Controller Design for an Expert Spacecraft Robot Performing Proximity Operations

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Abstract—*Due to the recent economic potential seen in on-orbit servicing, there has been a growing interest in spacecraft rendezvous and capture. It may now be economically advantageous to repair or refuel a satellite or vehicle in space rather than abandoning it or replacing it altogether. To achieve such a task, this paper proposes a design for an Expert Spacecraft Robot (ESR) that will have a docking mechanism attached to it via an Active Compliant Mechanism Interface (ACMI). The ESR uses two different controllers for its proximity operations with its target: one to navigate the ESR to within 1 meter of the target, another to guide the ESR in aligning the docking mechanisms prior to commencing final docking operations. During the approach, a Linear Quadratic Regulator (LQR) controller is used. The proximity operations of the ESR with its target are simulated in a variety of scenarios while orbiting 300 km over the earth's surface. The scenarios test the ESR's ability to approach the target from different directions and distances. Since all scenarios are in space, the dynamic model for the ESR and its target includes the appropriate orbital dynamics.*

I. INTRODUCTION

Space research today can be divided into two areas, planetary surface exploration and in-space operations. For in-space operations research, the technology readiness level is lower than the level for planetary surface exploration. In the last decade, a need for on-orbit capturing and servicing has also grown. In addition, during the development of the spacecrafts there has been a growing interest for spacecraft rendezvous and docking. Therefore, instead of abandoning a spacecraft that runs out of fuel, one may want to have the possibility of refueling. Other service tasks are refurbishing, re-supply, repair and, in the worst case, towing. Automating these tasks will further save mission time and decrease the operational cost. Thus, to make the spacecrafts long-lived in the severe environment, autonomous docking is necessary as well as critical. Since rendezvous and docking is a topical area there are similar projects, recently completed or ongoing, in the world.[1-6]

The Russian Kurs Rendezvous System is the first rendezvous system that implemented autonomous rendezvous and docking. This system is today in use to dock the manned Soyuz and unmanned re-supply ships with the ISS. The system is supplied with information from an antenna and can be interrupted at any time if a human needs to interfere and correct errors. Another successful docking system is the Japanese Engineering Test Satellite (ETS-VII), which was the first space program that succeeded in demonstrating automatic rendezvous and docking in 1998.[7-11] The most recent attempt to demonstrate autonomous rendezvous in space was the Demonstration for Autonomous Rendezvous Technology (DART). This demonstration has many similarities to research presented in this paper. It uses an Advanced Video Guidance Sensor (AVGS) system for navigation and control. The DART vehicle is unique in that no human will board the spaceship and all maneuvering is autonomously produced, planned and calculated. This NASA mission serves as a reference model to this paper. Another project under development is the Orbital Express Advanced Technology Demonstration Program. This is a program that will develop and demonstrate autonomous on-orbit refueling and reconstruction of a satellite. This project is planning to launch its satellite in 2006, funded by Defense Advanced Research Projects Agency (DARPA).[12] Other researchers have proposed a fly-by approach utilizing the orbital mechanics to ensure a fail safe mode where the chaser just passes by the target without any collision should the docking for any reason fail.[10]

The work of the University of Florida's Autonomous and Multi-Agent Systems (AMAS) Group represents a new space robotics paradigm which utilizes Expert

Spacecraft Robots (ESR) to perform advanced in-space operations. The umbrella project consists of the development of Heterogeneous Expert Robots for On-Orbit Servicing (HEROS) as the solution to the need for fully autonomous on-orbit servicing. The “expertise” of the ESR arises from the various classes of capabilities, e.g. rendezvous and capture, structural assembly, removal and installation of orbital replacement units, extra vehicular activity, and assists. Figure 1 shows typical scenarios with several ESRs working together. This paper addresses the initial research challenges of the proximity operations for the HEROS project. That is, the focus is on the development of a controller for the approach maneuvering of one ESR with its target (e.g., a satellite in need of service, Figure 1(b)).

