Autonomous Controller Design for an Orbital Debris Chaser Craft

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***Abstract*— Space is starting to become very crowded mostly in low earth orbit (LEO). Current projections are showing that without active debris removal (ADR) missions manned and unmanned operations in LEO will become in danger of collisions. While research is being done on removal techniques most approaches involve human pilots and/or are planned for a single use. A more effective solution in the long run would be to have a multi-use crafts that could navigate to rendezvous with multiple targets for de-orbiting. The purpose of this paper is to compare two different types of controllers used on a simulated nonlinear active satellite system to rendezvous with a certain target in orbit. The two types of controllers that are compared are a state feedback controller and a Fuzzy Logic Controller (FLC). Initial conditions are provided to the controller at first in order to ensure each controller works in a variety of start points. Simulations for both controllers are performed to compare operation while attempting to rendezvous with the target location. The simulation results provide details on the different strengths for both types of controllers that could be applied to different missions. One main result of this paper is that the State Feedback controller was able to reach the target location quicker but the FLC had a much smoother approach. Further detail on the results is presented in this paper.**

Keywords—Backstepping Controller; Fuzzy Logic; Autonomous Rendezvous; orbital debris

I. INTRODUCTION

The expansion into space has brought many new challenges to overcome. One such challenge is the growing threat of orbital debris. According to the National Aeronautics and Space Administration (NASA), orbital debris is classified as any object in Earth orbit that no longer serves a useful function [1]. These objects create numerous problems for manned and unmanned operations in orbit, because of the damage that can be done to these expensive systems. A study put out by NASA calls for more ADR missions to help alleviate the growing threat of debris. This study showed that with no debris mitigation, the number of debris would skyrocket by 2030 [1, 2]. More autonomous systems are being considered for the removal of debris and even for on-orbit servicing to repair object before they can become debris. Autonomous ADR systems have many different phases to operate in order to be able to rendezvous and capture the debris. The most important part of the whole mission is the rendezvous phases of the operation. The whole rendezvous stage of the operations is comprised of five phases [3]:

1. Separate Orbit: This phase started after the chaser craft has achieved orbit and is in the process of calculating how to start the next phase
2. Drift Orbit A: When this phase starts the target is still out of sight, out of contact and the chaser is in the process of orbital transfers thrusts to get into the same orbit as the target
3. Drift Orbit B: The target is now in sight and relative navigation begins
4. Proximity Operations A: This phase starts when the target is about 1km away from the chaser. This allows the chaser to get into a parking orbit to begin docking procedures
5. Proximity Operations B: This phase starts when the chaser is about 100m away from the target and has begun to move into dock or capture the target.

The concept of ADR has been bouncing around the space community for some time now. When attempting to rendezvous with the debris the first consideration is the size of debris that the chaser craft will be targeting as well as the location of the debris. The majority of the objects that are targeted for being ADR missions are in LEO. This is due to the fact that LEO is a high traffic area for both manned and unmanned missions. A number of different methods have been proposed to remove debris such as the use of tethers or nets to be able to actively capture the target. These techniques would involve a chaser craft that could rendezvous with the target in a higher orbit and "drop" these objects down to capture the targets. While this method could be used the logistics of the entire mission plan make it a very complicated mission.

Another method described is the most widely proposed method to remove debris and to manipulate satellites in orbit. This involves having the chaser craft reach the same orbit as the target, slowly maneuver towards it, and use the end effectors to capture the target. Once captured, the craft could maneuver the target into a lower orbit needed to de-orbit or return it to a human operated spacecraft for repair.

The proposed full scale space debris mission for this paper would entail the following steps for the chaser craft:

1. Reach the orbit of the target craft
2. Identify the target craft

3. Align itself for the proper approach with the target craft
4. Begin approach to the target craft
5. During approach phase check for obstacles
6. Inspect target craft
7. Capture target craft

This paper mainly focuses on steps 2 – 5 of the ADR mission where chaser will use its initial position relative to the target craft in order to perform the rendezvous operation. Once the chaser is in the right location proximity operations can begin which includes the rendezvous and inspection of the target.

