Summary

Fly Around Orbit and Capture Attitude Control for Space Debris Mitigation

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Abstract

Utilization of spaces for human activities has significantly expanded over the past several decades. Both private and government sectors are actively involved in improving the commercial and scientific value of space. With an increased number of functional objects populating the orbits around earth, the amount of space debris has also accumulated at an alarming rate. This is hazardous for both the current and future space missions because such objects require sudden evasive maneuvers and continuous monitoring Therefore, space debris mitigation has become an important theme in the sphere of space-related research.

Dealing with this issue is not simple because of the multiple stages of work involved in completing a successful implementation of a mitigation mission. One challenge is that target bodies such as debris and malfunctional satellites can have arbitrary rotational motions. The chaser satellite must then travel along a fly around orbit with close-proximity and formation flying. The velocity and position vectors of both objects should align simultaneously for safer docking opportunities. To keep the chaser at a constant distance from the target, the chaser's thrusters must be fired intelligently. Because resources are limited in space, optimizing fuel consumption while achieving control requirements is a challenge. To overcome this issue, a model predictive control (MPC) based algorithm is developed for a target-chaser rendezvous situation to optimize fuel consumption while considering the thruster constraints and memory usage. It is compared with several conventional controllers to evaluate the effectiveness of the algorithm.

Once the target and chaser are locked in fixed relative motion, the chaser satellite can move closer to capture the target using different types of grappling mechanisms. Here, another

challenge that occurs is in the form of ambiguities that arise in inertial properties while capturing objects. To stabilize the attitude of a spacecraft, a typical control algorithm requires accurate inertia measurements. When the spacecraft captures an unknown object, its body configuration and mass change, leading to changes in its dynamics and inertial properties. This can produce tumbling effects and possible deorbiting scenarios due to the sudden shift in momentum. Thus, the control algorithm needs robustness to cope with these ambiguities and parameter variations. To cope with this situation, an intelligent attitude control algorithm is developed for a satellite with partially known inertial properties. By combining inertia estimation with a neural network-based controller, the objectives of control design can be achieved. A comparison was performed with several other control schemes to evaluate the performance using simulation environments for validation.

Another underlying issue when dealing with space crafts in space is the perturbations that arise due to different reasons. One such reason is the perturbations due to fuel slosh. In general, a spacecraft comprises several flexible and rigid bodies. Fuel, in particular, is contained in a separate enclosure and could hold a significant portion of the total mass of the satellite; however, due to microgravity, it can move freely within its limited space. The motion of fuel can cause disturbances in the translational and rotational control of satellites. To overcome this issue, the sloshing dynamics are analyzed, and a control algorithm is developed considering the sliding mode control together with an error minimizing criterion to suppress the fuel slosh and attitude error of the satellite. This is compared with several conventional controllers for performance evaluation using computer simulations.

Keywords:

Space debris mitigation, Model predictive control, Neural-networks, Sliding mode control, Attitude control, Orbit control

Chapter 1. Introduction

Over the past several decades, utilization of spaces for human activities has rapidly increased. With easier access to space, the number of nations and organizations that are active in space has significantly grown. This is largely through joint research work at the International Space Station (ISS), advances in communication networks, and other space related activities. More than 2000 satellites are currently in operation with mega constellations in development, which will congest the remaining areas. However, as more and more objects are populating space, the amount of space related debris has also gradually increased over the years. As of 2021, the US Space Surveillance Network officially categorized more than 21000 space debris in the earth's orbit. This is excluding the small-scale debris which ranges from 1 to 10 cm and pieces that are less difficult to detect and monitor due to size and large number. Most of these are failed satellites, rocket upper stages, space-mission related parts, and fragments left from collisions between satellites and due to explosions. These cause frequent changes to orbital paths of active satellites and risky environments for commercially valuable orbital planes and increase the probability of creating a massive number of smaller debris via collisions. Thus, the risks that these debris pose for the safety of astronauts and space missions cannot be taken lightly. Furthermore, space debris also shortens the lifespans of active satellites as they must be constantly alert for potential impacts and have to perform evasive manoeuvres when needed. Therefore, active removal of space debris has been identified as a vital component in securing safe access to space for the future space related activities as well as for the sustainable development of space for mankind.