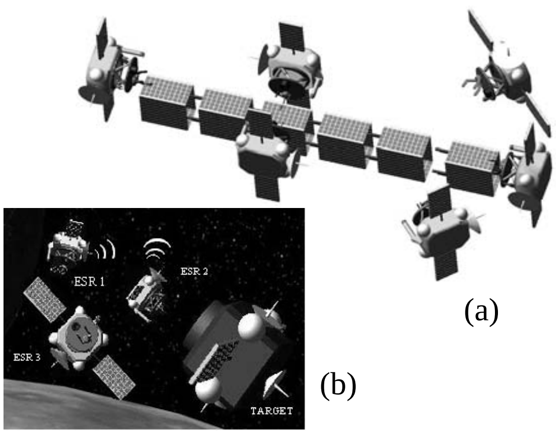

Figure 1: Typical scenarios: (a) ESR’s working together performing assembly of a space structure and (b) rendezvous and capture

II. PROBLEM DEFINITION

The problem to be addressed is the rendezvous and docking between two satellites in space. The satellite approaching is an expert spacecraft robot (ESR) and designed to endure the severe environment of space. The ESR is equipped with capture modules for the docking mechanism, a camera for video guidance and an Active Compliant Mechanism Interface (ACMI) for the fine motion control of the docking. The top platform of the ACMI is equipped with either a docking pin lock device(s) and/or a robotic grappler with which to capture the target. In general, the target satellite may or may not have fully functional docking devices such as docking pins or docking rings nor have attitude control depending on its state of damage/repair. However, for this paper it is assumed that the ESR has determined a grapple point (docking element) on the target for which to align its docking device or grapple. The ESR is actuated with thrusters for navigation in space. See Figure 2 for a visual description of the system.

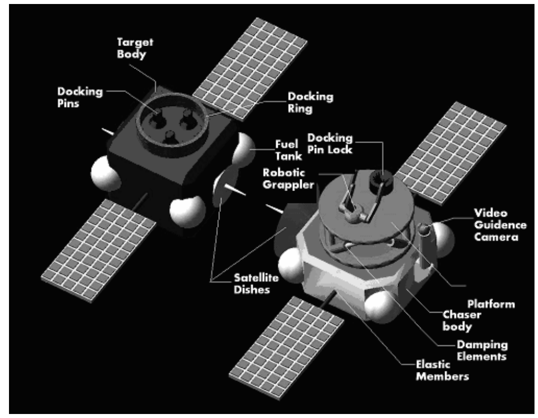

Figure 2: Expert Spacecraft Robot (ESR) and target satellite shown with passive components

The pre-capture proximity operation is subdivided into two controller modes: approach mode and the fine motion mode. The approach mode is defined as the maneuver of the ESR from a defined distance from the target, approaching the target and leaving the ESR near the target with little to no relative motion, ready for the fine motion control to take command. The fine motion mode maneuvers the ESR from the steady-state position provided by the approach controller to the point of docking on the target. The research of this project was performed in several steps and this paper shows the most recent results of the pre-capture mode. These results include orbital dynamics which are implemented in the model for which a controller is developed. In the simulation results, the ESR was actuated with thruster forces only. The thrusters were used to control both position and orientation. Emphasis was placed on controlling the position since Control Moment Gyros (CMGs) will perform the attitude control in future research.

More specifically, a guidance and navigation system maneuvers the ESR to a defined location in an orbit higher or lower than the target to prepare for an R-bar approach. When the ESR reaches the defined location the approach controller activates. When the ESR has reached a location one meter above or below the target, the fine motion controller activates and guides the ESR up to the moment of latching. The approach controller shall be deactivated when it can hold the ESR in a steady state for ten seconds at which time the fine motion controller activates. The switching between the two different controllers needs to be smooth. This means that the two different controller trajectories should have matching boundary conditions and no unexpected peaks in the thruster inputs. Hence, the approach controller is required to leave the ESR in an orbit one meter (with an acceptable error of positive or negative 10 cm) higher or lower than the target (depending on the direction of the approach) with an angle deviation of less than ±0.1745 radians (± 10°) and little to no relative motion.