This paper explores two types of controllers to control a chaser craft to rendezvous with a target. The types of controllers proposed are a nonlinear backstepping controller and a fuzzy logic controller that control the movement of the chaser craft. These types of controllers have been used in the past for control of mobile robots, unmanned aerial vehicles, and on some spacecraft [4-9]. Section II provides the design of the backstepping controller and the FLC. Section III presents the conditions for the simulations and the results of the controllers. Lastly, conclusions and future work planned are discussed in Section IV.

II. Controller Design

A. *The Spacecraft Frame*

Before the equations of motion of the chaser can be described, the coordinate system conventions need to be established. The reference frame is very important for all orbital operations. Since there are many different types of maneuvering operations that can be done in orbit, there are also many different reference frames that can be used to describe orbital motion. The large emptiness of space and lack of identifiable landmarks makes creating reference frames rather difficult.

Since modeling spacecraft's requires a rotating reference frame, the orbital frame is chosen. This is a popular reference frame for rendezvous and formation flights in orbits. The frame places the origin at the center of mass of the main spacecraft, in this case the target, and creates a coordinate system around the spacecraft using the orbital elements of motion [10]. For the rendezvous operation the system is described as relative to the target. This is done because as the chaser approaches the target so most of the relative orbital errors between the target and the chaser have minimal impact. This coordinate system has its origin at the center of mass of the target craft. This type of orbital reference frame is called the Local-Vertical-Local-Horizontal (LVLH) frame which allows for two separate spacecraft to either fly in formation or any rendezvous procedures. Fig. 1 shows the reference frame that is used in this paper. Using this reference frame, we can use the rotating Hill frame to better describe the motion of the chaser craft [11]. The orbital reference frame is earth centered, orbit based, and rotating which allows for the concept of row, pitch, and yaw to be used to described the motion in any direction.

From Fig. 1 we can see that the positive x direction is an extension of the r_c vector going from the center of the earth to the center of mass of the target. The positive y is the vector direction of the orbital velocity vector, and the positive z direction is the orbital normal.

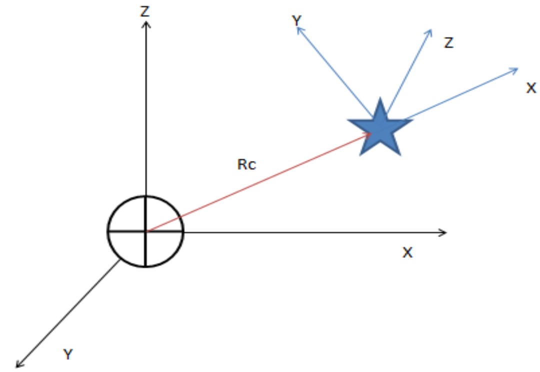

Fig. 1: The spacecraft in the LVLH frame.

This reference frame is used in textbooks for formation flying of spacecraft and rendezvous operations in orbit because it places the target or the main craft as the origin. This results in the full nonlinear equations of motion [11]:

$$\ddot{x} - 2\dot{\theta}\dot{y} - \ddot{\theta}y - \dot{\theta}^2 x - 2\left(\frac{\mu}{r_c^3}\right)x = \frac{-\mu(r_c + x)}{\rho^3} + \frac{\mu}{r_c^2} - 2\left(\frac{\mu}{r_c^3}\right)x + F_x/m \tag{1}$$

$$\ddot{y} + 2\dot{\theta}\dot{x} + \ddot{\theta}x - \dot{\theta}^2 y - \left(\frac{\mu}{r_c^3}\right)y = \frac{-\mu y}{\rho^3} + \left(\frac{\mu}{r_c^3}\right)y + F_y/m \tag{2}$$