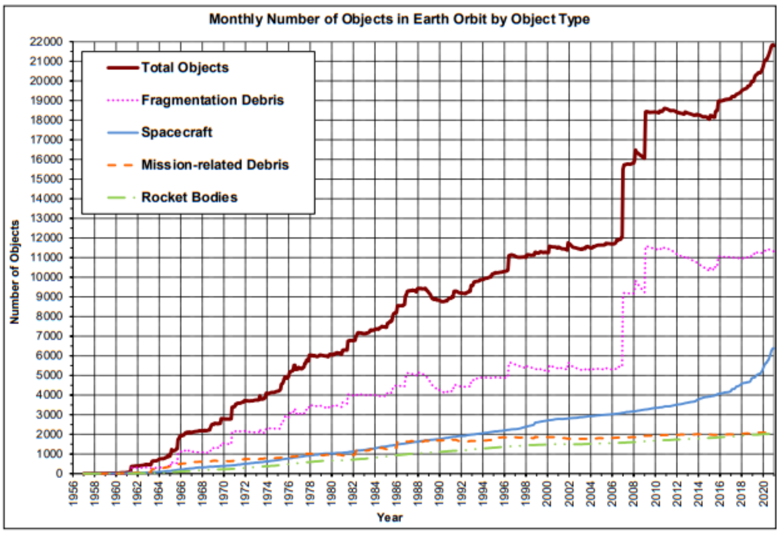

Figure 1 Accumulation of space debris over the years: Courtesy of Space Debris Quarterly News, NASA

The success of space debris mitigation programs depends on collaborative work among state and institutional bodies that govern and oversee the space industry. The primary goals of space debris mitigation can be summarized as follows: minimizing the growth of debris in the future space missions and reducing the space debris currently in orbit. The accumulation of future space debris can be minimized by adopting rigorous regulatory procedures for future space missions. The currently operative satellites can also follow such regulations at the end of their lifespans if the systems on board support such configurations and manoeuvres. The parts that are unable to move on their own, such as difunctional satellites, find it challenging to follow any such schemes. This is where an external mechanism can be applied to capture such objects. This, in particular, has been discussed and researched as a viable solution to regulate the growing amount of space debris. However, it is a process that involves background work both in space and on earth for successful implementation.