For the purposes of this paper, contact dynamics are not included since the fine motion mode acts until just before contact. Furthermore, this stage of the rendezvous and docking, the control action is independent of the kind of docking equipment with which the satellites are equipped. The ESR is actuated through thrusters and since most satellites have a very limited power supply on board, the fuel consumption needs to be minimized. Another reason for this is that everything except time is very expensive in space. Furthermore, the thruster firing directions are also limited as the ESR gets closer to the target. The target might already be damaged but the ESR shall not create additional harm to the target. This means that the ESR can not fire its thruster neither against the target's solar panels which are very sensitive nor against the target itself during the fine motion mode. Most thrusters in use today are on/off-thrusters. In this paper, it is assumed that proportional thruster capabilities exist, but with a limited range of thrust represented as saturation in the simulation models. The value chosen for these saturation levels (3.6 N) are based on the specification of the thrusters the DART vehicle is equipped with for proximity operations.[9]

The sensor system of the ESR is vision based and during missions the ESRs can use both on board and off board cameras. To alleviate sensing limitations, communication delays, and dropout signals, other ESR vision capabilities can be called upon. For the simulations in this paper, it is assumed that the measurement of the relative position and orientation between the ESR and the target is available all the time.

When the target and the ESR are docking, it is important to control the direction from which the ESR approaches. The docking equipment needs to face the target during the approach from either a higher or lower orbit. It is assumed that the external attitude control of the ESR can turn the ESR to make the docking equipment face the target. If the target is cooperative the attitude control of the target can also turn itself to make its docking equipment face the ESR. With these assumptions, the direction of the docking equipment is assumed to be pre-oriented so that only relative deviations require control action. During the approach of docking, the coordinate frames representing the center of mass on the ESR and on the target theoretically will line up and the relative orientation is determined from the angular deviation of these frames. If the approach is from a higher orbit, the ESR will find a steady state one meter above the target and vice versa for the approach from a lower orbit. The angular deviation is desired to be zero in both scenarios.

III. MODELING

III.A. Expert Spacecraft Robot

The base model was built in the MSC Software ADAMS/View and consists of a satellite with solar panels.[13] The ESR is equipped with a docking device consisting of a parallel kinematic mechanism (PKM) base unit with six struts containing springs. The number of struts is chosen to give the docking device six degrees of freedom (DOF). The desired stiffness and damping can be obtained as a function of the kinematics, the passive springs and dampers or active compliance and damping characteristics. Because of this design, the top platform can be adjusted during the approach to remain parallel with the target even though the ESR is approaching at some angle. The design is compact and developed for smooth docking and dexterity utilizing the ACMI's configuration dependent stiffness and its limited relative range of motion. When the ESR is under the control of the approach controller, the ACMI is held in a centered (neutral) configuration that corresponds to all struts at their mid-stroke length or position in their range of motion, with a platform orientation parallel to the ESR main body (see Figure 3). This ACMI configuration maximizes the fine motion controller's capacity to account for relative motion variations of the ESR and target. This neutral configuration defines the origin of the error bound on the approach controller's terminal ESR position and orientation or vice versa the resulting error bound on the approach controller yields minimal range of motion requirements of the ACMI. The base model has both the ring and the robotic grapple as docking equipment on the top of the ACMI platform. In the simulation studies, only the ring device is used as docking equipment and the ring is moved to the center of the platform.

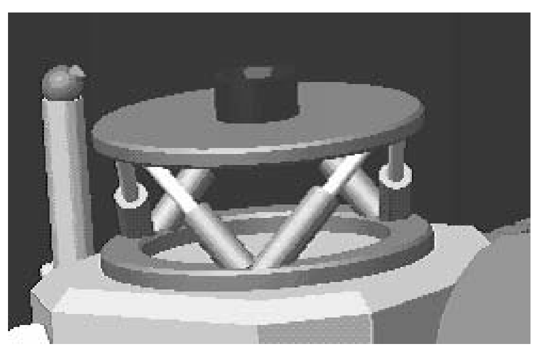

Figure 3: Active Compliant Mechanism Interface (ACMI)

When the ESR is not performing a mission the solar panels are rotated towards the sun for charging. During the pre-capture mode they are assumed to be locked in a fixed position. Also, the mass of the ESR is calculated to be approximately 86 kilograms.

The ESR is actuated through four four-way thrusters, placed an each side of the ESR (none at the top ACMI side or at the bottom). The points of application are chosen in the center of each side. The thrusters are not visually seen in the figures of the ESR but are implemented as forces in the simulation model. Each four-way thruster is represented by two perpendicular forces in the model. These forces can be positive and negative and naturally represent two firing directions. The points of application are shown in Figure 4, where the positive direction of the forces is represented as red arrows.

