ACTIVITIES OF THE SPACE ADVANCED RESEARCH TEAM AT THE UNIVERSITY OF GLASGOW

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A wide range of technologies and methodologies for space systems engineering are currently being developed at the University of Glasgow. Much of the work is centred on mission analysis and trajectory optimisation, complemented by research activities in autonomous and multi-agent systems. This paper will summarise these activities to provide a broad overview of the current research interests of the Space Advanced Research Team (SpaceART). It will be seen that although much of the work is mission driven and focussed on possible future applications, some activities represent basic research in space systems engineering.

Keywords: Space systems engineering, formation flying, Near Earth Objects, ESMO, trajectory optimisation, attitude control, mission analysis and design

1. INTRODUCTION

Research in space systems engineering at the University of Glasgow is centred in the Department of Aerospace Engineering with collaborations with the Department of Mechanical Engineering and the Department of Electronics and Electrical Engineering. A wide range of research activities is pursued in tight collaboration with industry, government and space agencies. Grant, contract and consultancy work is performed for many customers including, the European Space Agency (ESA), the Engineering and Physical Sciences Research Council (EPSRC), EADS Astrium, Thales-Alenia, QinetiQ, GMV and VEGA. This work involves mission studies, interplanetary trajectory optimisation, autonomy technologies for planetary rovers and spacecraft and guidance and control activities centred on attitude and formation flying.

The Space Advanced Research Team (SpaceART) at the University of Glasgow was set up in 2006 to take care of all these research activities. SpaceART is a team of young scientists and engineers coordinating a group of PhD students dealing with a wide spectrum of research topics. Although most of the activities are on the development of advanced research and cutting-edge technology, SpaceART is actively involved in the design of real space missions currently under development by the European Space Agency.

2. NEO MISSIONS

In the last 50 years astronomers have discovered a vast number of small asteroids orbiting the Sun. A tiny fraction of these objects follow trajectories, which bring them near to the Earth. These Near Earth Objects, which travel at very high speeds relative to Earth, range in size from pebbles to kilometre-sized objects. Such objects have collided with our planet since its formation and have contributed to shaping life on Earth. Near Earth Objects represent a huge risk to human kind, but no near-term means to mitigate the consequences of such impacts currently exists. This threat raises major issues: among them the inadequacy of our current knowledge of the orbits of such bodies, confirmation of hazard after initial observation, disaster management and communication with the public. Another crucial issue, which needs to be addressed, is how to reach a potentially dangerous NEO as quickly and effectively as possible, and how to minimise or indeed remove the threat it poses.

2.1 Deflection Comparison

For the first time in the history there are possibilities for mitigating or removing the risks of Near Earth Objects impacting the Earth. This depends on first improving our ability to detect such objects well in advance and to accurately measure their orbital parameters and physical properties. The only realistic course of action to avoid the devastating consequences of a large object impacting the Earth is to avert the predicted collision. A number of possible mechanisms have been proposed for deflecting or breaking up potentially hazardous Near Earth Objects; most require the use of a spacecraft with some means of transferring energy and momentum to the object. Although the methods of asteroid deflection are at a very primitive stage, they can be classified as impulsive or low thrust. Impulsive methods aim to instantaneously alter the linear momentum of an asteroid through an impact, which may, or may not, be explosive. The main drawback of this approach is that an impact or explosion on or below the surface could risk breaking it into a number of smaller pieces, which would still impact the Earth and potentially do more damage. Any proposal to use nuclear explosives to deflect an asteroid or comet could well also prove politically difficult in a world that is trying to reduce or abandon nuclear weapons. A less drastic approach would be to alter over a substantial length of time, months or even years, the trajectory of the asteroid. Here a wide range of approaches has been suggested. From changing the surface properties of the asteroid and exploiting the Yarkovski effect, to ablating the

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asteroid through lasers or reflected sunlight to orbiting the asteroid with a large spacecraft thus exploiting mutual gravitational attraction. Other low thrust approaches require a spacecraft to land on the asteroid and then deploy as solar sail, or thrusting at regular intervals or excavating asteroid material and ejecting it at high velocities.

An exhaustive comparison of different deflection methodologies, according to a set of different criteria, has been performed [1]. A collection of NEOs, differing for physical characteristics (i.e. size, mass and spin properties) and orbital parameters, was selected for this analysis. Then, a group of different mitigation strategies – nuclear interceptor, kinetic impactor, mass driver, in-situ propulsion, solar mirror and gravity tractor – applied to these asteroids was evaluated in terms of several figures of merit: achieved miss distance at the Earth, warning time, total mass into orbit and technology readiness considered here to be the estimated time to develop the required technology. The result of each deflection strategy for each of these asteroids is represented by a set of Pareto fronts. As an example, we present in Figs. 1-4 the solutions for Apophis. In order to improve the visualization of the Pareto fronts, for each figure an approximating surface has been generated from the scattered set of Pareto optimal solutions.