$$\ddot{z} + \left(\frac{\mu}{r_c^3}\right)z = \frac{-\mu z}{\rho^3} + \left(\frac{\mu}{r_c^3}\right)z + F_z/m \tag{3}$$

$$\ddot{r}_c = r_c\dot{\theta}^2 - \frac{\mu}{r_c^2} \tag{4}$$

$$\ddot{\theta} = -2\left(\frac{\dot{r}_c\dot{\theta}}{r_c}\right) \tag{5}$$

$$\rho = \sqrt{(r_c + x)^2 + y^2 + z^2} \tag{6}$$

Where x, y, and z represent the distances the chaser is with respect to the target relative to each axis, r_c represents the scalar distance from the center of the Earth to the target, ρ represents the scalar distance from the center of the Earth to the chaser, θ is the true anomaly at which the target debris is orbiting at, the values F_x, F_y and F_z represent the thrust force applied to the system and m represents the mass of the spacecraft. Some assumptions must be made in order to model the chaser system as it must move in a very complex environment. The following assumptions are made in this paper:

1. All orbital maneuvers have been completed upon the start of the simulations and the chaser is at the start of Proximity Operations A (~1000m apart).
2. The target and the chaser are in a circular orbit in LEO therefore the true anomaly has a constant velocity.

3. There are no outside disturbances on the chaser or the target
4. The chaser cannot run out of fuel
5. Force applied is in the form of F=ma
6. There is no roll applied to the chaser

Assumptions are made for the following reason: the approach phase of the rendezvous not the orbital mechanics of catching up to the target, LEO is where most of the human operations take place in orbital operations and where most debris is located, and the circular orbit is picked to help reduce the amount of nonlinearities in the state equations.

By using equations (4) and (5) the Clohessy-Wlitshire model (Hill's equations) can be formed which can be formed into nonlinear states:

$$\begin{bmatrix} \acute{x}_1 \\ \acute{x}_2 \\ \acute{x}_3 \\ \acute{x}_4 \\ \acute{x}_5 \\ \acute{x}_6 \end{bmatrix} = \begin{bmatrix} x_2 \\ 2\acute{\theta}x_4 + \acute{\theta}^2 x_1 - \frac{\mu(r_c + x_1)}{\rho^3} + \frac{\mu}{r_c^2} + F_x/m \\ x_4 \\ -2\acute{\theta}x_2 + \acute{\theta}^2 x_3 - \frac{\mu x_3}{\rho^3} + F_y/m \\ x_6 \\ \frac{-\mu x_5}{\rho^3} + F_z/m \end{bmatrix} \quad (7)$$

B. Backstepping Controller Design

Backstepping is a recursive method to create a nonlinear stabilizer for the system. This method is based on the use of Lyapunov theory which ensures that the system is stable for each state. The main idea behind the design of the controller is create a virtual controller that will stabilize each state until the final "true" controller is reached. These types of controllers are used in a variety of systems such as control of motors, path tracking, and flight controls. One of the advantages of using the backstepping method is that it can be used to create a controller that stabilizes each state. Backstepping controllers can be the basis for more advanced controllers such as state feedback and output feedback controllers.

The controller has to be able to successfully maneuver the chaser craft to the target, which is at the origin of the system. The controller is designed for each direction therefore three separate controllers are built for the thrust force, $F = [F_x \quad F_y \quad F_z]$. By creating three separate controllers we are able to better control the movement of the chaser craft. Using Lyapunov equations we are able to ensure each force is Lyapunov stable. The controller equations are:

$$F = \begin{bmatrix} m\left((-x_1 - x_2) - 2\acute{\theta}x_4 - \acute{\theta}^2 x_1 + \frac{\mu(r_c + x_1)}{\rho^3} - \frac{\mu}{r_c^2} - \xi_2\right) \\ m\left((-x_3 - x_4) + 2\acute{\theta}x_2 - \acute{\theta}^2 x_3 + \frac{\mu x_3}{\rho^3} - \xi_4\right) \\ m\left((-x_5 - x_6) + \frac{\mu x_5}{\rho^3} - \xi_6\right) \end{bmatrix} \quad (8)$$

Where:

$$\xi_4 = (x_4 - x_4\ ) \quad (9)$$
$$\xi_6 = (x_6 - x_6\ ) \quad (10)$$

$$x_4 \ = -x_3 \quad (11)$$

$$x_6 \ = -x_5 \quad (12)$$

This controller ideally should be more responsive then a linear stabilizing controller.

