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Space situational awareness – protecting assets in space from orbital debris (a RMIT University perspective on the Space Environment Management CRC)

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Abstract

Services delivered from satellites in the near-Earth space environment are under threat from orbiting space debris from over 50 years of space operations. Computational modelling studies have shown that even under optimistic mitigation scenarios remediation is necessary to curb the growth. In fact, certain regions of the low-Earth orbit are already demonstrating a collisional cascading instability. In these regions, even if mitigation scenarios are assumed and no future launches occur, there is still a growth experienced in the number of debris objects.

This paper introduces the newly established multi-million-dollar Space Environment Management Cooperative Research Centre – an Australian national research centre funded by the Australian Government's Department of Industry. The overall goal of the Centre is to build a cost-effective capability for space debris remediation using photon pressure delivered by ground-based lasers to move debris objects for collision avoidance. The research and development areas set out to achieve the goals are outlined and recent related research progress from the RMIT SPACE Research Centre perspective is reported.

Author (Presenting)

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Prof Kefei Zhang is the founder and director of the Satellite Positioning for Atmosphere, Climate and Environment (SPACE) Research Centre at RMIT University. Prof Zhang has over 25-years research experience in satellite positioning, geodesy and geospatial sciences. His current research interest is primarily involved in algorithm development and innovative applications of GNSS/GPS technologies for high-accuracy positioning, atmospheric studies (e.g. radio occultation, space weather, climate change, weather and environment), space situational awareness (e.g. space debris tracking, surveillance and collision warning, and orbit determination) and people mobility and object tracking. He is a co-inventor on eight patents and has authored over 250 peer-reviewed publications in these fields and has attracted in excess of 20 million dollars in funding from the Australian Research Council, government, research organisations and industry sectors since 1990. He is a finalist of the Australian Innovation Challenge Award 2014. Prof Zhang is the RP2 Program Leader of the SEMCRC.

Keywords: space situational awareness, debris, laser manoeuvre, CRC

Introduction

Modern societies have become highly dependent on services delivered from space. The reliance of the Australian community on space-based services cannot be over emphasised. Satellite communications, navigation and positioning, weather monitoring, remote sensing services for environment protection, agriculture, and mining, are just a few of applications requiring a sustainable and safe space environment.

Orbital debris was recognised as a serious threat to space operations in 1978 by Kessler and Cour-Palais (1978). Since then many modelling studies have ensued which show the instability in some low-Earth orbit (LEO) regions (Liou and Johnson, 2006, Liou and Johnson, 2008, Rossi et al., 2009, Bennett and Sang, 2011), motivating further studies to model the effects of mitigation and remediation scenarios (Braun et al., 2013, Inter-Agency Space Debris Co-ordination Committee, 2013, Liou, 2013, Mason et al., 2011, Phipps, 2014, Stupl et al., 2013, White and Lewis, 2014).

The largest public database of Earth-orbiting objects is provided by United States Space Command (USSPACECOM) using its Space Surveillance Network (SSN). The current USSPACECOM public catalogue contains data concerning 17,000 unclassified objects currently in orbit, including two line elements (TLEs)[1] representing their orbits which are updated regularly and accessible at www.space-track.org.

The 17,000 public catalogue objects are mostly larger than 10 cm in size, with only 7% of these objects being payloads, the rest is debris. It is estimated that 500,000 debris objects between 1cm and 10 cm in size reside in the near-Earth orbit environment, each travelling at ~7km/s and having the potential to cause catastrophic damage in a collision with a spacecraft. A proposed SSN upgrade to improve debris sensitivity will increase the catalogue size to over 100,000 objects. These uncontrolled objects comprise spent rocket bodies, non-operational satellites, tools, and fragments resulting from collisions, fuel ejections, and explosions.

With the collision between the operational Iridium 33 and the defunct Cosmos 2251 in February 2009 (Kelso, 2009), the *Kessler Syndrome* or *collisional cascading* of the space debris is increasingly becoming a reality such that space will eventually become un-usable if nothing is done. For example, the International Space Station (ISS) was forced to perform its 3rd orbital manoeuvre in July for 2014 to avoid a debris fragment which is a clear indicator of the increasing debris threat since the ISS has only performed a total of 19 collision avoidance manoeuvres since 1999 (NASA, 2014). As a result, space situational awareness (SSA) is now a global research and development priority with the aim to stabilise and improve the space environment.

