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An Autonomous Satellite Debris Avoidance System

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Abstract—Since the launch of Sputnik in 1958, thousands of satellites have been launched by governments and commercial entities for a wide range of purposes. Once a satellite has completed its primary mission, most operators de-orbit or move the satellite into a graveyard orbit to avoid collisions with active satellites. However, some spacecraft do not have any residual propellant. Other satellites suffer failures and become hazards themselves. Non-operational satellites in orbit have become an increasing collision risk for operational satellites and this problem will only become worse as the number of satellites launched every year increases. Although finding ways to clean up orbital debris is important, near term solutions is needed to mitigate the risk of debris colliding with an active satellite.

Traditionally, debris avoidance is performed by operators on the ground who calculate debris conjunctions and analyze the risk of moving the satellite. This paper proposes an alternate solution where the process of analyzing and avoiding orbital debris can be done autonomously by the satellite without human intervention. This provides advantages such as reducing the number of operators needed to maintain a satellite or a large constellation of satellites thus reducing operating costs. With the increased amount of processing power on modern satellites, this system is possible with current technology.

The system would first collect a database of two line element’s (TLE) for each piece of orbital debris. The satellite will then perform a conjunction analysis against each piece of debris and the satellites predicted future position. The satellite will re-assess these probabilities at set increments as it gets closer to the conjunction, or when the debris database is updated. The satellite operator will be able to set the collision probability threshold. If this threshold is exceeded, the satellite will calculate the most efficient maneuver based off the required delta v, time to the conjunction and staying in its operational orbit. The system will also attempt to combine any required avoidance burns with a normal orbit maintenance burn to minimize fuel consumption. When an appropriate avoidance burn is being considered, the system will check for debris conjunctions in this new orbit. If there is no danger of a collision, the maneuver will be executed.

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1. INTRODUCTION

Since the launch of Sputnik in 1958, thousands of satellites have been launched by governments and commercial entities for a wide range of purposes. Once a satellite has completed its primary mission, most operators de-orbit or move the satellite into a graveyard orbit to avoid collisions with active satellites. However, some spacecraft don’t have any residual propellant and others suffer failures and are unable to do this. Non-operational satellites in orbit have become an increasing collision risk for operational satellites and this problem will only become worse as the number of satellites launched every year increases.

Currently satellite operators request information about possible collisions from the US Strategic Command (run by the Department of Defense) who tracks all objects orbiting earth larger than 10cm. Satellite operators use this data to determine if their satellite is at risk of being hit by space debris and calculate an avoidance maneuver if necessary. Although much of this process is automated by commercial software, it still requires advanced planning and lots of man hours. As the number of active satellites in orbit grows and satellite constellations get larger, satellite operators will require more people to handle the debris problem. This paper proposes a system that would run on board of the satellite calculating debris conjunctions, determining the risk level and moving the satellite if it is deemed necessary. This paper takes a systems engineering approach to the system meaning this system does not propose any new algorithms meaning the system is agnostic to any current or future conjunction and avoidance algorithms.

2. BACKGROUND

There has been extensive research since the beginning of the space age about the movement of satellites through space and how orbits change over time. There is a research community that maintains and improves the simplified perturbations model 4 (SPG4) which is a software library for calculating the propagation of an orbiting object over time. In more recent years, there has been a lot of new research into determining the risk of satellites colliding with other orbiting objects as the orbital environment gets more crowded. However, this system puts these elements together in a completely new way. The system proposed in this paper takes
all of these elements in order to create a system that allows a satellite to make its own decisions in regards to avoiding collisions with other orbiting objects.

3. System Description

In order for the satellite to avoid debris, it needs a way to know where the debris is. Although the technical aspects of how to detect debris is beyond the scope of this paper, several methods will be proposed using existing or near future technologies. First, a debris list could be created using ground based sensors. The Haystack Auxiliary Radar operated by the Massachusetts Institute of Technology is the primary observatory used by NASA to catalog debris using Ku-band radar. NASA occasionally uses radars at Goldstone and Kwajalein for radar based ground debris tracking. NASA also has several optical telescopes that are used for debris tracking: MCAT which is being constructed on Ascension Island in the Atlantic Ocean, the MODEST telescope in Chile and the NASS spectral telescope on the island of Hawaii. The US Air Force is currently in the process of building a network of ground based radar stations, called the Space Fence. The radars use S-band radio waves to detect debris with initial capabilities online in 2017.