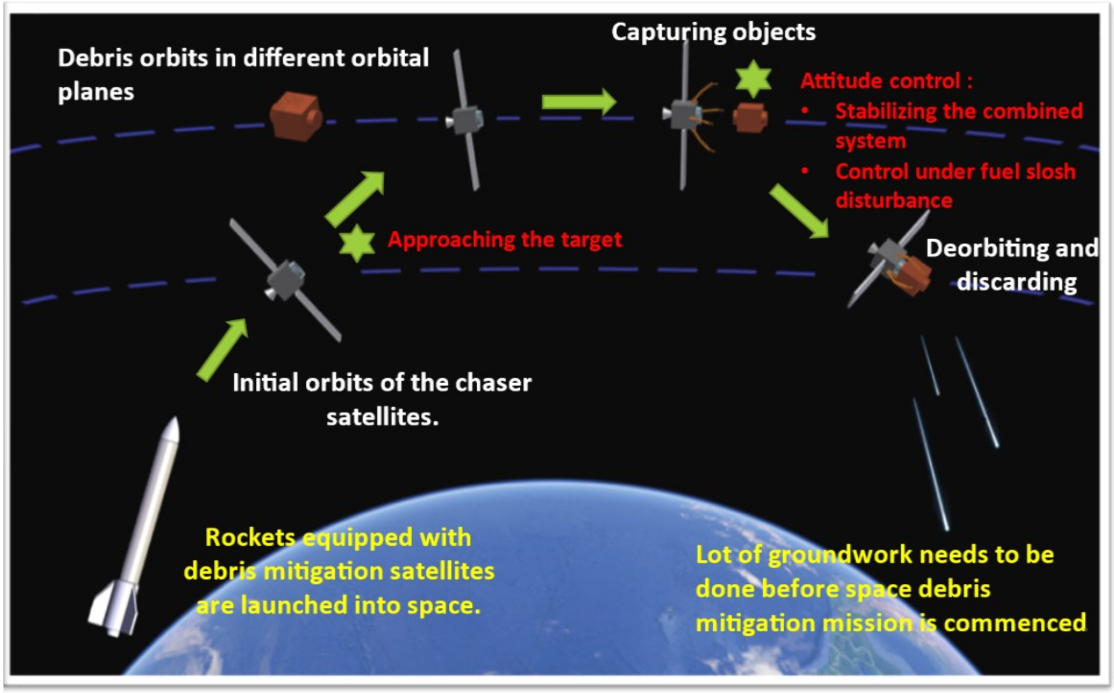

Figure 2 Sequence of the space debris mitigation procedure

As demonstrated in Figure 2, the process of capturing space debris can be stripped down to a few key points for simplicity. The first part is launching of the shuttle equipped with a spacecraft specifically designed to capture space debris. This comes at the end of groundwork that includes identifying the type of debris that is to be captured, research into the required technology and mechanisms, development of such systems and testing. Once all systems are in place, the chaser satellite can be launched into space and deployed to its initial orbit. In parallel, the target debris must be tracked for preliminary studies. Since these debris can be in space for extended periods of time, their physical properties could be different from their original status. For example, in the case of fuel leakages, the inertial properties could unnoticeably change. Apart from this, these debris do not have any internal mechanisms to control themselves and could be orbiting on a plane with arbitrary rotational motions. Once the capturing satellite settles in its initial orbit, a manoeuvre is performed to change its orbit and move the chaser satellite close to the target body. When both objects are in close proximity, their relative motions are aligned and an external mechanism such as robotic arms, tethers, and nets could be used to capture the unknown object. After completing this step, the attitude and orientation of this combined body must be brought to a desired value. Then, the final phase of the removal process can be performed by increasing the orbit of the debris to a graveyard orbit or by decreasing the orbit by reducing the speed and discarding it safely by burning with the help of atmospheric drag.

- Contributions in this dissertation

Developing control algorithms for space systems dealing with the above situations is a complex issue which involves several steps including identifying the target using visuals and other means, approaching the target in an efficient manner, deploying a capturing mechanism, and controlling the combined system after the capturing process to safely deorbit the debris. Considering all these aspects, the author has concentrated on developing controllers that can be utilized for a space debris mitigation program considering both orbit and attitude control scenarios. The first objective focuses on the orbit control aspect. The second and third objectives focus on attitude control considering the two situations in which it can be utilized.

1. Orbit control of a satellite considering a target chaser situation.
2. Attitude control of a satellite when an uncooperative object is attached.
3. Controlling satellites under fuel slosh situations.

1. Orbit control of a satellite considering a target chaser situation.

When capturing an arbitrary object orbiting the earth, it is important to move closer to the object before deploying any grappling mechanism. Generally, these objects do not have any stored energy to control their movement; thus, they can remain in rotational motion about their principal axes. The chaser satellite must assess the distance between the target and chaser itself and the rotational movement of the target before safely connecting with the target itself.

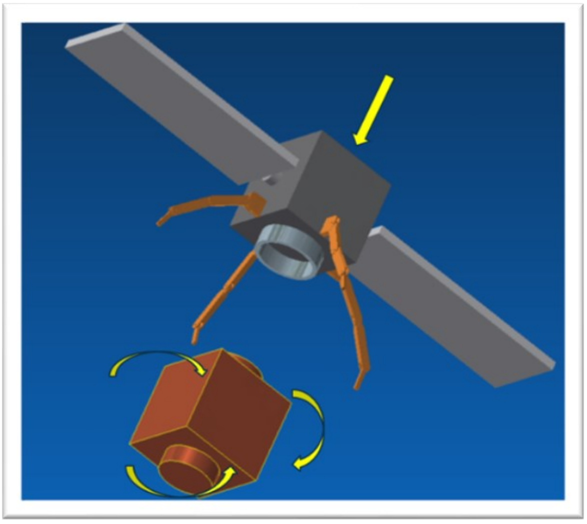

Figure 3 Motion of target and chaser bodies when approaching the capturing process

