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ON-ORBIT SATELLITE SERVICING USING MULTIPLE TETHERED ROBOTS

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Rapid advancement and miniaturization of earth-orbiting spacecraft has led to the rise of constellations that perform global positioning, remote sensing, earth-imaging and relay communication. With the increased space traffic, there are many more obsolete and a few abandoned satellites. The proliferation of these abandoned satellites poses severe risks to newly launched spacecrafts including current and future constellation missions. Moreover, these abandoned satellites are economically valuable orbital real estate that could be reused, repaired or upgraded for future use. On-orbit servicing of a satellite requires satellite rendezvous, docking and repair, removal and replacement of components. Launching a big spacecraft that perform satellites servicing is one approach. However, sending multiple, small-robots with each robot specialized in a specific task is credible alternative, as the system is simple and cost-effective. In this work, we analyze the feasibility of sending multiple robots that can work cooperatively to perform on-orbit satellite servicing. The multi-robot system will be deployed in a formation interlinked with spring-tethers and that will perform one-time autonomous rendezvous, capture and servicing of satellites in LEO and GEO orbits. After docking with the target satellite, each robot secures itself on the satellites surface using spiny gripping actuators. The multi-robot system can crawl on the satellite's surface with each robot moving one by one using rolling and hopping mobility capabilities. If any robot loses grip, the multirobot system with robots anchored to the surface keeps the entire system secure. The system can also be used to carry larger components and place them on a specific location of the satellite. Through this distributed controls approach, the risk is distributed, and it can perform multiple servicing tasks on the satellite simultaneously.

In our work, we analyze the feasibility of using tethered robots to perform capture and docking with a target spacecraft using dynamics and control simulations. This approach works for relative velocity of 10 m/s which is typically expected in on-orbit servicing missions. Using our design approach, we are developing low-cost methods for on-orbit satellite servicing using multiple small robots.

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INTRODUCTION

The last 60 years of space activities has led to more than 4,500 launches having placed more than 5,000 satellites in orbit, out of which merely 1,000 are still operational today. The proliferation of these obsolete and abandoned satellites poses severe risks to newly launched spacecrafts, current and future space missions and hence threatening the future of space utilization for both commercial and scientific purposes. However, some of these abandoned satellites are economically valuable orbital real estate that could be refueled, repaired and upgraded for future use. Use of robotics in space appears to be the most promising approach for on-orbit services such as docking, berthing, refueling, repairing, upgrading, transportation, rescuing and orbital debris removal[1]. Many enabling techniques has been developed recently and several technology demonstration missions have been completed. ETS-VII of JAXA is considered the first robotic OOS demonstration mission[2]. DARPA developed an advanced technology demonstration mission called Orbital Express[3]. The US AFRL in 2002 demonstrated some key elements of rendezvous and proximity operations with the eXperimental Satellite System 11 (XSS-11) mission[4]. NASA sponsored the project DART (Demonstration for Autonomous Rendezvous Technology), which flew in 2005[5]. Another recently planned OOS mission was called TECSAS (TEChnology SAtellites for Demonstration and Verification of Space Systems) which was jointly developed by DLR of Germany, CSA of Canada, and BSC of Russia[6]. These specialized OSS missions of sending a big satellite with dexterous robotic arms is one approach. However, performing rendezvous and docking with an uncontrolled abandoned target satellite with the help of robotic arms will be difficult as the targets may have unpredictable spinning motion and no suitable grasping points.

In this paper, we study the feasibility of sending multiple small robots that can work cooperatively[15,16,17] to perform on-orbit satellite servicing. The multirobot system will be deployed in a formation interlinked with spring-tethers and that will perform one-time autonomous rendezvous, capture and servicing of satellites in space. The tethered robotic system, upon rendezvous with the target satellite, impacts and wraps around it. The advantage of a tethered multirobot capture and docking system over a conventional robotic gripping system is its ability to handle unknown target satellite's physical and dynamics characteristics like shape, material and attitude of the target satellite[7,8,9]. Furthermore, unlike rigid docking systems like robotic arms, this tethered capture system does not need fine relative attitude control, the tethers can collide with the target satellite from any direction and perform the capture and docking process. After docking with the customer target satellite, each robot secures itself on the satellites surface using spiny gripping actuators. The multirobot system can crawl on the satellite's surface with each robot moving one by one using rolling and hopping mobility capabilities. If any robot loses grip, the multirobot system with robots anchored to the surface keeps the entire system secure[10,11]. The system can also be used to carry large components and place them at designated ocation on the target satellite. Through this distributed controls approach, the risk is distributed, and the multirobot system can perform multiple servicing tasks on the target satellite simultaneously. In the following section, we model the multibody dynamics,

MULTIBODY DYNAMICS MODELING

The tether connecting the robots can be most efficiently described as a flexible body as a series of point masses connected by massless springs and dampers in parallel as shown in Figure 1. The tether geometry is represented by numbering the point masses as nodes and creating a graph $G = (N, E)$, where $N = \{1,2,\ldots,n\}$ is a finite nonempty node set and $E \subset N \times N$ is an edge set of ordered pairs of nodes.