Despite the physical and orbital differences among the NEOs considered the shape of the Pareto fronts is mostly dependent on the mitigation strategy used. NEO orbital characteristics, size and rotational period play an important role in modelling the surface of the Pareto front, sizing it and changing slightly the inclination and position in the criteria space. All the computed Pareto fronts for all the asteroids have a number of common features. In particular, the linear or quadratic increase of the deviation with m_0 (initial mass), which is directly related to the models used, and the periodicity along the warning time (t_w) axis which, is directly related to the point along the orbit where a variation of the asteroid velocity is most effective.

2.2 Surface Ablation via Solar Collector

One deflection methodology that has achieved good results through the multi-criteria approach presented above is that of using mirrors to direct sunlight onto the surface of the asteroid. This method was first suggested in the 1990s and conceptualised directing solar energy using mirrors onto a small area on the surface of the asteroid. This concentrated heat then sublimates the surface matter creating narrow but expanding jets of gas and dust that produce a low continuous thrust. This low thrust would finally alter the orbit of the NEA by producing a change in velocity, similar to the effect of the 'tail' on a comet. A thermal and gravitational model for the NEO was developed in order to analyse the thrust, and by extension the achievable continuous Δv given the solar power collected and the total thrust time [2]. Two mirror configurations, a single flat mirror and a more complex 3 units (parabolic reflector, collimating

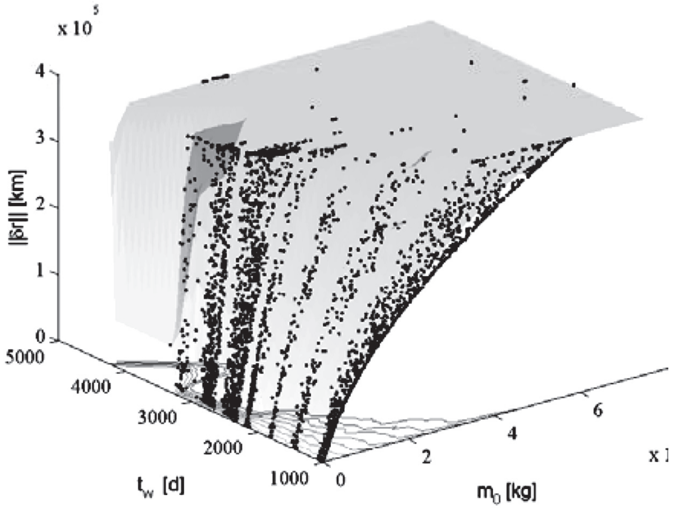

Fig. 1 Nuclear blast Pareto front for Apophis.

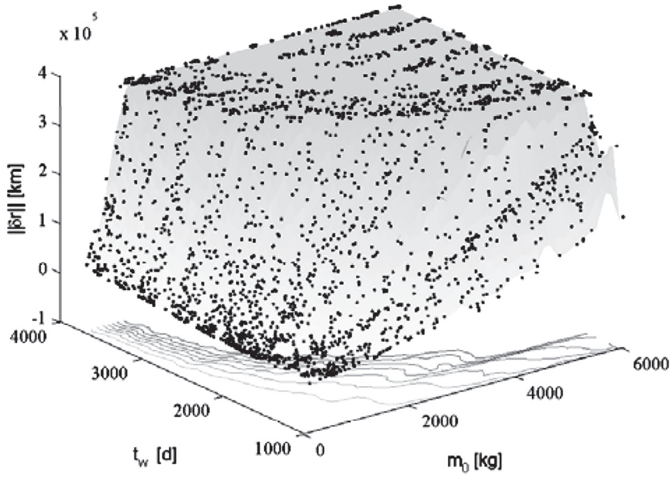

Fig. 3 Solar Collector Pareto front for Apophis.

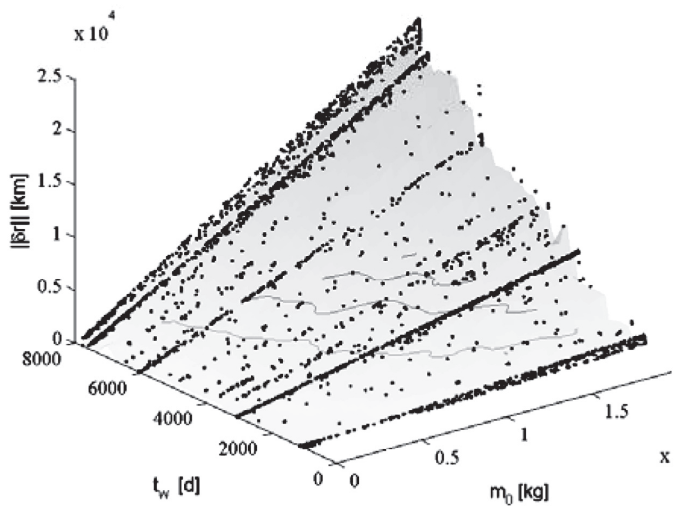

Fig. 2 Kinetic Impactor Pareto front for Apophis.