The first part of this research involved identifying the relative motion between objects in space. After that, an analysis of an model predictive control (MPC)-based algorithm was performed to analyse the orbital rendezvous for a target chaser situation with limitations on controller outputs to minimize fuel consumption. In conventional MPC algorithms, high processing power and memory usages are some of the setbacks when limitations are considered. To overcome these issues, a region-free based algorithm is proposed. With this method, the requirement for on board solvers is removed by performing calculations offline, and then, the memory usage is reduced in comparison to general and explicit MPC-based controllers because only the applicable values are selected for storage. The methodology explains the relative motion between objects in space and the development of several controller designs based on the above method, linear quadratic regulator (LQR)-based methods, and Clohessy-Wiltshire (CW)-based methods for performance comparison.

2. Attitude control of a satellite when an uncooperative object is attached.

The second objective of this research is developing an attitude-control system for a satellite while capturing uncooperative objects in space. The challenge is that it is not possible to entirely know the actual mass and inertial properties of these objects. To cope with the complexities associated with designing such a system, this research concentrates on two key areas explicitly. The initial system is a combination of two separate parts: the chaser and the target. The chaser (assumed to be a satellite) has known inertial properties, and the target's inertial properties are partially known. When the two objects are combined after the capturing procedure, the new system is expected to have known initial velocity and orientation. The first part of the research was to identify the system's inertial matrix. This is performed using the recursive least squares algorithm combined with satellite velocity and acceleration.

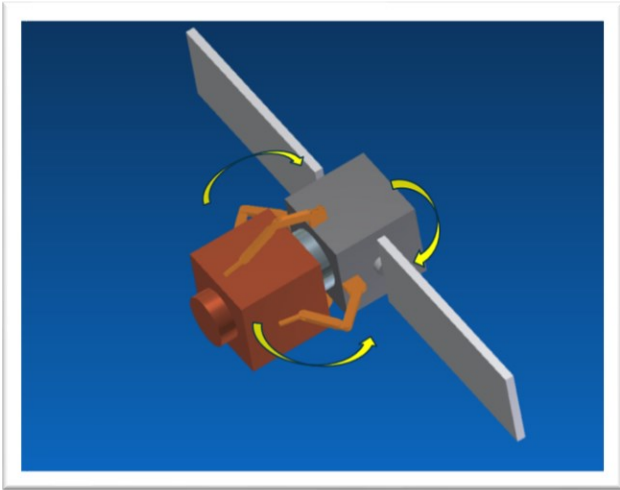

Figure 4 Target and chaser bodies soon after the capture process

The next priority in this research is designing a control algorithm to control the attitude of the combined system. This can range from using simple control schemes derived using state feedback to using optimal nonlinear controllers such as linear quadratic regulators and sliding mode controllers as well as artificial intelligence-based controllers like fuzzy logic controllers and neural network-based controllers. Initially, the derived the equations of motion of a rigid body spacecraft in space based on Euler's method are used to implement a simple proportional derivative (PD)-based controller with a feedback system. Then, a fuzzy based controller is implemented to further improve the performance. After that, an adaptive PD-based controller along with estimated inertia is used to control the system. Finally, a neural network-based adaptive controller is introduced as in improvement over these controllers. Although neural network-based controllers could require a high processing power to complete the calculations, it is assumed that this controller can be strategically utilized for the stabilization process of the combined system soon after the capturing procedure is completed.

3. Controlling satellites under fuel slosh situation.

The third objective of this research is to control the attitude of the satellites under fuel slosh situations. A satellite comprises rigid and flexible components. When the satellite is in transitional or rotational motion, it generates additional forces and moments in these parts. Generally, free moving liquid fuel is stored inside fixed containers inside the satellite. The above-mentioned movements can cause oscillations and arbitrary motion of the liquid. This leads to changes in the centre of mass of the satellite and leads to inaccuracies and disturbances in the stability of the system. Because the satellites can store large amounts of total mass in liquid form to carry out missions in space, the vibrations and disturbances can be considerably large and must be compensated properly when designing the control algorithm.