C. Fuzzy Logic Controller Design

Fuzzy logic is widely used in control of mobile systems to assist in obstacle avoidance while navigating along paths. Fuzzy logic controllers have a crucial advantage because one can transfer experience to the controller. This means that the fuzzy controller can be trained with human knowledge, such as from a pilot. Due to the usefulness of the controller type, many researchers have published 2D applications of fuzzy logic controllers. Stabilization of spacecraft and UAVs [4, 12, 13] is a popular 3D application of fuzzy logic controllers. Of the work that has been done for spacecrafts, most work has been done with attitude stabilization of small satellites and obstacle avoidance for rendezvous operations [14, 15]. Most of the fuzzy controllers in the literature tend to be Takagi-Sugeno type instead of the Mamdani type. The Takagi-Sugeno type uses linguistic rules and linear functions and is used in many nonlinear systems [16]. These types of fuzzy systems are very useful for spacecraft operations.

The controller designed in this paper is a Mamdani model, which is the most common type of fuzzy controller to use. This type of model is preferred in most cases because it's easier to translate human experience into the controller. The fuzzy controller that is being designed will take in the error of the chaser's position in relation to the target and the error of the velocities of the chaser to create rules in the form of *IF...AND...THEN...* to ensure that the chaser applies the proper thrust to move in the intended direction. The rule base was designed so that the error in the position and velocity for x only affects the thrust in the x direction. The same was done for the y and z states in order to create a fuzzy controller that is able to control the chaser states to get close enough to the target point.

The membership functions that were chosen were Gaussian, Z, and S functions in order to create smoother transitions between the functions. The membership functions for the position and velocity errors where designed to be the same across all three states due to the fact that all three thrust values must all accomplish the same goal. The fuzzy controller has 25 rules per state, which means that there are 75 rules total. The rules are based on which direction the thruster will be firing in for example if the position error is zero and the velocity error is zero then no force is needed and the force output is zero.

Fig. 2 describes the membership functions for the error in the inputs and the resulting output force. The top plot is for the error in the x direction, the middle is for the y direction and the bottom is for the z direction.