This system will allow for the detection of much smaller objects than any other system and deliver data much faster than existing systems. The Air Force is also in the process of deploying a constellation of satellites place in a near geosynchronous orbit to detect orbital objects. Since this is a military program, high accuracy data may not be available for civilian or commercial use so other approaches may be needed. There is a potential business opportunity for private ground and or space based tracking system and sell the data to satellite operators. A distributed approach to this problem could also be taken. Each satellite that is launched could be equipped with sensors and report the position of objects surrounding it. This data would be combined with similar data sets from other satellites to create a database of orbital objects. This paper does not pick any one method assumes that a database of debris TLE’s is acquired from an external source. A TLE is a set of variables that describe the orbital parameters of an Earth orbiting object at a point in time.

3.1. Filters

Since computing conjunctions is very computationally expensive, several filters are used to remove objects that have an extremely low chance of collision. First a simple apogee/perigee filter is used. This filter will compare the apogee and perigee of each object and compare it with the apogee and perigee of the satellite. If the apogee and perigee are above or below that of the satellite, plus or minus some margin, the object will be skipped. An extension of this method is called the orbit path filter is then run on the remaining objects. This filter computes the shortest distance between the two orbits determining if there is any further risk of collision. This filter improves on the first filter by accounting altitude differences at all points in the orbits.
The final filter is called the time filter. This filter looks at the distance each object will be from each other at the point their orbits cross (plus or minus some margin). If the satellite and the object will not reach this intersection at the same time (given a reasonable margin) the object is skipped. By combining these filters, we eliminate all the objects with no chance on collision and we can then move onto calculating the probability of conjunction with the remaining objects. [1]

This last filter requires that an orbit propagator algorithm (SPG4) be run in order to determine the future position of the objects. This filter works by checking if the satellites are near their closest conjunction points at the same time. This filter will rule out most of the remaining objects in the database even if a large buffer is built in.

How many of these filters are implemented depends on the efficiency of the conjunction analysis algorithm that is chosen. The time filter is already doing a rough estimate of a conjunction so it may be more efficient to skip the time filter and go straight into the conjunction analysis. The time filter could also store the computed position data for the objects which would be used by the conjunction analysis algorithm so it doesn’t need to be computed again.

3.2. Conjunction Analysis

Before we can calculate the probability that a given satellite will collide with a piece of debris, the satellite needs to know its current position in order to calculate its future position. A satellite can use the global position system (GPS) or another positioning system such as the European Galileo or the Russian GLONAS. Using a combination of these systems could provide more accurate and more reliable positioning. Satellite based positioning data could be complemented with an inertial measurement unit or even data from ground based sensors to improve tracking precision.

After the TLE database has been run through the filters, the remaining TLE’s will be put through a conjunction analysis algorithm to determine the likelihood that each element could collide with the satellite.

As this paper is taking a systems engineering approach, the system makes use of existing algorithms to calculate the probability of conjunction. Bernard proposes a method which reduces the probability calculation to a two-dimensional integral. This calculation is only run at the position of estimated closest approach and thus reduces the amount computation necessary to get a collision probability. [2] If the time filter has been performed, the closest approach of the two objects is already known and it is a simple matter of integrating the two values.

A second method proposed by Xu and Xiong calculates the probability of a collision based off of two factors; difference in altitude and difference in time. These two separate probabilities are combined to create one final probability. [3] By performing the time filter before this method means that the system only has to compute the difference in altitude probability.

These two models are just a small sample of the many different collision probability algorithms out there. This is an active area of research and there will be improved algorithms in the future that increase the result certainty. The purpose of
this system is to be algorithm agnostic as to allow for easy integration of new collision analysis algorithms.