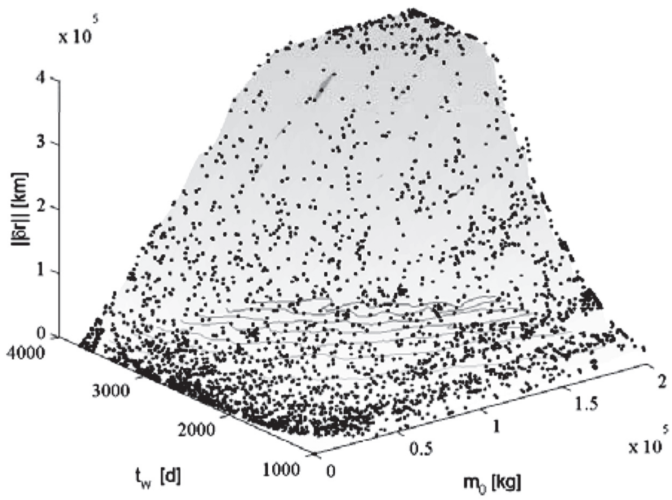

Fig. 4 Mass Driver Pareto front for Apophis.

lens and flat mirror) system have been evaluated, outputting the power density and illuminated area on the asteroid surface. The design of low-fuel, periodic orbits about an asteroid was examined for both single and multiple spacecraft. The cost in terms of propellant and mass for the control of the spacecraft, as well as the transfer cost from each, were examined and compared for a variety of scenarios as shown in Figs. 5-7.

More recently extensive work has been done on the design and control of a spacecraft formation in the vicinity of an asteroid [3]. A first approach exploits the orbital environment by finding the artificial equilibrium points in the Sun-asteroid-spacecraft three body problem. The second approach uses an extension of the proximity-quotient law, originally developed for low-thrust transfers [4].

3. EUROPEAN STUDENT MOON ORBITER

The European Student Moon Orbiter (ESMO) is the third mission within ESA's Education Satellite Programme and builds upon the experience gained with SSETI Express (launched into LEO in 2005) and ESEO (the European Student Earth Orbiter planned for launch into GTO in late 2010). Some 300 students from 29 Universities in 12 countries are participating in the project, which has successfully completed a Phase A Feasibility Study and is proceeding into preliminary design activities in Phase B. The ESMO spacecraft is designed to be launched into Geostationary Transfer Orbit (GTO) as a secondary payload in the 2011/ 2012 timeframe. The mission objectives are to place the spacecraft into a lunar orbit, acquire images of the Moon

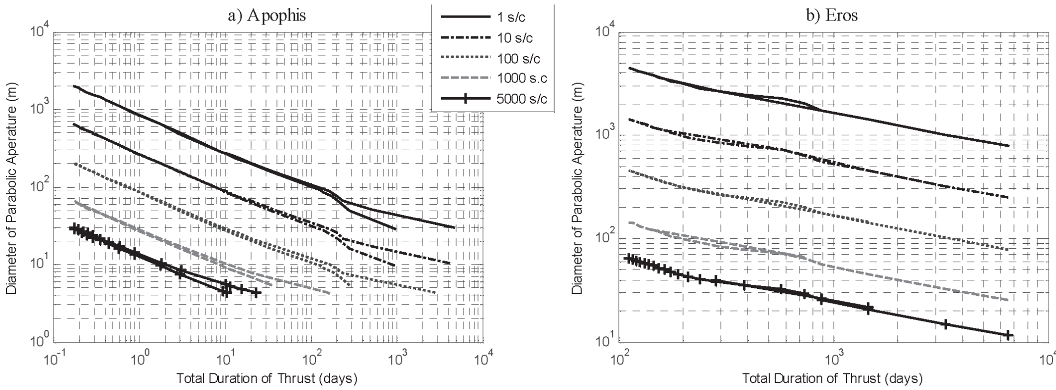

Fig. 5 Comparison of the parabolic aperture diameter for two different spot areas (0.5 m and 1.5 m), with the number of spacecraft and total duration of thrust arc.