The sensor system of the ESR is vision based and during the simulations it is assumed that all the desired states can be measured. The desired outputs from the system are the position and the orientation of the ESR. All the measurements are made to be relative to the target satellite, expressed in the target reference frame. The position measurement is implemented as a translation measurement between two points in the x, y and z direction. The points of measure on the ESR and target are located at their centers of mass. To account for the distances from the vehicle centers of mass to their respective docking mechanisms, the ESR is considered to be docked with the target when their centers of mass are 1 meter apart. The orientation measurements are defined as rotation (about an axis) and the relative orientation is measured as the difference between the orientation of the frames attached to target and ESR.

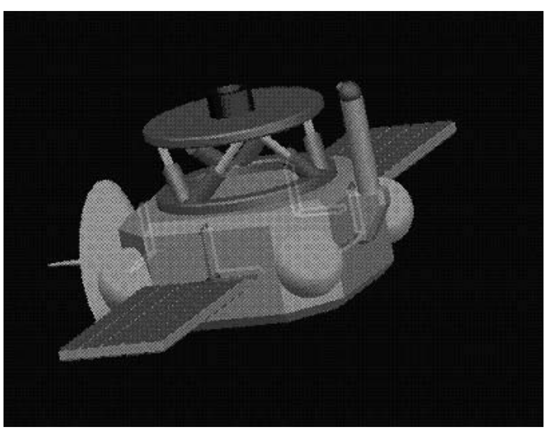

Figure 4: Force input on the ESR, four 4-way thrusters

III.B. Target

For the docking purposes, the target is supposed to be a damaged satellite or a satellite in need of service, e.g. either needing repair or refueling. The mass of the target satellite is often much larger than the mass of the ESR. In the simulations, a generic target with a docking device is assumed. The target in the pre-capture mode is used as an object to follow and approach. No contact dynamics are implemented and therefore the knowledge of the mass of the target is not important during the pre-capture mode.

III.C. Orbital dynamics

For space vehicles (including space robots), the orbital dynamics effects can not be ignored. Furthermore, the behavior due to the orbital effects can be manipulated in such a way to minimize fuel requirements for maneuvering and docking. Thus in this paper, the simulation models include the orbital dynamics. The target in these simulations is assumed to move with an orbiting frame. The ESR is commanded to follow and approach this orbiting frame as if it was the target.

Because the thruster forces change the orbit of the ESR, the solution attempted is to determine a way to place objects into orbit by using applied forces. Thus, the orbit would change with the sum of the forces. The theoretical description of the implementation is simple. For an orbit in the xy-plane (see Figure 5), the force required to maintain a counter clockwise circular orbit is as follows.

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = m(n^2 r)\begin{bmatrix} \sin(nt) \\ -\cos(nt) \end{bmatrix} = m\frac{\mu}{r^2}\begin{bmatrix} \sin(nt) \\ -\cos(nt) \end{bmatrix}, \quad n = \sqrt{\frac{\mu}{r^3}} \qquad (1)$$

The force magnitude is represented by the mass multiplied with the radial acceleration where m is the mass of the body, r is the radius of the orbit and μ is an astronomical constant. If this equation describes a circular orbit, then an initial velocity is required, either an angular velocity of n about the z axis or a tangential velocity of nr in the V-bar direction (tangential to the orbit, see Figure 5). Since r is a very large number, the tangential velocity for an orbit with a radius of 6600 kilometers is almost eight kilometers per second. One should also note that the tangential velocity for a satellite in orbit increases when the radius of the orbit decreases. This fact can be verified through the equation of the tangential velocity.

$$v_{\text{tangential}} = nr = r\sqrt{\frac{\mu}{r^3}} = \sqrt{\frac{\mu}{r}} \qquad (2)$$

The theoretical model is successfully implemented in Matlab/Simulink. The initial position of the ESR is assumed to be zero in the x and z direction and 6600km in the y direction. The initial velocity is set to *nr* in the x direction and zero in the y and z direction. The equations are based on the equations for the orbital force and then twice integrated with respect to time.

$$\begin{bmatrix} {}^{I}x_T \\ {}^{I}y_T \end{bmatrix} = \frac{\mu}{r_T^2 n^2} \begin{bmatrix} -\sin nt \\ \cos nt \end{bmatrix} \quad (3)$$

The equations of orbital motion are implemented both for the target and the ESR to describe their movement. For the analysis, only the kinematics of the target is considered. The ESR is modeled as a rigid-body with motion defined relative to an orbiting frame. While this orbiting frame is not the target body, the ESR's controller performance is evaluated in its ability to bring the ESR's motion to coincide with this frame. The consequence of these assumptions is that the simulations can not include different kinds of target movement and orientation. For example these simulations can not describe a target tumbling or in precession. Thus, the target is considered as a moving frame traveling coincident with the orbiting frame for the ESR to follow and align with.

