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Towards Passive Object On-Orbit Manipulation by Cooperating Free-Flying Robots

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***Abstract*—Space exploitation will require efficient techniques for manipulating passive objects on orbit. This work presents a manipulation concept that utilizes both the on-off thrusters and manipulator proportional forces to manipulate passive objects on orbit more efficiently. The system dynamics arising from the unilateral constraints and the on-off thrusting are discussed. The manipulation concept is illustrated using a simplified one-dimensional model. A novel controller based on backstepping and Lyapunov stability is presented and its performance, stability and robustness are discussed. The performance of this system is compared to that of a standard using on-off thrusters only, and is shown to use less fuel.**

I. INTRODUCTION

The commercialization of space and the growing number of structures in orbit, require systems capable of fulfilling tasks such as construction, maintenance, astronaut assistance, docking and inspection, or even orbital debris handling and disposal. These tasks fall under the concept of On-Orbit Servicing (OOS), a relatively new but growing area of interest in space. Some of these tasks are currently performed by astronauts in Extra Vehicular Activities (EVA). However, these are dangerous tasks, subject to limitations such as the magnitude of a force/torque an astronaut can apply, motions that can be performed, or even EVA time limitations. In order to relieve the astronauts from as much EVAs as possible, enhance EVA performance and expand the EVA with tasks that astronauts cannot perform, robotic systems acting as servicers in the form of orbital agents will be required.

Robotic OOS has been studied for the last two decades and many architectures have been proposed [1]. Important tasks requiring robotic EVAs, such as orbital assembly, debris handling etc., require manipulation of passive objects. The first step in the handling procedure is to securely and firmly grasp the passive object, a task called docking. Studies in this field have provided several theoretical approaches [2, 3], some of which have also resulted in some experimental servicers [4, 5]. Nevertheless, actual handling of the firmly grasped passive object has not been studied adequately. This task poses several challenges, combining issues from cooperative manipulation of passive objects on earth [6] and coordinated motion of interacting objects in space. The later becomes a challenge in this environment, since there is no fixed ground to support the manipulator, thus leading momenta accumulation to play a key role in body motion.

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Although several prototype robotic servicers have been proposed and studied since the 1990's [4, 5, 7, 8], there are only a few theoretical studies concerning the dynamics and control of the motion of an already grasped body. Dubowsky et al. proposed a control method for handling large flexible objects, where several robots with manipulators grasp them, and use their thrusters as a low frequency control of object rigid body motion, while they use their manipulators, via a high frequency control, to cancel out vibrations this motion causes on the flexible bodies [9]. Not all objects requiring handling in the orbital environment are flexible, though. Both in orbital construction and in orbital debris handling, a wide variety of rigid bodies needing handling exists. Fitz-Coy and Hiramatsu presented a post-docking control approach based on game theory, which minimizes the interaction forces, and thus helps avoiding the loss of firm grasp [10]. Everist et al. proposed a free-flying servicer concept for handling and assembling space construction rods, using proportional thrusters under PD control [11]. Orbital system thrusters, though, operate under on-off control.

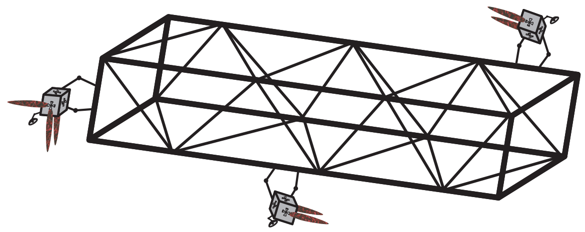

Figure 1. Handling of a rigid passive body by a number of smaller cooperating free-flyers equipped with manipulators.

This work presents a strategy that utilizes both on-off thruster propulsion and manipulator proportional forces/ torques from several robotic servicers, see Fig. 1, enhancing the performance of the control exerted on the handled passive body. The concept of a number of cooperating free-flying servicing robots with manipulators handling a larger passive rigid body is presented and the system dynamics is discussed. A simplified model, developed to gain basic insight, is presented, along with its equations of motion. A control algorithm based on backstepping is derived and its performance, stability and robustness are studied. Finally, the controller performance is compared to that of a controller that uses only on-off thruster forces, showing an improvement in system positioning accuracy and efficiency.

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II. Manipulation By Free-Flying Robots

Several methods exist that can be applied in handling a passive rigid body. One such method requires using thruster on-off forces only, e.g. by thrusters attached to the body. Another one is by controlling it via free-flying robotic servicers, as shown in Fig. 1. In this case, the only external forces being able to move the system's center of mass, are the forces applied by the on-off thrusters.

Moreover, the total forces and torques acting on the passive body are of proportional nature, i.e. those exerted by the manipulators. This has the effect of filtering the on-off forces/torques of the thrusters and enabling both point-to-point and trajectory tracking control of the body.

Note that, to avoid damaging an object, the thrusters pointing toward it would have to be turned off. The robots should also deactivate any thrusters pointing towards each other, for the same reason. Thus, the placement of the robots around the passive object should be carefully planned, so as to keep as many thrusters operational as possible, while keeping the robots and the object secured.

Another issue that needs to be pointed out is the type of attachment of the manipulators to the passive body. To manipulate a passive body, three forces and three torques must be exerted on it, so as to control its six degrees of freedom (DOFs). The obvious solution for the attachment of the free-flyers is to firmly grasp the passive body. However, this is not always feasible. When firm grasping is achieved, a single free-flying robot can produce the required control on the six DOFs of the passive body. Since some thrusters of the robot must be inactivated for safety reasons, one single servicer will face the problem of not being able to exert any thruster force towards one or more directions. Thus, a number of cooperating free-flyers is needed, even in the case of firm grasps. It is easy to see that the minimum number needed for 3D manipulation is two robot servicers, attached roughly opposite to each other. Nevertheless, the number of the robots required depends also on whether they are capable of applying the required forces/ torques.