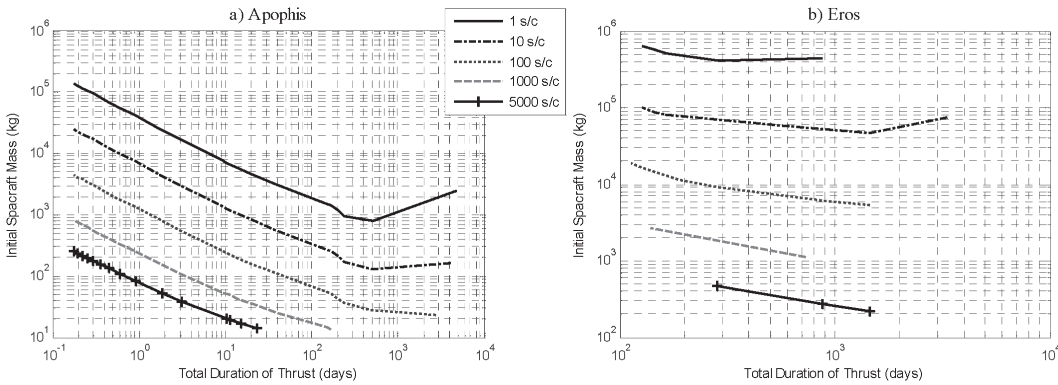

Fig. 6 Comparison of the initial spacecraft mass-in-orbit for an average spot diameter of 1.5 m, with varying number of spacecraft and total duration of thrust arc.

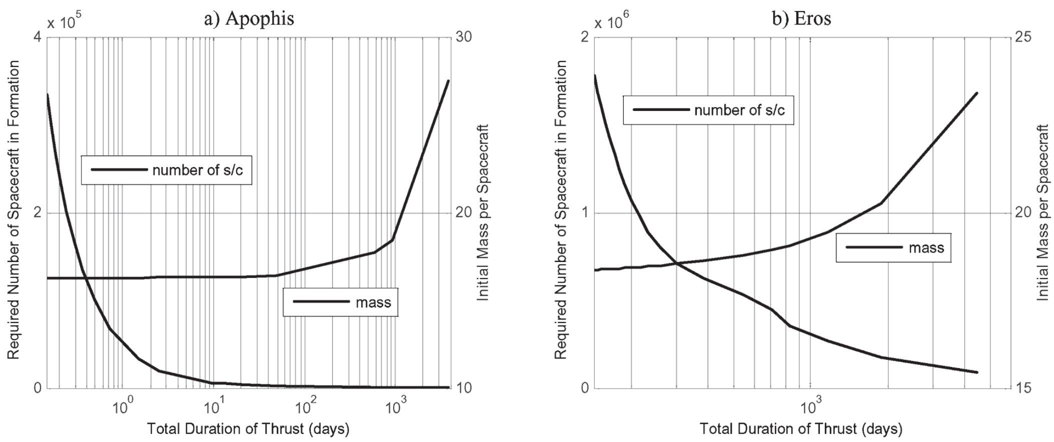

Fig. 7 Comparison of the required number of spacecraft and initial mass-in-orbit for various thrust durations, assuming a mirror diameter of 5.76 m.

from a stable lunar orbit and deploy a small satellite to conduct global, precision lunar gravity field mapping. SpaceART was the primary team for the mission analysis study during Phase A. Two transfer strategies were investigated an Weak Stability Earth-Moon transfer through use of chemical propulsion system and a low thrust Earth-Moon transfer via solar electric propulsion [5-8]. Two different target orbits had to be considered; a 250 x 3600 km altitude polar orbit for the outreach objectives of the mission and a more demanding 100 x 135 km altitude polar orbit for the scientific objectives as shown in Figs. 8-10.

4. INTERPLANETARY TRAJECTORY OPTIMISATION

In recent times there has been a flourishing interest in methods and tools for preliminary mission analysis and design. In particular the key point is the generation of a large number of mission alternative that can serve as first guesses for more detailed and sophisticated analysis. It has been statistically demonstrated that the success of this preliminary phase decreases drastically the development cost, the time from concept to launch and increases the chances of a successful design. In order to be successful, the preliminary analy-

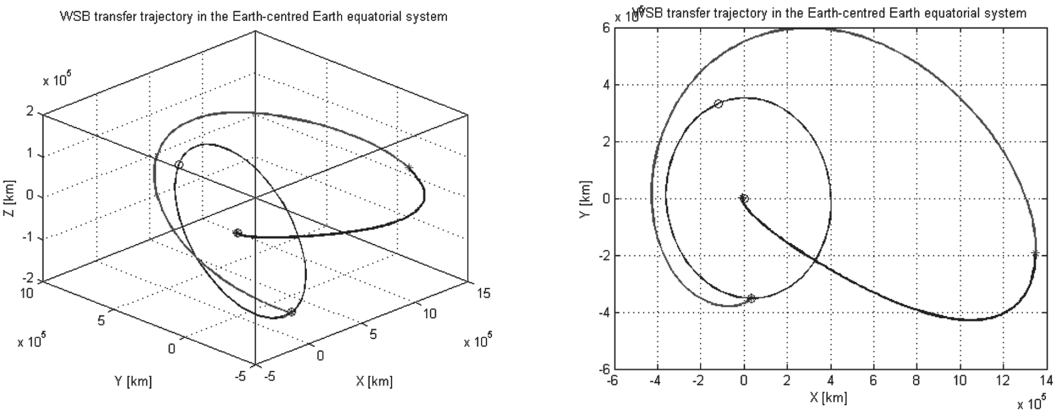

Fig. 8 WSB transfer for outreach mission.