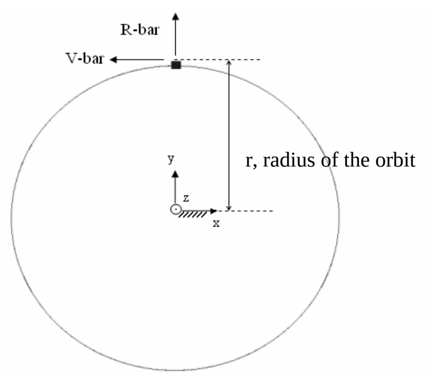

Figure 5: Satellite in orbit: R-bar and V-bar (body-fixed)

There exist two different kinds of orbits, earth pointing and 3-axis stabilized. The only difference between these two orbits is the orientation of the satellite. In space, elliptical orbits also exist. For the case studies in this paper, only scenarios with circular earth pointing orbits are included.

III.D Model dynamics

In this section, the full set of the dynamic equations of motion and the kinematics are derived. These form the base model from which the controller is designed. As stated earlier, the ESR has four four-way thrusters, placed on each side of the ESR (none at the top or at the bottom). This corresponds to eight inputs to the model. The points of application are indicated by the arrows in Figure 4. One four way thruster represents of two perpendicular forces which both can take positive and negative values. This provides the model with four thruster forces pointing upwards in the y direction and four perpendicular thruster forces pointing in the x and z directions, defined in the ESR body fixed frame.

The input thrust vector is shown in equation (4) and consists of eight elements. The subscript denotes which thruster and which ESR frame direction of thrust.

$${}^{ESR}th_{input} = \begin{bmatrix} F_{th1x} & F_{th2x} & F_{th3x} & F_{th4x} & F_{th1y} & F_{th2y} & F_{th3z} & F_{th4z} \end{bmatrix}^T \quad (4)$$

The thruster forces need to be transformed from these eight components to the resultant six components of the force and moment pair defined about the center of mass. By multiplying the thruster input vector with the transformation matrix L_{th}, this force and moment pair is obtained as follows.

$$\begin{bmatrix} {}^{ESR}\sum F \\ {}^{ESR}\sum M \end{bmatrix} = L_{th} * {}^{ESR}th_{input} \quad (5)$$

The transformation matrix L_{th} consists of the corresponding constant moment arms for the thruster forces, described as the distance between the point of application of the force and the center of mass. Since the thrusters are attached to the ESR, their firing directions are in the body fixed coordinates of the ESR. Therefore, the resultant forces and moments of equation (5) are expressed in the ESR frame.

To derive the equations of motion, three different reference frames need to be established: the inertial reference frame, the ESR reference frame and the target reference frame. The inertial frame is used to define the orbital dynamics and is space fixed. All actuator loads applied to the ESR are expressed in the ESR frame. The measurements of relative distance between the ESR and the target, ($\delta r(t)$) are coordinatized in the target frame. These are detailed in Figure 6. Both the ESR and the target's reference frame are body fixed. The target frame's x-direction is pointing away from the earth as the R-bar and the y direction is tangential to the orbits as the V-bar. The z direction is pointing up from the plane, forming a right hand coordinate system.

It is important to note which frame the variables are expressed when the calculations of the equations of motion is performed. Per the Clohessy-Wiltshire (CW) equation[14] derivations, the motion of the ESR and the actuator inputs is transformed to the target's frame. Thus, the equations of motion are also expressed in terms of the motion relative to the rotating frame which is referred to as the target frame in the derivations.