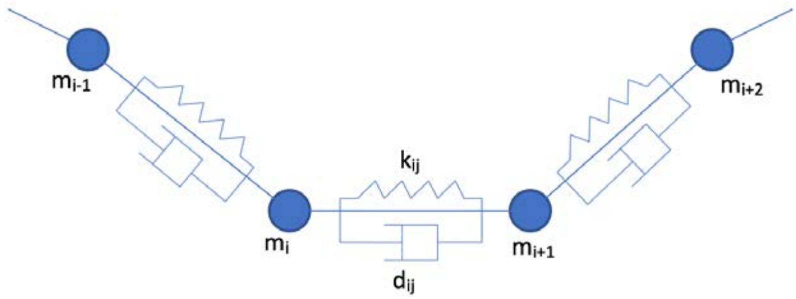

Figure 1. Discrete Tether Model.

Flexible Dynamics Model

Using the Kelvin-Voigt model, the tether can be modeled as a viscoelastic material having the properties both of elasticity and viscosity through a combination of spring-dampers resulting in different tension laws. Tension on a rope element linking the i^{th} node to the j^{th} node can be expressed as Eq. (1):

$$T_{ij} = \begin{cases} \left[-k_{ij}\left(\left|r_{ij}\right|-l_0\right)-d_{ij}\left(v_{ij}\cdot\hat{r}_{ij}\right)\right]\hat{r}_{ij} & if\ \left|r_{ij}\right| > l_0 \\ 0 & if\ \left|r_{ij}\right| \leq l_0 \end{cases} \tag{1}$$

Where, k_{ij} is the stiffness parameter of the tether element ij which depends on the material properties and geometry of the tether, d_{ij} is the damping coefficient of the tether element ij. r_{ij} and v_{ij} are the relative position and velocity between the ith node and the jth node. $\hat{r}_{i_j}$ is the normalized unit vector along the position vector. Also, l_0 is the nominal un-stretched length of the tether element. The stiffness parameter is directly proportional to the tether cross-sectional area A and the Young's modulus E and inversely proportional to the nominal length of the tether as shown in Eq. (2). Also, the damping coefficient depends on the damping ratio ξ, mass of the tether element between nodes i and j and the stiffness parameter as shown in Eq. (3).

$$k_{ij} = \frac{AE}{l_0} \tag{2}$$

$$d_{ij} = 2\xi\sqrt{m_{ij}k_{ij}} \tag{3}$$

Contact Dynamics Model

During the wrapping and docking phase, multiple contact events will occur between the tether and the target satellite and also among different part of the tethered system. As a result, efficient collision detection and accurate representation of contact dynamics becomes key to the fidelity of the simulation to reality. The target spacecraft is modeled as a convex polyhedra and the Gilbert, Johnson and Keerthi (GJK) collision detection algorithm is used to detect collision between the tether and the target satellite and to calculate the penetration depth during every collision[12,13].

After detecting the collision, Hertz contact force model has been implemented to model the contact dynamics. When two bodies collide, local deformations occur resulting in penetration into each other's space. The penetration results in a pair of resistive contact forces acting on the two bodies in opposite directions. Every collision consists of a compression phase and a restitution phase which can be modeled as a non-linear spring-damper as shown in Eq. (4):

$$f_N = K\delta^n + d_c\dot{\delta} \tag{4}$$

Where, K is the stiffness parameter, which depends on the material properties and the local geometry of the contacting bodies, δ is the penetration depth, d_c is the damping coefficient, $\dot{\delta}$ is the relative velocity of the contact points, projected on an axis normal to the contact surfaces and $n = 3/2$. For two colliding spheres with radii R_i and R_j, the parameter K can be determined as Eq. (5) and (6):

$$K = \frac{4}{3\pi(h_i+h_j)}\left(\frac{R_iR_j}{R_i+R_j}\right)^{\frac{1}{2}} \tag{5}$$

$$h_i = \frac{1-\nu_k^2}{\pi E_k} \; ; k = i, j \tag{6}$$

Where v_k and E_k are the Poisson's ratio and Young's modulus of each sphere. Also, the damping coefficient d_c can be considered as a function of the penetration depth, δ and the hysteresis damping factor, μ as shown in Eq. (7) and (8):

$$d_c = \mu\delta^n \tag{7}$$

$$\mu = \frac{3K(1-e^2)}{4\dot{\delta}^{(-)}} \tag{8}$$

Where, e is the coefficient of restitution and $\dot{\delta}^{(-)}$ is the penetration speed at the start of the compression phase.