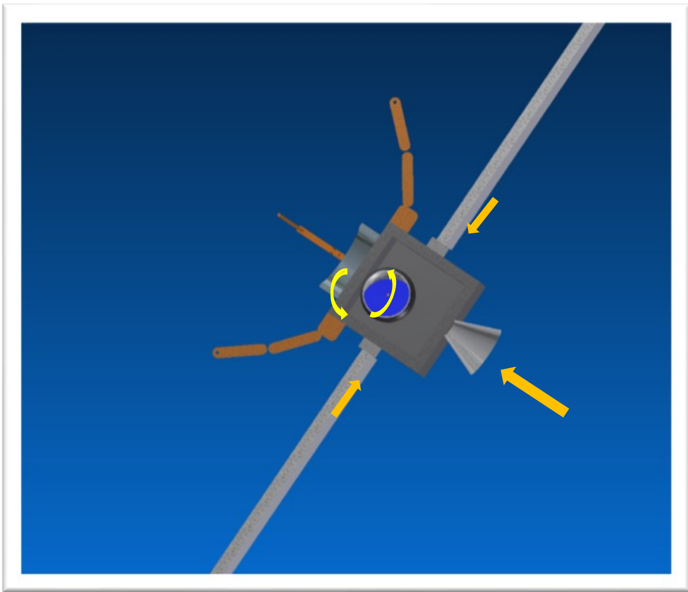

Figure 5 Fuel slosh phenomena as seen when moving on a fixed frame

To solve this, a novel sliding mode control-based algorithm is developed to supress fuel slosh while achieving the control goals. Sliding mode control (SMC) is considered a robust control method with the added advantages of resilience toward disturbances and system uncertainties. However, chattering phenomena form a inherent drawback of this method. By incorporating the proposed SMC, this issue can be solved in the control design phase. Furthermore, with the addition of optimal control concepts, which is a systematic approach to solve the required performance criteria, this approach is further expanded. The optimization process is performed offline, thereby reducing the computational requirements for the onboard controllers. The performance analysis is performed using computer-based simulations, and the results are compared with those of conventional controllers in the form of conventional SMC and PID control to verify the effectiveness of the proposed algorithm.

Chapter 2. MPC-based orbit controller design for the fly-around scenario considering fuel optimization

The chapter is structured as follows. Introduction conveys the broad overview of this research theme. With the methodology, the controller design based on MPC and other control schemes are discussed. Next, the simulation results pertaining to the derived control algorithms and dynamic equations are provided. A summary of the work is mentioned at the end.

- Background

General idea about causes of space debris is discussed. The involvement of public and private organizations around the world on seeking solutions are elaborated. The problems associated with constraints and manoeuvring of a target-chaser scenario is discussed with prior work. A new method is proposed to solve some of the issues connected to fly-around scenario considering fuel optimization and error tracking.

- Methodology

Initially the relative motion between two objects in space is discussed. The relevant equations of motion are then derived using the Clohessy Wiltshire (CW) method. It is then modelled in state-space representation for the ease of usage in simulations.

Next part is based on controller design considering different methodologies. A model predictive control (MPC) based controller is considered at first due to its advantages in solving optimization problems considering constraints. Here the relevant equations are derived and calculated. The problem associated with conventional MPC in online implementation is discussed. A solution is given by extending the current controller using algorithms based on Karush-Kuhn-Tucker (KKT) and region free method. This is to reduce computational requirements and memory storage requirements for online implementation.

After that, a linear quadratic regulator (LQR) based optimal controller is designed considering constraints. This is to give a solution based on optimal control under limitation to show the shortcomings.

Then a CW based conventional controller is also developed for performance comparison due to its classical usage and ease of implementation. It also reveals the inadequacy of the classical method when dealing with fuel optimization and error tracking.

To imitate the propulsion systems which have limitations in the activation procedure, a static quantizer is designed to simulate limitations on a thruster system with applicable equations.