A key part of SSA is space debris surveillance, which generates and delivers orbital information of space objects. This orbit information is fundamentally important to space environment management for conjunction assessments. It is also necessary for future active debris removal methods, for example, dock and capture debris removal techniques.

The international community has sought to address the space debris problem by first protecting operational spacecraft, because these can at least be moved out of harm's way whenever a debris collision in imminent. Space debris orbital data is obtained, principally from US space catalogues, and the data is then used to identify (predict) potential collisions. Accurate orbit information of space objects is fundamentally important to the space environment management efforts now under way internationally.

The Space Environment Management Cooperative Research Centre

Cooperative Research Centres (CRCs) are an Australian Government scientific research program administered by the Department of Industry. The CRC Program was initiated in 1990 to enhance Australia's industrial, commercial and economic growth through the development of sustained, user-driven, cooperative public-private research centres that achieve high levels of commercialisation and technology transfer. The CRC Program targets key industry-focused problems and innovation needs and facilitates close collaboration between industry and academia. It also has a strong education component with a focus on producing graduates with skills relevant to industry needs (Zhang, 2014).

On February 21 2014 the Australian Government announced that the Space Environment Management CRC (SEMCRC) was successful in the 16th round of CRC funding[2]. The SEMCRC, managed by the Space Environment Research Centre (SERC),[3] will build on Australian expertise in measurement, monitoring, analysis and management of space debris to develop new technologies to preserve the space environment. This will have strong social, environmental and economic benefits for Australia, as well as long-term commercial applications for Australian space industry. The CRC will bring together business and research institutions (domestic and international) to mitigate and ultimately remove the risk of space debris collisions.

The current research members of the SEMCRC are:

- RMIT University (AUS);
- EOS Space Systems Pty Ltd (AUS);
- ANU University (AUS);
- Lockheed Martin (US);

[1] http://celestrak.com/columns/v04n03/, CelesTrak, Center for Space Standards & Innovation, accessed 13-Nov-2014.
[2] http://www.minister.industry.gov.au/ministers/macfarlane/media-releases/driving-research-and-delivering-results-australia, Department of Industry, Australian Government, accessed 16-Oct-2014.
[3] Space Environment Research Centre, www.serc.org.au, accessed 22-Oct-2014.

- Optus (AUS);
- National Institute of Information and Communications Technology (JPN).

RMIT University, EOS Space Systems Pty Ltd and ANU University are the three essential partners.

Collisions can be avoided by moving a satellite to safety, provided the debris orbits are accurately known and the satellite is manoeuvrable. The SEMCRC won't develop active debris removal or laser removal (deorbiting) but instead work to curb the growth of the debris population by reducing the number of space environmental catastrophes using lasers for collision avoidance. New technology is required to track 10 times the amount of space debris, for objects 10 times smaller and with 10 times the existing orbit accuracy in the future collision zone (Smith, 2014, Zhang, 2014) .

The SEMCRC was formed because of strong national interests and the need for additional funds to achieve efficiencies from diverse pooled resources. It is expected that the cooperative R&D proposed here will bring significant societal, commercial, technological and credibility benefits to Australia.

Aims and objectives

The SEMCRC objectives relate to the management and protection of the space environment, with particular emphasis on mitigating the damage currently caused by space debris and remediating its future impact on space assets and space services.

Collision risk in space remains at unacceptable levels because of the following key issues:

i. Difficulties in tracking and maintaining orbital information for enough debris objects;
ii. Debris tracking is inaccurate so orbit determinations (ODs) are poor, requiring more frequent re-tracking, adding to the effective tracking burden;
iii. The propagated orbits are inaccurate;
iv. Collision prediction is unreliable and no spacecraft could manoeuvre in response to every potential incident without quickly running out of fuel on orbit;
v. We have no ability to reduce collisions between space debris objects themselves, the primary long-term cause of future proliferation of the space debris field.