Friction Model

Each collision between the tether and the target satellite results in a tangential frictional component of contact force which is computed using Coulomb's law of dry friction which opposes the relative motion. It has been experimentally found that the transition of friction force from zero to nonzero relative velocity is not instantaneous, but it takes place during a short period of time. This transition called the Stribeck effect is implemented to the equations of motion of the multibody system using the Anderson function to avoid stiction as shown in Eq. (9).

$$f_t = f_N\left(\mu_d + (\mu_s\text{-}\mu_d)e^{-\left(\frac{v_{i,j}}{v_s}\right)^p}\right)\tanh(k_t v_{i,j}) \tag{9}$$

where, μ_s is the coefficient of static friction, μ_d is the coefficient of dynamic friction, $v_{i,j} = v_i - v_j$ is the relative speed, v_s is the coefficient of sliding speed that changes the shape of the decay in the Stribeck region, exponent p affects the drop from static to dynamic friction and the parameter k_t adjusts the slope of the curve from zero relative speed to the maximum static friction.

Aerodynamic Force Model

To compute the aerodynamic forces acting on the tether, the model presented by Aslanov and Ledkov is implemented[14]. One of the fundamental assumption of the model is that every half of the tether part connecting two-point masses is considered rigid and hence moves at the same speed of the node. The aerodynamic force acting on a node *i* can then be computed as shown in Eq. (10).

$$F_{ai} = \frac{\rho v_i d}{4} c_d \left(\frac{n_i}{r_{i,i-1}} + \frac{n_{i+1}}{r_{i+1,i}} \right) \tag{10}$$

where, ρ is the atmospheric density, v_i is the velocity of node *i*, *d* is the tether diameter, c_d is the drag coefficient, $r_{i,i-1}$ is the distance between node *i* and *i-1*, and $n_i = (v_i \times r_i) \times r$.

The block diagram to simulate the docking mechanism for the tethered system is shown in Figure 2. The algorithm first computes the elastic and damping tension forces along with the aerodynamic forces acting on each node and then integrates the dynamic equations of motion to compute its positions and velocities. The collision detection algorithm is then carried out to detect impending collisions. The colliding nodes along with their penetration depth and relative velocities are computed and the corresponding contact normal and tangential forces are calculated which are then used to integrate the dynamic equations of motion.

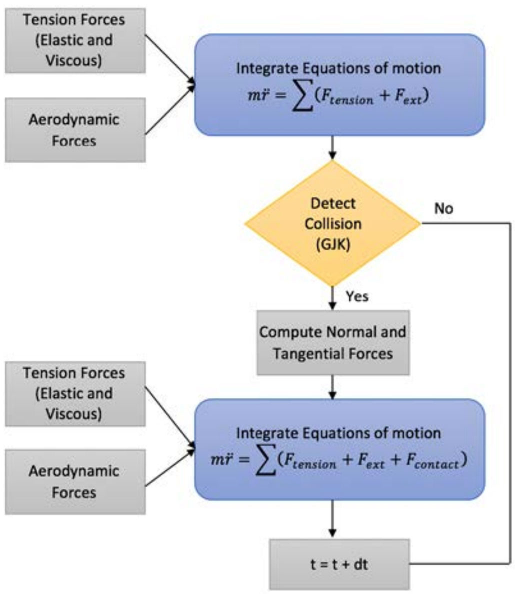

Figure 2. Algorithm to solve dynamic equations of motion.

SIMULATIONS AND RESULTS

Dynamics simulation are performed on a simplified cubic target satellite. The tethered system is modeled using 121 nodes, connected to four robots. The tethered system is deployed in a '+' configuration with initial relative velocity w.r.t. the target satellite of 0.1 m/s along the y-axis. The tether material is Technora used to suspend the NASA Mars rover Opportunity from its parachute during descent. For our simulation the Young's modulus of the tether is set at 25 GPa, the damping ratio is 0.3 and the density as 1,390 kg/m^3. For the contact dynamics, the stiffness parameter is considered as 500 N/m and the damping coefficient as 0.5. For the friction model, the coefficient of static and dynamic friction is 0.7 and 0.5 respectively and the parameters $v_s = 0.001$, $p = 2$, and $k_t = 10{,}000$. The dimension of the target satellite is 1.15 × 1.15 × 1.15 m. Figure 3 shows the capture and docking process at different timesteps.