- Simulation

For the fly-around simulation, only the X–Y plane is considered. Simulation is performed for a period of 1000 s for each control scheme, to follow a circular orbit around a target point while orbiting the earth. The graphical data expresses the outputs generated by the satellite model on each occasion with respect to the changes in fly-around radius, angular velocity and generated control inputs in each X-Y directions. This is followed by the qualitative representation of the calculated root mean square error (RMSE) values pertaining to fly-around radius and angular velocities. The control input requirement for the total simulation time is also calculated for each control method. This is followed by a comparison between the memory requirements for conventional Explicit MPC and the proposed method with different parameter values.

- Summary

The chapter concludes with explaining the problem associated with the fly-around scenario and the proposed methods applicability and performance increment compared with the conventional methods.

Chapter 3. Neural networks based adaptive attitude controller design for a satellite with partial known inertial properties

The structure of this chapter is as follows. Background explains the overview of this chapter. Methodology explains the development of different controllers to solve the problem at hand. In simulation, the results related to the above algorithms are given. This is followed by a summary of the contributions of this research.

- Background

An introduction is given about the problems that can arise when trying to capture space debris. The problem associated with inertia variation is then discussed with previous research work. To cope with the complexities of designing such a system, a solution is given with a concentration on two areas: inertia estimation and controller design. This is further explained with prior work dealing with each area separately.

- Methodology

Initially the dynamical model of a satellite is considered, and a regression model based on linear least squares is used to estimate the unknown inertia of the combined system. Here, the equations and models related to inertia estimation is derived and developed. Then, several types of controllers are introduced to stabilize the system after the inertia is being estimated.

First controller is based on proportion and derivative (PD) control. This is due to the simplicity of implementation of such kind of control mechanisms.

Then a Fuzzy based controller is designed which has the advantages with its usage of human expertise and intuition to design control algorithms without a proper knowledge of the dynamical model of a system. Two fuzzy models are used considering the variations in quaternions and angular velocities of the system with separate membership functions and rule tables.

After that an inertia-based controller is developed based on the estimated inertia along with proportional and derivative gains. This works as a pseudo adaptive controller to stabilize the system.

Finally, a neural network-based adaptive controller is developed with two identical neural networks for the quaternion errors and angular velocity errors to adaptively change the parameter gains. The neural network comprises a three-layer neuron perceptron and uses gradient descent method with the backpropagation algorithm to minimize the error function and update the weights corresponding to adaptive parameter gains. The advantages it has over the previous algorithms are discussed.

- Simulation

To compare performance, two sets of situations are analyzed using computer simulations based on MATLAB/SIMULINK. In the first set, each controller is simulated corresponding to the instant when the inertia variation is assumed to be at the maximum attainable value with the given initial angular velocities and attitude angles.

In the second set, an unknown inertia is added to the system. With the linear squares method, the inertia of the combined system is estimated by applying small constant torques for each axis for a total of 500 s. The estimated inertia is then sent to the dynamical equation of the satellite plant along with the updated angular velocities and attitude angles. The output behavior is then simulated with each controller for 500 s. This is conducted for 50 different occasions while varying the unknown inertia added to the system.

The graphical and qualitative results corresponding to the above algorithms are illustrated and compared. To compare performance, root mean square error (RMSE) values of quaternion errors angles, angular velocity errors, required torques and settling times are calculated for each of the controllers.

- Summary

In summary the problem associated with inertia is described along with the proposed solution. It is further extended by explaining the performance increment the proposed method has over the other controllers discussed in this chapter.

Chapter 4. Novel sliding mode control-based controller design for a satellite with liquid fuel slosh disturbances

The chapter is arranged as follows. Background gives an overview of the problem associated with this research theme. The methodology explains the mathematical model of the system and controller design. The results section summarizes the performance with simulations and data analysis of several controllers. This is followed by the conclusions drawn from this research.

- Background

Another aspect of controlling satellites in space is discussed in the form of disturbances due to fuel motion. The literature work linked to controlling satellites under disturbances is explained. A novel method is proposed to solve this issue in comparison with past work.

- Methodology

For simplicity only the motion of a satellite in a fixed frame is considered for the derivation of the mathematical model. The dynamical equations are derived considering the rigid satellite and the free-floating fuel mass inside the container using Kirchhoff's and Lagrange modelling.