Each SEMCRC Research Program (RP) addresses a different aspect of the debris issues and can make a strong contribution in its own right. At the same time the programs are closely inter-related and each will leverage off progress in other programs. To mitigate research risk each program has been designed to initially depend only on current results and momentum in the other programs, while being positioned to take advantage of later advances in them.

The CRC builds on recent progress in debris tracking, orbit determination, and photon pressure technology amongst its participants to address the issues through four RPs:

a) RP1 aims to improve our observational capacity and orbit determination accuracy using new observational technology and techniques;
b) RP2 aims to improve our ability to make rapid orbit determinations and accurately propagate the orbits forward in time;
c) RP3 aims to improve our ability to predict collisions, with better propagation and more targeted tasking of sensors to high risk conjunctions;
d) RP4 aims to create new, non-destructive technologies for prevention of collisions between space debris, to prevent an avalanche of debris generating collisions.

Research roadmap and relationships

The RPs were designed to have strong standalone outputs but also multiple interdependencies. Below each RP is briefly described and the relationship between them is shown in Figure 1.

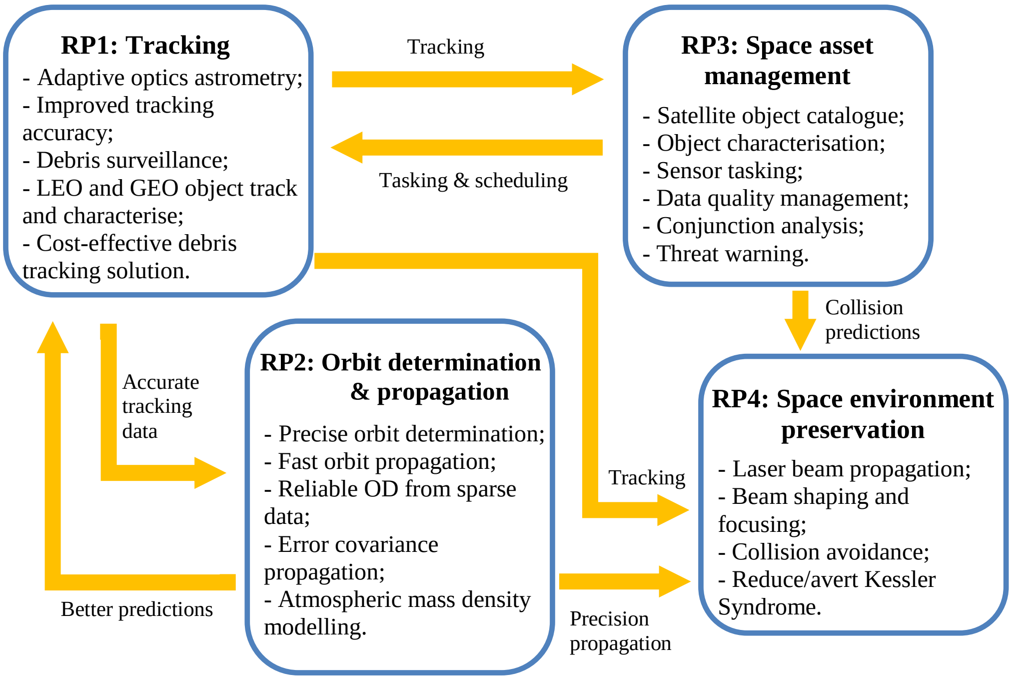

Figure 1: Research program relationships and task summary

Research Program 1 - Tracking, Characterisation and Identification of Space Objects

This research program will develop innovative techniques of active and passive object tracking to provide sufficient accuracy for orbit propagation and conjunction prediction. This research program will investigate and develop non-terminator acquisition and tracking of LEO debris objects, i.e. the laser can fire without the need for the optical camera system. The research will also develop novel techniques to detect and provide precision orbit determination for new (currently un-catalogued) objects. Tracking data and target signatures will be recorded into a new database of orbit and physical information about each object. The database will also allow us to monitor changes in time as objects age, aid identification of a target and correlation with previous or future tracks when tracking data becomes sparse. High resolution imagery using adaptive optics will be used to further develop the characterisation and identification of space objects.