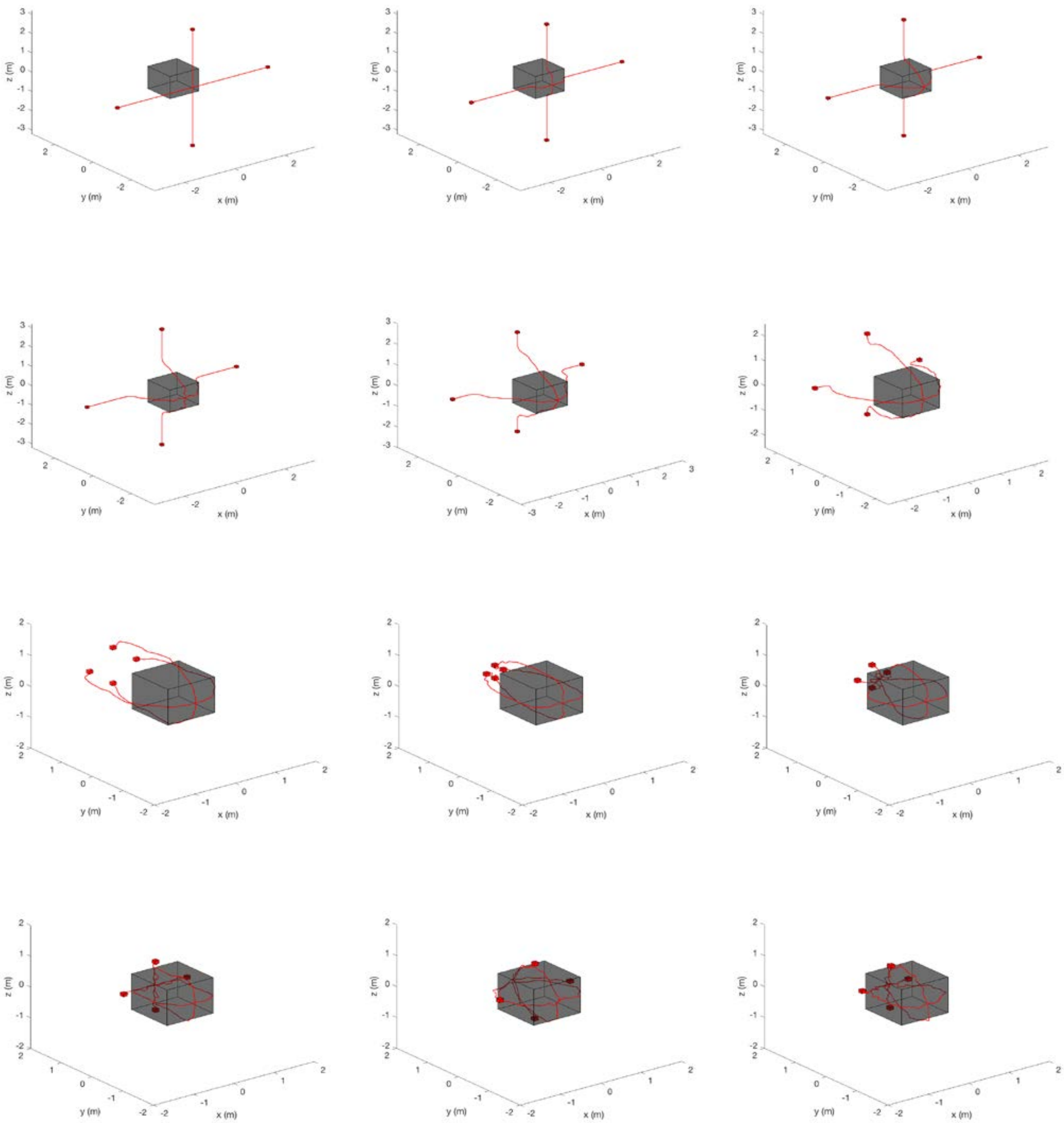

Figure 3. Capture and docking process at different timesteps.

Further simulations were performed with the target satellite rotating with a constant angular velocity of [1 0.5 0.2] deg/s as shown in Figure 4. The tethered robotic system was able to capture the target satellite.