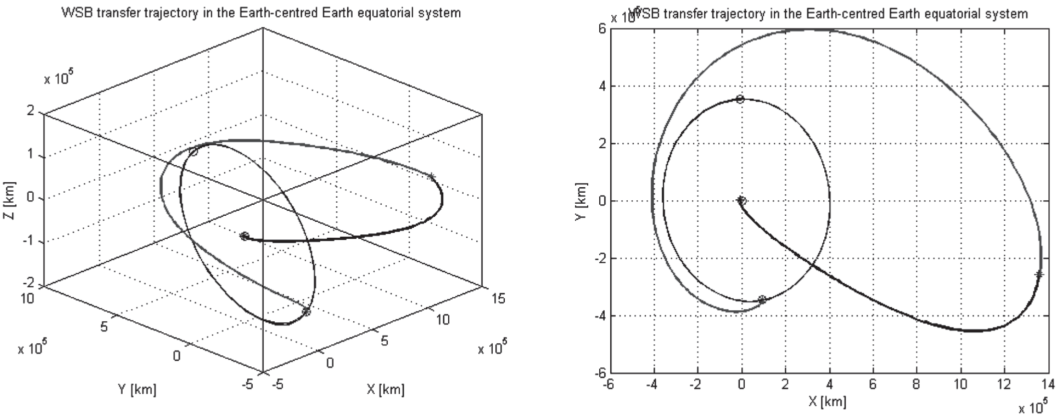

Fig 9 WSB transfer for science mission.

Fig. 10 Low thrust transfer for outreach and science missions.

sis phase has to analyse in a reasonable short time a large number of different mission options. This applies to one of the first steps of mission analysis, which consist of the design of an optimal trajectory. In mathematical terms the problem can be seen as a global optimisation or as a global search for a solution. This search goes along with the definition a mathematical model for the problem under investigation. In general, the preliminary phase requires the definition of a model and the application of a search strategy. Since the difficulty of the search is directly related to the complexity of the model a simplified model is usually desirable. On the other hand an oversimplification, though leading to a very efficient search, produces unreliable results. Depending on the strength of the relation between search method and trajectory model we can classify the approaches for trajectory design in two categories: problem dependent, problem independent. This classification of global approaches is dual to the traditional classification of local approaches, which distinguish between direct and indirect methods. Traditional problem dependent approaches are enumerative methods or branch and prune methods that make use of problem dependent information to prune undesirable portions of the solution space. Problem independent methods are, for example, those that are based on the use of evolutionary algorithms to find a solution to black-box problems. The approach developed here, implemented in a code called EPIC, blends the characteristics of evolutionary algorithms with the systematic search, typical of branching techniques [9-12]. The idea is to use a limited set of possible solutions and evolve them over a limited number of generations – the stochastic step – in certain regions of the search space identified by the branching procedure – the deterministic step. Some trajectories identified with this approach are shown in Figs. 11-14 for missions to Jupiter and to asteroids, and Table 1 for alternative solutions to the Cassini mission to Saturn.

5. ROBUST MISSION DESIGN

In the early phase of the design of a space mission, it is generally desirable to investigate as many feasible alternative solutions as possible. At this particular stage, an insufficient consideration for uncertainty would lead to a wrong decision on the feasibility of the mission. Traditionally a system margin approach is used in order to take into account the inherent uncertainties within the subsystem budgets. The reliability of the mission is then independently computed in parallel. An iteration process between the solution design and the reliability assessment should finally converge to an acceptable solution. By combining modern statistical methods to model

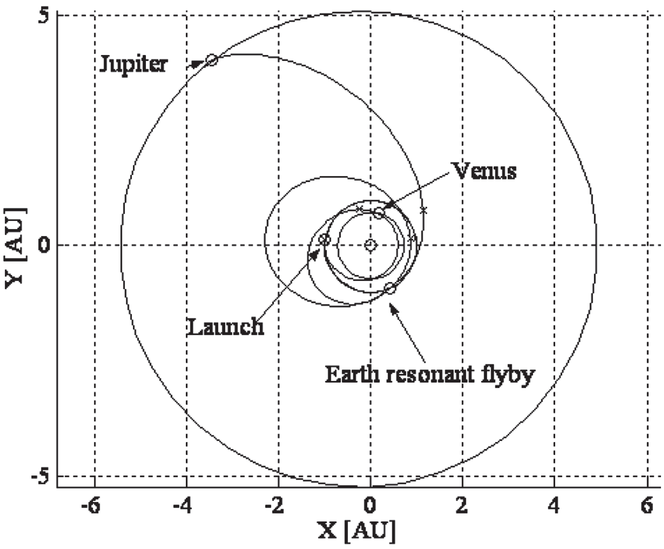

Fig. 11 Solution for a EVEEJ sequence for 2009 launch.