This program will also develop concepts and designs for a high power tracking laser in combination with a high-end adaptive optics system that is able to provide metre level tracking accuracy to Geosynchronous (GEO) objects. An adaptive optics system will be used to reduce the point spread of a passive sensor to the diffraction limit, vastly improving the ability to accurately track the object.

Research Program 2 - Orbit Determination and Predicting Behaviours of Space Objects

To predict future collisions between space objects, accurate orbit predictions (OPs) are required that properly account for the variable space environment, e.g. the Earth's gravity field, atmospheric drag, solar magnetic disturbances and other perturbing forces. The primary objective of RP2 is to develop advanced high precision orbit propagators.

Accurate orbit predictions are a fundamental element required for any remediation technique (such as remote manoeuvre of space debris described in RP4) to stabilise the orbital debris environment. For an object in LEO, determining the atmospheric mass density to a high accuracy is required to estimate the drag effects, and hence improve the prediction capability of the orbit. This RP will work on improving atmospheric mass density models using precise orbit determination. Precise orbital information will be used to improve the accuracy of atmospheric mass density models by analysing the drag-perturbation equation of the semi-major axis of a satellite orbit which relates the rate of change of the semi-major axis to the atmospheric mass density. Models commonly employed to estimate the atmospheric mass density have a reported accuracy estimated at 15%. Recently, improvements have reduced this error to 10%, however, for applications such as unaided debris laser tracking this error should ideally be reduced to ~2%.

The precise orbit determination studies undertaken for satellites will primarily be used to improve the accuracy of atmospheric mass density models to obtain the required increase in accuracy. The satellite studies will ultimately be used in an accuracy assessment to verify the methods described below for reliable orbit determination of debris objects.

The ability to predict conjunctions between orbiting objects requires propagating many object orbits to a high accuracy. Operationally, accurate seven-to-ten day predictions are desirable. Numerical integration of the force model equations, whilst highly accurate, is prohibitively slow in computation time for applications such as debris acquisition scheduling, laser clearing, and collision warning systems. Propagating many orbits using purely analytical approximations is extremely fast, however, lacks the accuracy required for reliability. Semi-analytic satellite theory falls between numerical integration and the analytical approximations with an accuracy approaching that of the numerical solvers and a computational speed approaching that of the purely analytical approximations. Semi-analytic satellite theory involves recasting the governing equations for an object's orbit, separating the effects that occur on a "fast" time scale from those that occur on a "slow" time scale. This technique allows the numerical integration to be performed using a longer time step. This RP will improve the accuracy and reliability of semi-analytic satellite theory, providing fast and accurate orbit predictions for all known objects, hence providing more reliable conjunction assessments.

The reality for most orbital objects is that data is usually sparse. It may also be from different sources, for example, radar, optical and satellite laser ranging. Reliable orbit propagation using sparse observational data is required for debris objects. This RP will develop new algorithms and software to predict an object's orbit using the publicly available TLE data, extending on previous analyses by the authors. Methods will be developed to improve the reliability of predictions from TLEs and applied to conjunction analyses as well as other applications. The improvements in orbit prediction accuracy are necessary for remote laser manoeuvre of space debris detailed in RP4.

To determine the effect that potential remediation methods (RP4) will have on stabilising the orbital debris environment, an evolutionary model will be developed to simulate their effect. The result will be a sophisticated software model for the evolution of the space debris environment.

Research Program 3 - Space Asset Management

This research program will provide a transparent and rational means to make decisions about asset management and how best to optimise assets and preserve the space environment. Techniques, algorithms and databases to predict and avoid potential collisions will be developed. A major focus will be the development of systems that allow multi-national contributions to space object catalogues and a global distribution of asset management.

A core function of the CRC will be to develop a specialised Satellite Object Catalogue (SOC). The SEMCRC has the participants and cooperation of a multi-national sensor network for space object tracking. The SEMCRC will develop techniques, processes, data formats and distribution methods to develop the SOC, leveraging existing catalogues as initial sources of information and including the SEMCRC's precision tracking capability. The catalogue will contain orbital elements, associated covariance matrix of space objects, and characterisation data, such as reflectivity, magnitude, and any manoeuvre history. The semi-analytic orbit propagator developed in RP2 is to be used as the main orbit computation method. Numerical precision orbit propagation and TLE will also be generated for some purposes. The catalogue will be developed, assessed and refined through use within the CRC members' own space operations, and then in the wider space community.