### 3.3. Avoidance Maneuver

Once the system has determined the collision probability for all the remaining objects, it looks at each probability and makes a list of the conjunctions that exceed the collision probability threshold. The system then needs to make a decision on how to move the satellite in order to reduce the collision probability below the threshold for each of the objects in the list. The algorithm will consider several additional factors when calculating the optimal avoidance maneuver. Most satellites need to operate in a specific orbit in order to complete their mission. For example a communications satellite only makes money when it is in its operational orbit and a science satellite may need to pass over certain parts of the earth at specific times in order to collect data. This maneuver also needs to avoid creating any high risk conjunctions. This will be determined by running the proposed resulting orbit through the conjunction analysis algorithm to determine if there is a risk of debris conjunctions being created by moving the satellite. The amount of ΔV that will be used to perform the maneuver. ΔV is a measurement of the change in velocity of the satellite in order to move it to a new position. This value can be directly related to the amount of fuel needed to perform the maneuver. Fuel is used to maintain the satellites operational orbit and any time that fuel is used for other purposes, the operational life of the satellite is shortened. Fuel also may be needed to change the attitude of the satellite, this additional fuel cost will be added to the total maneuver. Like the conjunction analysis algorithm, the system is agnostic to avoidance maneuver algorithms. An algorithm such as that proposed by Sánchez-Ortiz, Belló-Mora and Klinkrad would be well suited. This algorithm accommodates many features of this system such as a probability threshold and finding a minimal ΔV maneuver. [6]

Figure 5 above shows how the debris avoidance system would be integrated into a satellite. When the satellite receives a list of TLE’s from the ground, it passes this list off to the debris avoidance system. The debris avoidance system can be run asynchronously from the satellites system as it only talks back to the main system when it has finished. During the collision probability section, the debris avoidance system will request positioning data from the attitude determination and control system (ADCS) to compare against the TLE database. Once the debris avoidance system has finished, it returns parameters for an avoidance maneuver or an all good message. If an avoidance maneuver is required, the satellite will wait until a specified time before the burn needs to start, then send a message to the ADCS to move the satellite into the correct attitude. Once the satellite is in the correct attitude, the computer fires the thrusters for the
designated amount of time. This process will vary between different satellites depending on what type of attitude control and altitude thrusters are on the satellite. The idea is that main computer would receive the maneuver information form the collision avoidance program and decide how to best execute the maneuver given the time constraints. [7]

4. CONCLUSION

Although the debris environment of today is a manageable risk, this problem becomes greater as the debris gets denser and the number of operational and defunct satellites increases. An autonomous system like the one proposed in this paper could reduce the number of operators needed to operate a satellite or a constellation of satellites reducing operating costs. This system has a modular design so that future advances in collision probability and avoidance maneuver algorithms can be accommodated without major system redesign.

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BIography

Michael Hlas is an undergraduate senior-year student at the University of North Dakota majoring in Computer Science and minoring in Space Studies. His interests include space engineering and consumer electronics. He has been a part of the software team for the CubeSat project run by the UND Computer Science department and recently took over as software lead. Michael has experience developing and testing avionics software at Rockwell Collins.

Jeremy Straub conducts research in 3D printing, spacecraft development, autonomy and policy at the University of North Dakota. He has published over 35 journal articles and 120 full conference papers (in addition to numerous other conference, panel and other presentations) on topics ranging from the development and assessment of technology to technology policy and law. As a result of this work, Jeremy has won multiple best paper/poster awards, been included in Marquis Who's Who in the World and Who's Who in America and been inducted into several professional honorific societies including Sigma Xi. Jeremy's work at UND has been featured in numerous media publications, coast-to-coast, including coverage in the Albuquerque Journal, Houston Chronicle, Washington Times, Oklahoman and San Francisco Chronicle. Prior to returning to academia, Jeremy had a successful career in industry where he held progressively responsible positions in software and technology development, technology management and management. He was responsible for the development of North America's first traffic-adaptive navigation solution and his work was featured in numerous media articles in publications including Entrepreneur, Forbes and the Silicon Valley Business Journal.