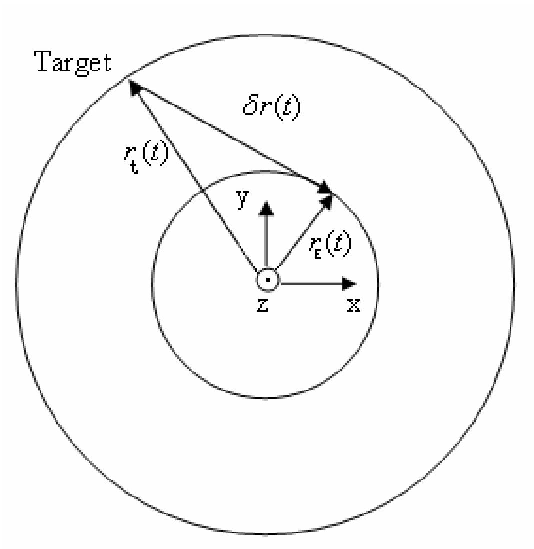

Figure 6: Orbit reference frames

In the case with the orbital dynamics, the equations of motion are the linearized relative to the motion equations. They are governed by Clohessy-Wiltshire (CW)[14] and expressed as:

$$\begin{bmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\end{bmatrix} = \begin{bmatrix}3n^2 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & -n^2\end{bmatrix}\begin{bmatrix}x\\ y\\ z\end{bmatrix} + \begin{bmatrix}0 & 2n & 0\\ -2n & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix} + \frac{1}{m}{}^{T}\sum F\ , \qquad (6)$$

where n is the angular velocity about the inertial z axis shown in Figure 6 and is a function of the astronomical constant μ and the radius of the rotating frame orbit where $n = \sqrt{\frac{\mu}{r^3}}$.

IV. ESR CONTROLLER

IV.A. Control Strategy

Linear Quadratic Regulator (LQR) design is used to solve this problem. The design technique derives the optimal gains for the operation point used in the linearization and minimizes the cost function including the penalty matrices. The solution is optimal for the setup used but that does not mean that it is optimal in all cases. Therefore it is important to fine tune the penalty matrices and make sure the operating point chosen for the simulation represents the system well enough. If suitable design variables are used, it will result in an optimal solution of the problem, if that optimal solution exists.

The plant that needs to be controlled is a MIMO system and has six DOF which gives the model twelve states. The control gains are derived to minimize the cost function J.

$$J = \int \{x^TQx + u^TRu\}\ dt \qquad (7)$$

where x represents the states of the plant and u the plant input. The Q and R are the penalty matrices and J is the cost function to be minimized. This solution suits this problem well because even though the plant is very complex the linearization about the operating point represents the system very well. This is necessary for a satisfactory solution.

The first six states chosen are the position (three states) and orientation (three states) of the ESR and the other six states are derivatives. Since the output of the plant is the first six states, the second six states need to be acquired in order to have full state feedback (12 states). To avoid the problems encountered with the use numerical derivatives an estimator is built.

IV.B. Linearization

Per the Clohessy-Wiltshire (CW)[14] derivation of the equations of motion, equation (6) is already in its linear form about the circular orbit of the target. Hence, the constant angular velocity *n* appears in the equations. In the basic simulation setup, the ESR starts 30 meters below the target to perform an R-bar approach. The initial relative angles in this case are zero and the angles are desired to stay close to zero during the approach. Therefore, the linearization point shall be the angle zero. The initial position in the y and z direction is zero where the only deviation from the final position is in the x direction. The operating point is chosen to represent the plant at its desired final position. When the two satellites are close unexpected movement can have bad consequences and it is important to keep all the velocities close to zero at that point.

To derive the linear system some assumptions are necessary. The linearization is performed using Taylor series, dropping higher order terms. Substituting these linearized approximations into the Euler equations of motion, a set of equations of motion are obtained expressed in ESR coordinates for which the inertia matrix is constant.

IV.C The Controller

Using the linearized state space model of the system the LQR controller u is derived by minimizing the cost function J using Matlab's *lqr* function. The controller is implemented in Simulink per the block diagram shown in Figure 7. Note, the L is the transformation matrix L_{th} in equation (5) and k is the controller and the 'State-Space' block is the estimator. The thruster saturation block is used to introduce the effects of actuator limits on thrust. These are expressed in terms of the resultant force and moment pair of equation (5).