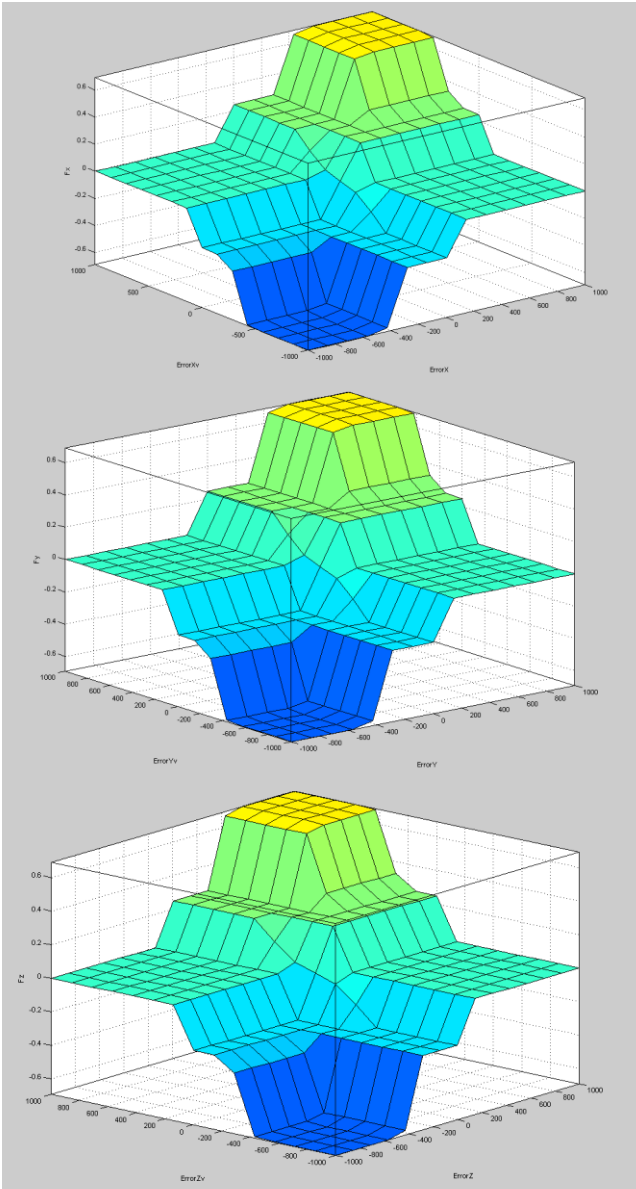

Fig. 2: These are the membership function of the FLC

III. SIMULATION SETUP AND RESULTS

A. Simulation Setup

The assumptions from Section II are chosen to help simplify a very complex system in order to accomplish the task of controlling the movements of the chaser craft. The main mission objective is to have the chaser craft maneuver to the target craft starting from a point no less than 100m away. Since the center of mass of the target is the origin of the coordinate system the position states must converge to zero, as well as the velocities. In the simulations the target point is fixed, but in the real world system the chaser would end up following the target after it successfully rendezvoused. The chaser craft that will be modeled in these simulations is deigned to a small satellite much like a Microsatellite or Nanosatellite which are flown for inspection or for various other tasks on orbit. These are a type of small satellites have a wet mass of up to 10kg for Nanosatellites, and 100kg for Microsatellites . These types are designed for station keeping operations, constellations for communications, or inspections of larger satellites. The chaser craft dry mass is selected to be 30 kg while the wet mass is 50kg. After the mass of the craft is chosen, we choose to set the shape of the chaser up as a cube. Fig. 3 shows the chaser shape and thrust output. The control thrusts of the chaser are represented as the red arrows. This allows for a more ideal application of thrusts for the simulation.

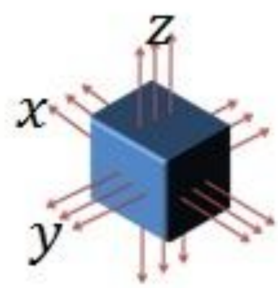

Fig. 3: The proposed chaser craft

Simulations are performed in MATLAB/Simulink environment. This environment is chosen because of the ode functions that are used in solving the system. The membership functions and rules were created with the aide of the Fuzzy Logic Toolbox GUI provided by MATLAB. Constants that are important to the simulation of orbital maneuvers are listed in Table 1.

TABLE 1: ORBITAL CONSTANTS

Parameter (units)	**Value**
Gravitational Parameter ($\frac{km^3}{s^2}$)	3.986004418e14
Distance from the center of the earth (Km)	6371
LEO altitude (above the Earth's surface) (Km)	500
Orbital period (seconds)	5668

Parameters for the simulation are provided in Table 2, which provide the different approach vectors and velocities.

TABLE 2: INITIAL CONDITIONS OF SIMULATIONS

Trial #	**# steps**	$x(0)$ **(m)**	$y(0)$ **(m)**	$z(0)$ **(m)**	$\acute{x}(0)$ **(m/s)**	$\acute{y}(0)$ **(m/s)**	$\acute{z}(0)$ **(m/s)**
1	500	-100	-100	-100	0	0	0
2	500	-500	-100	-50	0	0	0
3	500	-100	-100	-100	10	10	10
4	500	-100	-100	-100	-10	-10	-10
5	500	-500	100	50	50	100	5

B. Backstepping Simulation Results

MATLAB's ode45 function was used to simulate the controller. The first run used no control input, and used the initial conditions described in Table 2 for Trial #1 with t =

[0,1000]. This time was selected empirically to see a good portion of output of the uncontrolled system.