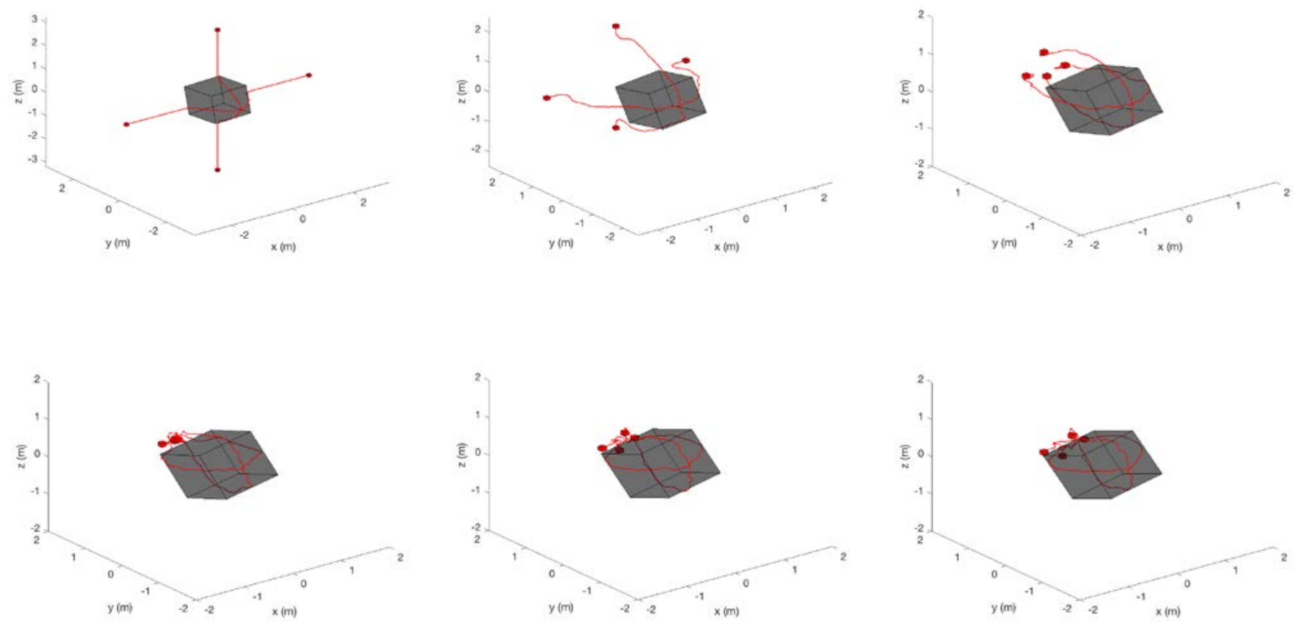

Figure 4. Capture process of a rotating target satellite.

Figure 5 shows the maximum tensile stress experienced by the tethers at any time instant. It is clear that the maximum stress experienced is 4.617 MPa which is less than the longitudinal tensile strength of Technora (2800 MPa).

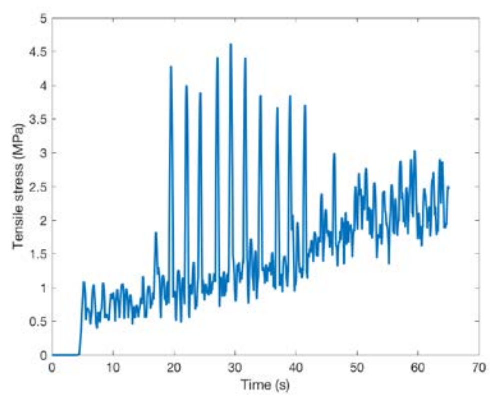

Figure 5. Maximum Tensile Stress on Tethers

These results show preliminary feasibility of using multiple tethered robots to capture a satellite. Beyond capturing the satellite, the tethered robots then need to climb and crawl to get to designated locations on the target satellite to perform repairs, add or replace components.

CONCLUSION

In this paper, we presented a detailed dynamic model of a tethered robotic system for capture and docking with a tumbling abandoned target satellite. Flexible body dynamics is used to model the tethers and then GJK collision detection algorithm is used to detect collisions and compute the contact normal and friction forces. In addition, disturbance forces like aerodynamic drag forces are taken into consideration. Detailed simulation results are presented where the effect of contact dynamics and flexible dynamics of the tethers can be seen. The tensile stresses acting on the tethers were within the limit of the tensile strength of the tether material. Our future work will include performing simulations with more complex shaped target satellite and also high velocity impact collisions.

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