After that, algorithm development is discussed. A conventional sliding mode controller (SMC) is designed with the combination of equivalent control and switching control components to show robustness. This is followed by the development of a novel sliding mode controllers with parameter optimization using particle swarm optimization technique (PSO) to increase the robustness while reducing control input requirements.

Finally, a proportional-integral-derivative (PID) controller is also derived to illustrate the classical method of satellite control.

- Simulation

Computer simulation is carried out using MATLAB/SIMULINK to compare the performance. Simulation is conducted considering 3 distinct situations associated with fuel mass. Graphical representations are given considering the changes in attitude angles, rate of change of attitude angles, slosh angles, rate of change of slosh angles and controller inputs. For qualitative analysis, the root mean square error (RMSE) values corresponding to the above situations are calculated along with settling times.

- Summary

In summary the problem associated with fuel motion disturbances in acknowledged. The performance increment associated with the proposed method over the conventional methods is then described.

Chapter 5. Discussions and Conclusions

• Discussion

The discussion is span over three points pertaining to the three chapters discussed above. It also includes the possible expansions on further research using these research topics as a guideline.

1. Discussion on MPC

The usage of MPC on 2-dimensional and 3-dimensional planes are discussed with relevant advantages and disadvantages. The problems related to different parameter usages are then discussed considering the current method and potential developments. Improvements to algorithm to increase the efficiency is also discussed considering implementation and limitation restrictions.

2. Discussion on Neural based Adaptive Controller Design

The advantages and disadvantages of this type of a framework design is discussed with other potential usages. The importance of identifying specific implementation scenarios is discussed for these types of algorithms. The cost of online implementation is also addressed with future technology development.

3. Discussion on Sliding Mode Controller Design

The application of these types of controllers for 2-dimentional and 3-dimensional systems are described along with their advantages and disadvantages. The importance of system design with practical models and parts are discussed to improve the performance. The evaluation method and the need for a thorough analysis based on theoretical aspect is highlighted to further improve this algorithm.

- ## Conclusion

As increasingly more debris clogs the valuable orbital space areas, it is a timely requirement to seek methods to actively remove space debris for the safety of future space missions. This process requires extensive research into many different fields. Analyzing such processes is both rigorous and time consuming. This dissertation is a small attempt to explore some of the issues space debris mitigation satellites face in space while performing orbital and attitude maneuvers. In the first chapter, an introduction is given regarding the bases this dissertation is going to cover. In the second chapter, an MPC based control algorithm is developed for a fly-around orbit control situation between a target and a chaser satellite to realize fuel optimization while considering limitations in the storage capabilities of satellites. In the next chapter, the development of an adaptive neural network-based control algorithm for an attitude control system while capturing objects with partially known inertial properties is detailed. In the final chapter, the sloshing situation is analysed while controlling a satellite in space and a SMC based control algorithm is developed to compensate for such situations. For all these situations, computer-based simulations have been conducted to compare the performance with those of several other conventional controllers to validate the developed control algorithms.

Publication List

Papers that constitute the dissertation.

(1) Model Predictive Control-based Control Algorithm for a Target-Chaser Maneuvering Situation
Amila Sri Madhushanka Gilimalage, Shinichi Kimura
Advanced Robotics (2021), 35:21-22, 1265-1276
DOI:10.1080/01691864.2021.1955002

(2) Development of a Mode-Predictive-Control-based Algorithm for a Target-Chaser Rendezvous Maneuvering Scenario
Amila Sri Madhushanka Gilimalage, Shinichi Kimura
The International Symposium on Artificial Intelligence, Robotics and Automation in Space 2020, 5018（i-SAIRAS 2020）

(3) Attitude Control Algorithm for Satellites with Partially Known Inertial Properties
Amila Sri Madhushanka Gilimalage, Shinichi Kimura, Manukid Parnichkun
Proceedings of the 71st International Astronautical Congress (IAC 2020)

(4) Development of a Novel Sliding Mode based Control Algorithm for a Satellite with Sloshing Dynamics
Amila Sri Madhushanka Gilimalage, Shinichi Kimura
(Accepted and in press) 33rd International Symposium on Space Technology and Science (ISTS 2022)