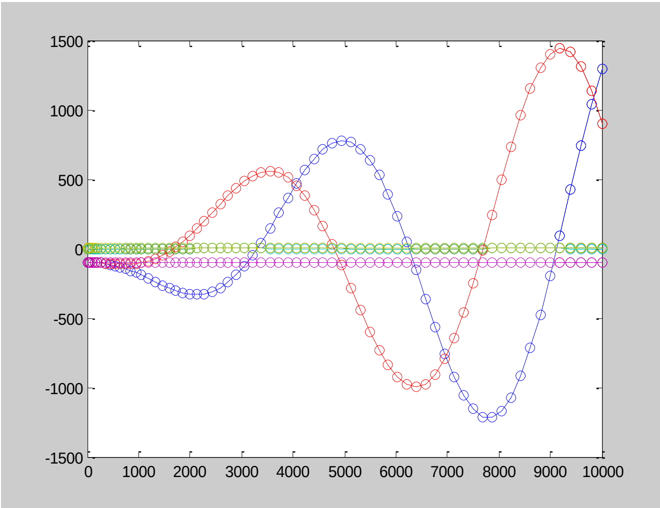

Fig. 4: The output of the ode4 function with no controller

As Fig. 4 shows the system with no control is indeed unstable. This simulation was a baseline test to be able to see the difference between the uncontrolled and the controller chaser system. Next using the same initial conditions as before and at time t = [0,10] we again used ode45 to evaluate the system with the backstepping controller this time. The results show that the controller did stabilize the system at its equilibrium point. The velocity and position states are equal to each other because the system and controller are linear. After proving that the controller was indeed working we were then able to change the properties of the simulation to test the different initial conditions. Fig. 5 shows that the controller did stabilize the system at its equilibrium point. The velocity and position states are equal to each other because the system and controller are linear.

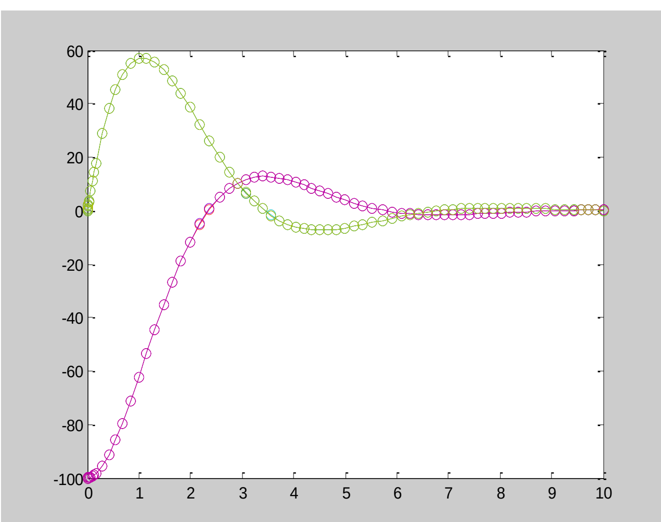

Fig. 5: The output of the ode45 function with a controller

After proving that the controller was indeed working we were then able to change the properties of the simulation to test the different initial conditions. Only the 3D plots are shown to conserve space. Fig. 6 shows the results of Trial #3 from Table 1. As the 3D plot shows the state feedback controller moves very linearly and has a pretty large overshoot. This can be accounted for in a real system with sensors but for now this simulation and the others show that the system is able to rendezvous with the target point.

