debris limited. In cooperation with the national space agencies and industry partners, ESA is developing mission concepts to clean up and deorbit space debris. In addition to a number of complex technical challenges, active debris removal is a costly undertaking [6-8].

Due to the risk of a collision cascading, measures taken early on are desirable. As space agencies, as well as commercial players, have an interest to launch more and more satellites over the next decades, the necessity for active removal is growing and at some point will be imminent to secure operational safety for current and future missions. An active debris removal mission will have a positive effect (or risk reduction) for all satellites in the same orbital band. This leads to a *dilemma*: every player has an incentive to delay its actions and wait for others to respond. Each player is faced with the decision between acting now or postponing to take action, i.e., either take an individually costly action of debris removal, which has a positive impact on all players; or wait until others jump in and do the 'dirty' work, as this will be at their own benefit and reduce their own costs. 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'.

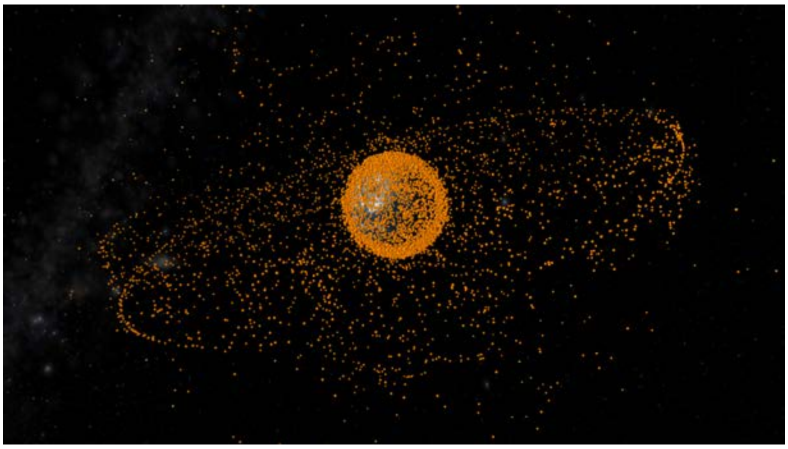

Figure 1: Space debris objects in orbit (Credits: ESA)

Proposed Methodology

Game theory studies strategic interactions where multiple players act rationally in order to maximise their expected payoffs. The origin of modern game theory dates back to the seminal work by von Neumann and Morgenstern (1944). Game theory has since found applications in very diverse fields beyond the initial interest in the economical playing field. This study is aimed to investigate optimal active space debris removal strategies of players in the space sector. The study will cover the following 3 aspects:

Dynamic game

We propose to devise an abstract model in form of a dynamic game. The dynamic game will include the change in debris density on orbits of interest, the risk governed by debris accumulation, as well as the effect and cost of active debris removal efforts. Debris density changes due to launches, end-of-life of a spacecraft, collisions or orbital breakups as well as controlled or uncontrolled de-orbits manoeuvres. The level of abstraction of the dynamic orbital debris model as well as the representation of removal actions needs to be chosen carefully to capture enough detail to allow meaningful conclusion yet not too complex to avoid a computationally intractable problem.

Optimal strategies

The subsequent step is to identify the optimal strategies of rational players in this dynamic game. In particular, it is of interest to study the difference between optimal strategies of self-interested players and an optimal collaborative strategy. Assuming self-interested players, the dynamic game is likely to pose a dilemma (tragedy of the commons), i.e. each player has an interest to delay removal actions until a later point and thus act contrary to the collective interest.

Mechanism design

Mechanism design is also known as 'inverse game theory'. Instead of analysing a specific (given) game one tries to design the structure of a game in a way to influence the players' behaviour. The third part of the study is concerned with the development of a mechanism to steer self-interested players away from the to 'tragedy of the commons' to a more desirable outcome. This can be accomplished by various means, for instance using financial incentives or fines (e.g. taxes). Mechanism design for related games, in particular in the context of dynamic pollution games, has been studied in the past [2,3,4].

ACT Contribution

The project will be conducted in close scientific collaboration with ESA researchers. In particular, ESA researchers will provide technical expertise in modelling orbital debris accumulation, risk assessments as well as access to space debris databases [5].

Bibliography

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