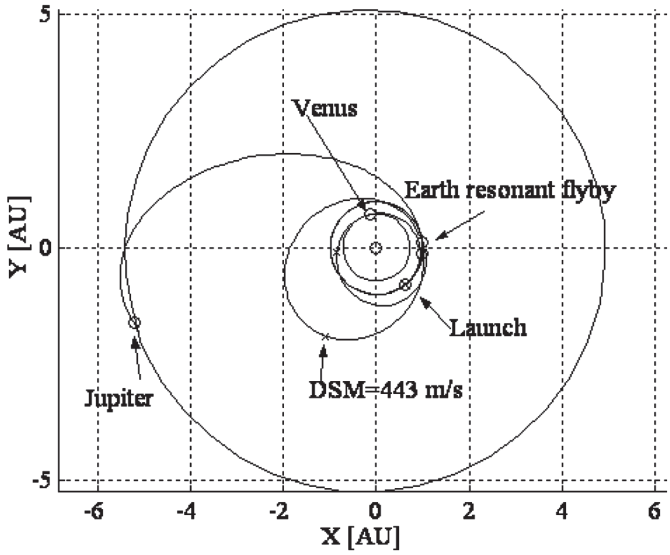

Fig. 12 Solution for a EVEEJ sequence for 2010 launch.

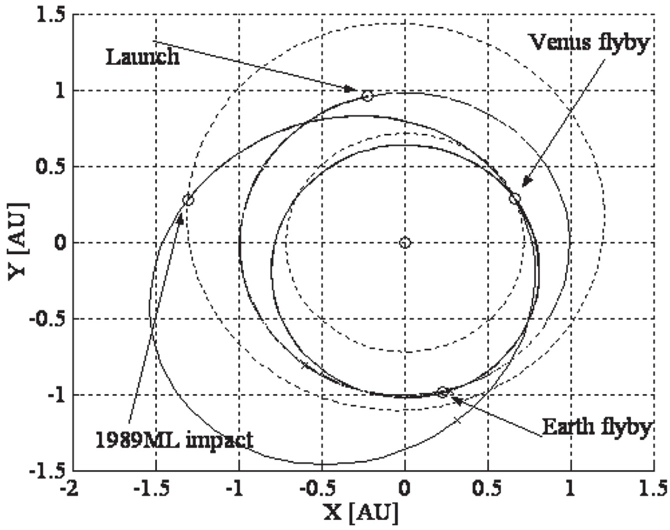

Fig. 13 Projection into the ecliptic plane of an impact trajectory with asteroid 1989ML.

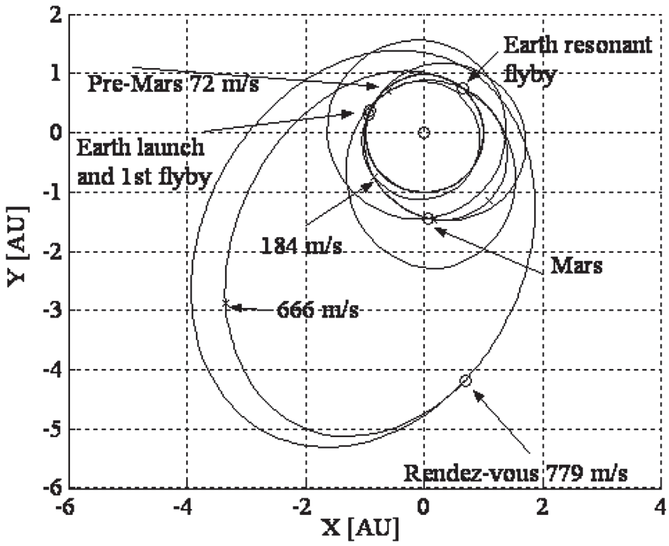

Fig. 14 Projection into the ecliptic plane of an optimal trajectory for the Rosetta mission.

TABLE 1: *Optimal Transfers for the Cassini Mission.*

		CASSINI	EPIC Sol 1	EPIC Sol 2
Launch date		15/10/1997	20/10/1997	17/10/1997
v_0^∞	(km/s)	3.93	4.04	4.03
E-V TOF	(days)	194	191	191
V-V DSM	(km/s)	0.471	0.432	0.414
V-V TOF	(days)	425	421	420
V-E DSM	(km/s)	0	0	0
V-E TOF	(days)	54	53	53
E-J DSM	(km/s)	0	0.132	0
E-J TOF	(days)	499	493	540
J-S DSM	(km/s)	0.376	0	0
J-S TOF	(days)	1267	1216	1656
Total Δv	(km/s)	10.14	10.18	9.06

uncertainties and global search techniques for multidisciplinary design, the current work proposes a way to introduce uncertainties in the mission design problem formulation. Using evidence theory both aleatory and epistemic uncertainties, coming from a poor or incomplete knowledge of the design parameters, can be effectively modelled [13, 14]. The values of uncertain or vague parameters are so expressed by means of intervals with associated probability. Ultimately all the information is collated to yield two cumulative values, belief and plausibility, that express the confidence range in the optimal design point, as shown in Figs. 15-16.