The SEMCRC will develop a conjunction analysis capability system for all objects (all-on-all conjunction analysis) in the SOC and provide alerts to subscribers. The CRC conjunction system will also distribute priority tasking to sensors in the SOC network to provide increased tracking and updating for serious potential collision prospects. The conjunction analysis and sensor tasking feedback loop will be optimised to minimise the risk of a real collision, that is, the more likely the collisions the more intensive the tasking and tracking.

Research Program 4 - Preservation of the Space Environment

This research program will develop leading edge adaptive optics capabilities that allow high intensity laser beams to be propagated through the atmosphere and is an enabling technology for remote manoeuvre. This program draws on the extensive experience in laser development at EOS Space Systems, as well as adaptive optics developed by ANU for the billion-dollar international project The Giant Magellan Telescope. This research program is strengthened by atmospheric physics, ray tracing and simulation modelling expertise contributed in-kind by RMIT University.

This research program will develop high power laser technologies to be used in photon pressure experiments and also develop techniques to combine and phase multiple lasers for increased power, beam shaping and beam control.

The momentum properties of light make it possible to effect small orbit changes to a debris target if a high intensity laser beam can be delivered to the orbital target. Detailed modelling shows that that using a 10 kW continuous wave laser can deliver this momentum change. This program combines the outputs of active tracking, orbit computation and beam propagation through the atmosphere to make small but measurable changes to an orbit. A demonstration of a practical active collision avoidance system using photon pressure is proposed. The demonstration will be undertaken at the EOS Space Research Centre at Mt Stromlo.

For a collision avoidance manoeuvre even a small perturbation is useful as long as it results in reduction of the probability of a collision. A potential debris manoeuvre campaign would entail multiple engagements illuminating the target (or targets) for a time-integrated orbit manoeuvre of small “nudges”. A concept drawing of one of these “nudges” is shown in Figure 2. The manoeuvre needs to be larger than the uncertainties in orbital predictions in order to be confident that the manoeuvre doesn’t cause a collision. The Iridium-Cosmos event had a predicted miss distance of 580 m but the spacecraft still collided. This highlights the uncertainty in conjunction analysis based on the TLE data alone.

The RP4 research plan leads to a proof-of-concept experiment and extensive evaluation of the results for laser manoeuvre, building on earlier work performed for the *LightForce* project (Stupl et al., 2013). The main experiment will use the following approach:

1. A selected debris object is laser-tracked multiple times to allow high-fidelity orbit determination and constrain the errors on orbit prediction. This is also used in a simulation to determine if the photon pressure manoeuvre reduces the probability of collision;
2. The selected debris object is illuminated with a high power laser when it passes over the ground station;
3. The object is laser-tracked to evaluate the change in orbital parameters induced by the laser illumination.

The space debris tracking systems at Mt Stromlo has demonstrated much higher accuracy in orbit measurement and prediction than this measure (Sang and Smith, 2011, Sang and Smith, 2012). The Mt Stromlo tracking system provides precision measurement accuracy in three dimensions (azimuth, elevation, and range) and fitting this high accuracy data in an orbit determination process yields high accuracy predictions.