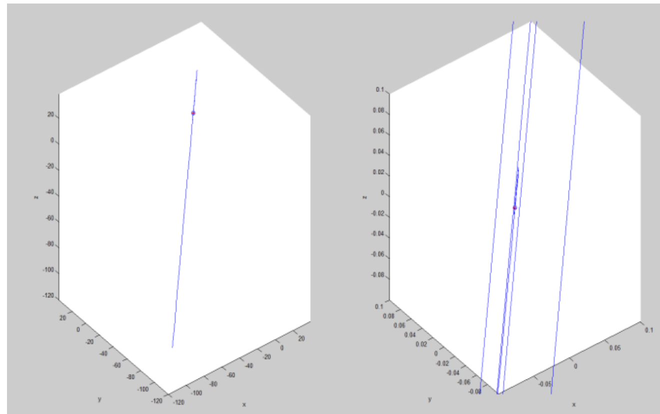

Fig. 6: 3D plot of the chasers movement

C. FLC Simulation Results

The next couple of simulations were run on the fuzzy logic controller. The controller uses the same initial conditions as the backstepping controller. The FLC simulation is run for 2000 steps, instead of the 500 steps used in the backstepping controller simulation. For the first simulation we ran the same conditions described in Table 2. Only one of the simulation results is shown below. Fig. 7 shows the simulation run of Trial #2.

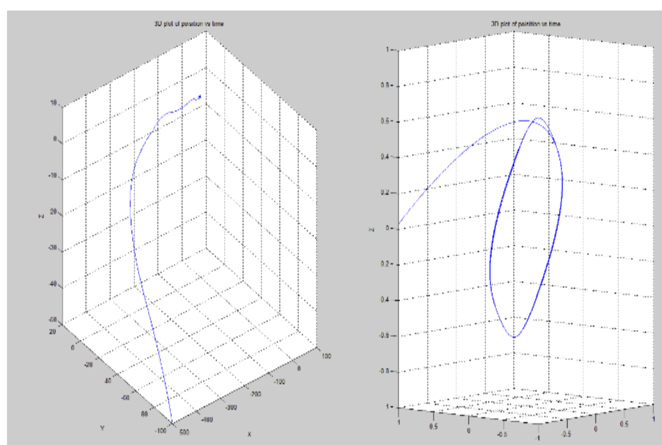

Fig 7: The output of the FLC controller on a 3D plot

As it can be seen the FLC simulation creates a much smoother path when compared to the backstepping controller. While the FLC reaches the point slower it also has less overshoot. This could result in a crash between the target and the chaser.

IV. CONCLUSION AND FUTURE WORK

The main goal of this paper was to design and simulate two controllers that operate during Proximity Operations B of a rendezvous phase for a spacecraft with given initial conditions. In order to create controllers for the chaser craft, we then used assumptions that aided in the design of the controllers. After both controllers were designed they were tested individually to see their behavior during a simulated rendezvous phase. From the simulations of each controller it could be seen each controller worked well and got to the target point. There were notable differences between the two controllers. First off, the fuzzy logic controller would orbit around the target point. Depending on the initial conditions, the orbit would be either tighter or would be more spaced out. The orbit can also be adjusted by making the zero membership function of the velocity wider. What this effectively does is set the parking velocity for the chaser. The more narrow the zero membership function for position and velocity are the close the chaser gets to the target position. Therefore, a delta function would be the most ideal to use as the membership function. The backstepping controller performed very well in every simulation. Although the controller had some overshoot, it was already very close to the target point. In a real system with a constant update to the position the backstepping controller would settle faster than the FLC.

The most significant future goal is to add the rotation of the chaser craft into the system. This will allow us to simulate true satellite system to get a better idea of how the chaser craft will react during the approach. Also we wish to model the orbit as an ellipse rather than a circle since most orbits are more elliptical in shape thus resulting in a nonlinear system. The controllers will be modified to better control the movements of the chaser. One planned modification is to design a Takagi-Sugeno FLC to determine if it can control the nonlinear system better than the current FLC in use. With that we will be able to simulate a fully functional chaser system that can identify any target and being rendezvous procedures. Once, the rotation of the system has been added into the full system we wish incorporate a LiDAR sensor to advance to the ultimate goal of testing a full scale ADR mission.

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