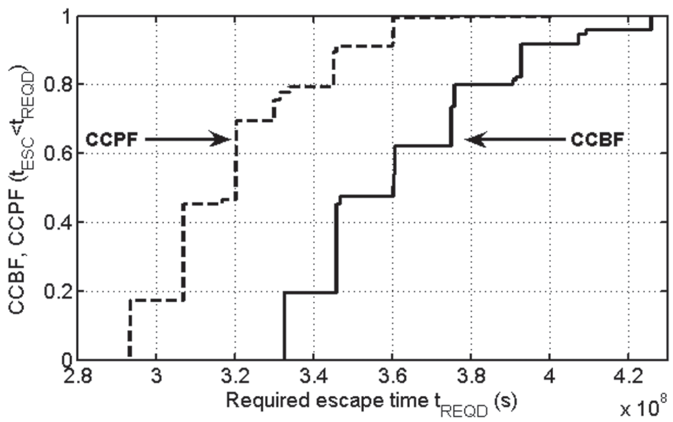

Fig. 15 Complementary cumulative functions for a low thrust escape from GEO.

6. SPACECRAFT ATTITUDE CONTROL

To address and solve the problem of attitude stabilization and tracking we have made extensive use of a control methodology based upon the concept of artificial potential functions. This originates from Lyapunov's Second Theorem but instead of achieving only some desired state for the system it extends the methodology for avoiding any undesired states for the system [15-18]. In this way the Lyapunov function for the system consists of two parts: an attractive component and a repulsive component. One of the drawbacks of this approach is that the required control input may be above the capabilities of the actuators. There is therefore the need to limit the effort imparted by the actuators and avoid any control input saturation as shown in Figs. 17-18.

More recently this approach has been used to derive a gimbal position command to address the singular gimbal states for a cluster of control moment gyroscopes [19].

7. FORMATION FLYING

The coordination and control of a constellation of spacecraft, flying a few meters from one another, dictates several interesting design requirements, including efficient architectures and algorithms for formation acquisition, reorientation and resizing. The spacecraft must perform these transitions without interfering or colliding into each other. Furthermore position keeping is fundamental for formation efficiency. Spacecraft thrusters send gas streams of various species onto spacecraft surfaces. The plume of gas particles emitted by thrusters may cause contamination, degradation or damage to surface and can either directly or indirectly cause localized heating and contamination. Plumes and the resultant impingement phenomena are currently not well understood.

Simple engineering models are used conservatively to estimate plume effects. The problem of plume impingement is a major concern for a cluster of spacecraft with close relative motion. The problem is compounded by the fact that when approaching each other, the spacecraft will have to fire the thrusters towards the incoming satellite to manoeuvre away from it [20, 21]. By implementing an appropriate strategy it is possible to ensure that plume impingement is avoided, as shown in Figs. 19-20.

8. CONCLUSIONS

This paper has presented a broad and top-level overview of the research activities carried out at the University of Glasgow by SpaceART. As can be seen, the topics covered here are wide ranging and encompass a number of different space systems engineering areas and while most of the activities represent fundamental research in the field, some is also focused on future exploitation.

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The students at the University of Glasgow, associated with these activities in space systems engineering, and whose work is presented here are: Imran Ali, Matteo Ceriotti, Camilla Colombo, Nicolas Croisard, Christie Maddock, Daniel Novak, and Joan Pau Sanchez Cuartielles.

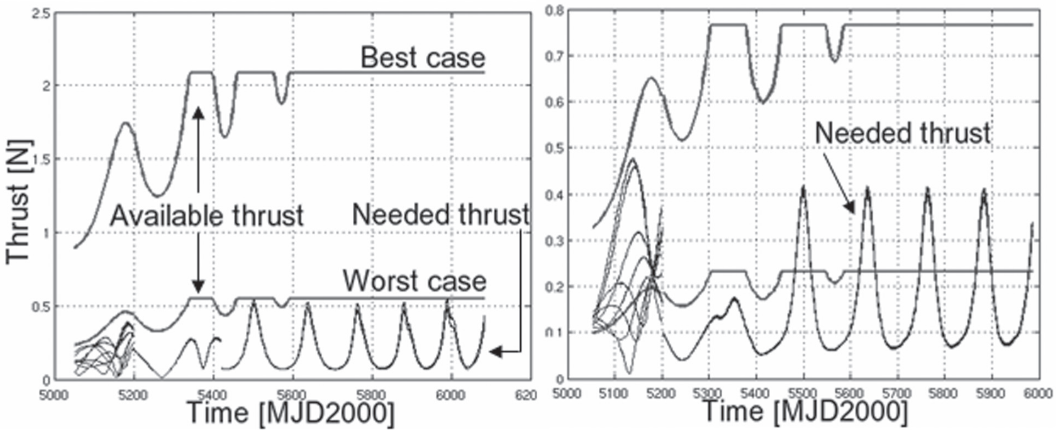

Fig. 16 Comparison between a robust and deterministic solution in the case of an Earth-Venus-Venus-Mercury trajectory.