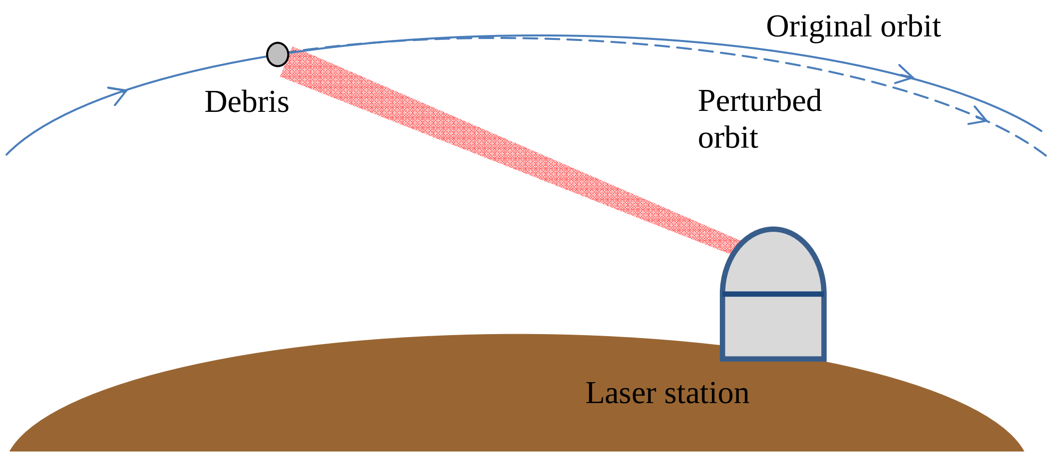

Figure 2: Laser manoeuvre concept using photon pressure

Recent progress on debris orbit prediction and outlook

RMIT University is the leader of RP2. The authors have made significant progress to date on debris orbit prediction which will be built upon and developed as part of the SEMCRC. The following is a summary of some of the work that is applicable to the SEMCRC objectives.

Significant improvements have been obtained in orbit prediction accuracy for satellites using only the publicly available TLE data sets using the TLE-OD/OP method (Bennett et al., 2012, Bennett et al., 2013b). The TLE-OD/OP method fits pseudo-observations generated from multiple TLEs in an OD process using a highly accurate numerical integrator. Recently, the method was tested for debris objects and although it resulted in improved OPs for debris objects overall over SGP4 propagation from a single TLE, the results were less convincing (Bennett et al., 2014b). There are a number possible reasons for the method performing worse for debris, for instance, debris may not be tracked as accurately as the satellites which results in less accurate TLEs. This tracking accuracy aspect is something RP1 aims to address. This inaccuracy could result in erroneous TLE pseudo-observations corrupting the results which would need to be removed in the OD process. Methods to address this will be developed in future work and is important for RP2 and RP3.

Good progress has been made producing reliable OPs from sparse optical and laser tracking data (Sang et al., 2014, Sang and Bennett, 2014) and it has been shown that sufficient accuracy for unaided debris laser ranging (i.e. the laser can fire without the need for an optical track) is achievable (Bennett et al., 2013a). The recent advances are due to a method to estimate the ballistic coefficient of the debris using long-term TLE data (Sang et al., 2013).

More recently, work has been done on investigating the minimum data requirements for reliable OP from sparse very short-arc tracklets where as little as two 5 seconds passes, separated by 24 hours is sufficient when fitting optical and laser observations (Bennett et al., 2014a, Bennett et al., 2014c). The accuracy and minimum data requirements are dependent on the availability of the range observations from the laser system *and* the angles (azimuth and elevation) observations from the optical system. If either of these is not available for an OD fitting then the results are not reliable, indicating the importance of 3-dimensional observational data. Data fusion with TLE pseudo-observations has also been investigated and the weakly-weighted TLEs provide sufficient constraining for an otherwise indeterminate system caused by the lack of observational data (Bennett et al., 2014c). This research is very useful for the catalogue in RP3.

The SEMCRC will benefit from these analyses but also build upon them. A key aspect will be developing a fast orbit propagator for the purpose of accurate conjunction assessments.

Summary and concluding remarks

It is anticipated that the SEMCRC will be formally launched before the end of 2014. The SEMCRC will develop knowledge, methods and capability to preserve the orbital space environment. It builds on long-term collaborations and builds on capabilities developed therein. All the three essential partners were the recipients of the Australian Space Research Program projects and the new collaboration through the SEMCRC presents a great opportunity to further consolidate their respective research strengths and hopefully this new centre will open a chapter in the Australian space research and innovation.

This paper briefly outlined the research programs towards laser manoeuvre. While significant advancements have been made in the individual research areas listed. Further development is needed to realise laser manoeuvre remediation. The SEMCRC is the mechanism to bring together discrete research efforts for mutual gain to deliver an effective mitigation scheme.

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