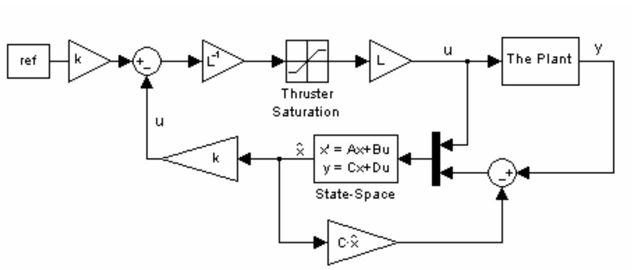

Figure 7: Control block diagram

V. RESULTS

There are six scenarios for which the proximity operations are completed. There is one approach from a 30m lower orbit and another from a 30 meter higher orbit. In addition, there are two more approaches from a 30m lower orbit with negative and positive V-bar displacements. Also, there are two additional approaches from 30m higher orbits with negative and positive V-bar displacements. The last four simulations describe a possible limit for the V-bar displacement that the system can handle. The simulations are similar in pairs. The two simulations with negative V-bar displacement can both handle a displacement of 200 meter and the output is similar with a change of sign in the x direction (naturally since the ESR starts above or below the target). The two simulations with positive V-bar displacement are similar in the same way but they can not handle the displacement of 200 meters; a 100 meter displacement is instead used in these simulations. Figure 8 shows the R-bar distance of the ESR's approach as a function of time.

In all six scenarios, the approach mode controller guides the ESR towards the target successfully. Since during the approach mode the ESR can fire thrusters towards the target, it is able to slow down and move alongside the target until it reaches its goal position. During the fine motion control, the ESR cannot fire thrusters towards the target so its ability to slow down is greatly diminished. This is why in all six scenarios, it appears that the ESR approaches the target with more speed in the fine motion mode than in the approach mode.

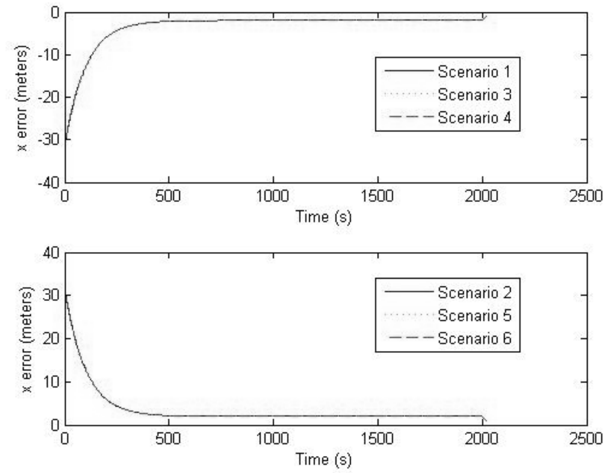

Figure 8: X error (target frame) between ESR and target

Table 1 shows the final error values at the instant just before docking for the ESR. Since for all six scenarios, there is no more than a fraction of a centimeter of error in displacement and just over 2° of error in angular displacement, the controller can be considered to be successful. This is because the small errors exhibited by the ESR during its approach can be mitigated by the ACMI when it is in its active mode.

Table I: Errors at Point of Docking

Y error (m)	Z error (m)	θ1 error (rad)	θ2 error (rad)	θ3 error (rad)
-7.45E-03	-7.15E-03	-5.29E-05	5.10E-03	3.52E-02
7.21E-03	7.18E-03	6.63E-05	-5.07E-03	-3.50E-02
-7.45E-03	-7.15E-03	-5.29E-05	5.10E-03	3.52E-02
-7.60E-03	-7.15E-03	-5.27E-05	5.09E-03	3.52E-02
7.20E-03	7.18E-03	6.63E-05	-5.07E-03	-3.50E-02
7.20E-03	7.18E-03	6.63E-05	-5.07E-03	-3.50E-02

VI. CONCLUSION

The controller meets the requirements for the base scenarios when the ESR starts thirty meters away from the target in the R-bar direction and approaches it. The requirement is that the ESR when it has reached steady state has a translational deviation of less than ten centimeters and an angle deviation of less than 0.1745 radians (10°). These requirements are all fulfilled not only for the basic scenario but also for the scenario when the

ESR starts before or behind the target. In addition, the fine motion controller is capable of guiding the ESR to its target with extremely small error values that are well within the range of the ACMI.

There exists a desire to develop a controller that can take the command from the free flying controller whenever the ESR is anywhere in the orbit e.g. thirty meter lower than the target and then approach and dock it. As it is required now the ESR can not be more than $\pm$100 meters away from the target in the V-bar direction to be sure to align with it, which puts more requirements on the free flying controller.

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