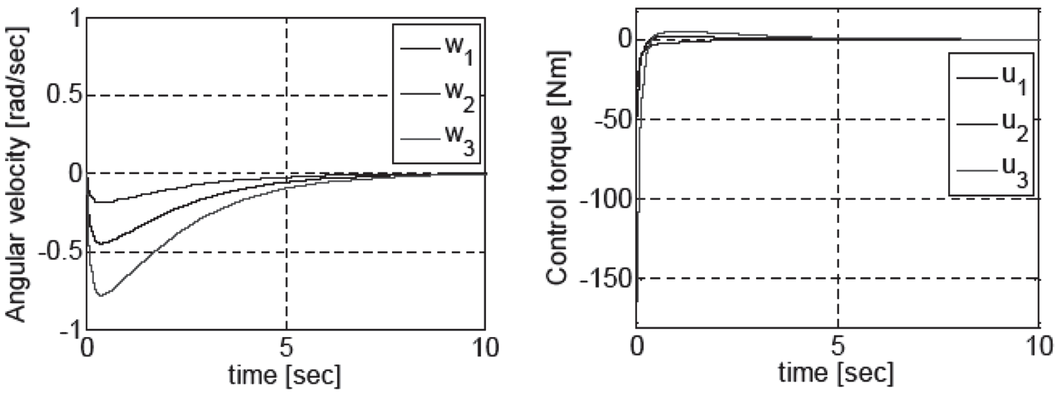

Fig. 17 Unbounded controller.

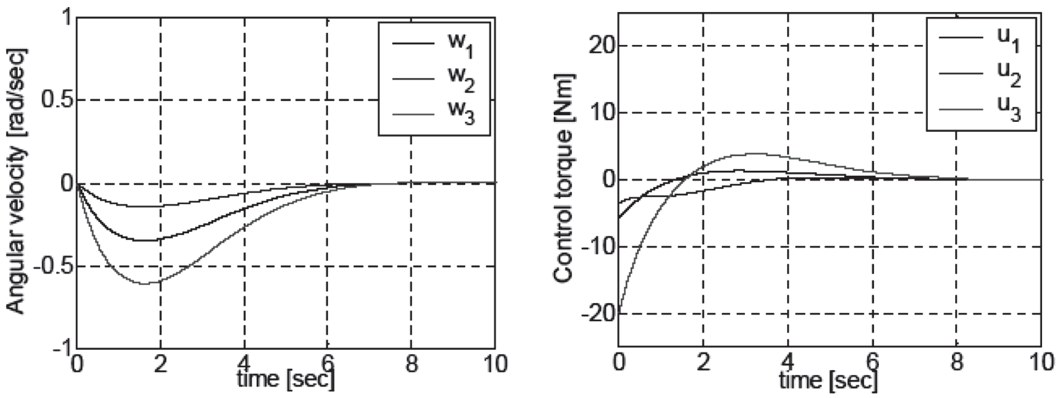

Fig. 18 Bounded controller.

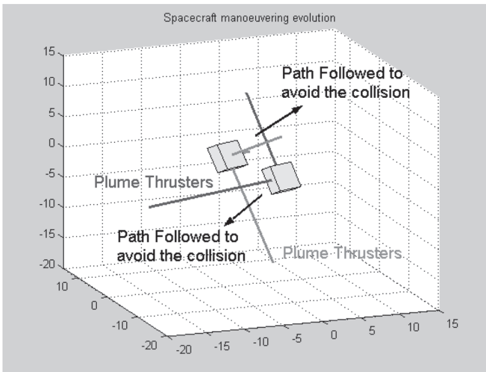

Fig. 19 Plume impingement during deceleration.

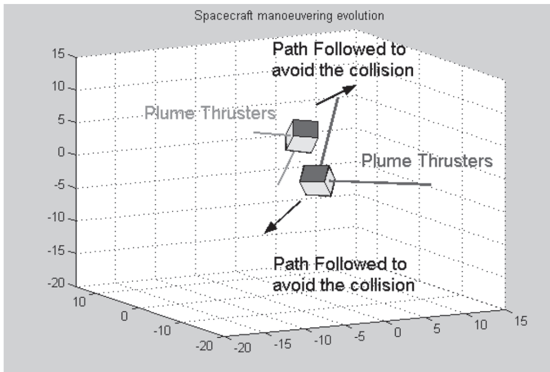

Fig. 20 Plume impingement during avoidance phase.

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