Whenever firm grasping is not an option, the manipulators can only push the passive body (unilateral constraint). This is a far more complicated problem and the minimum number of robots required for this task depends on many issues, such as how many manipulators each robot has, how easily each end effector can slip on its contact point/area, the nature of the desired motion etc. Such issues have been studied for terrestrial systems but not for systems in zero-g, where the absence of a fixed base or of gravity, pulling all bodies towards one direction, makes the aspect of loosing contact a possibly fatally important parameter.

To study the handling of objects on orbit, we first study the dynamics of orbital robotic servicers attached to a rigid passive body. The equations of motion of such a system are

$$\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{J}^T \mathbf{Q} \tag{1}$$

In (1), $\mathbf{q}$ is the $n \times 1$ vector of the generalized coordinates, that includes the 3(m+1) positions and 3(m+1) Euler angles of the m robot bases and those of the passive body, along with the joint variables of each robot's manipulator. $\mathbf{Q}$ is a $k \times 1$ vector of the generalized forces, that is the forces of all thrusters and the torques of all reaction wheels of the m robots and the joint torques of all robot manipulators, $\mathbf{J}$ is a $k \times n$ Jacobean matrix of the generalized forces, $\mathbf{H}$ is an $n \times n$ mass matrix related to the inertia properties of all the bodies in the system, and $\mathbf{C}$ is an $n \times 1$ vector that contains all the nonlinear velocity terms.

In the case of handling a passive object by attaching thrusters on it or by using free-flyers with rigid appendages (as opposed to employing manipulators), the result would be the same as trying to control a rigid free-flying system (such as a satellite etc.) by its thrusters only. At present, the control on these systems is on-off, initiated by PD control on an error variable. On-off control is used in order to protect the thrusters from the extreme space environment and especially in order to prevent ice from forming in the nozzles of the thrusters. This type of control, leads to limit-cycles around a desired state or even chattering, a phenomenon that consumes a lot of fuel and wears out the thrusters.

In order to demonstrate the issues arising in this direct actuation method, the dynamic equations of motion of a simplified, one-dimensional model are derived

$$m\ddot{x} = u_1 + u_2 \tag{2}$$

where m is the system mass, x its position, u_1 and u_2 are the on-off control forces acting on it, see Fig. 2.

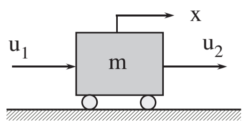

Figure 2. Model of a passive body controlled by thrusters.

A PD initiated, on-off controller is given by

$$u_1 = \begin{cases} u_{\max} & \text{if } K_P e + K_D \dot{e} \geq f_t \\ 0 & \text{if } K_P e + K_D \dot{e} < f_t \end{cases} \tag{3}$$

$$u_2 = \begin{cases} -u_{\max} & \text{if } K_P e + K_D \dot{e} \leq -f_{trig} \\ 0 & \text{if } K_P e + K_D \dot{e} > -f_{trig} \end{cases} \tag{4}$$

where e = x_{des} − x, is the position error of the controlled body, u_{max} is the force applied by an open thruster and f_t inserts a deadband on the controller, in order to avoid chattering. Fig. 3 shows a typical response of such a system, where a fuel consuming limit-cycle can be observed, even though chattering is avoided.

To enhance the control performance over the passive body, the introduction of manipulators in the control of the body is studied next. Our goal is to perform fine positioning of a passive rigid body, without any limit-cycle effects on its motion, while the controlling robotic servicers stay within the range of their manipulators. We will also look at the fuel efficiency problem, which is very important in space.

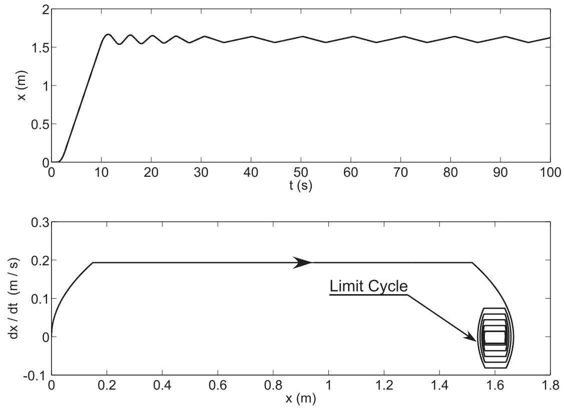

Figure 3. Typical response of On-Off PD control, with limit cycle.

III. SIMPLIFIED EXAMPLE

To obtain basic insight on the dynamic behavior and the control requirements of the dynamic system, a simplified one-dimensional model is analyzed. A passive rigid body of mass m_0 moves along a line and a number of robots with thrusters firmly grasp the passive body via manipulators.

As already discussed, to protect each body from the thruster plumes, the robot thrusters pointing towards other bodies must be inactive. Thus, more than one robots are needed, to be able to apply thruster (external) force towards both directions. As a result, two robots of masses m_1 and m_2 are chosen to manipulate the body, placed one at each side of it. The only external forces acting on the system and moving its center of mass are the thruster forces u_1 and u_2, as shown in Fig. 4. The position vectors x_0, x_1 and x_2 refer to the controlled body, the robots of masses m_1 and m_2.

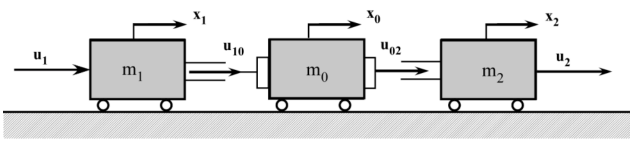

Figure 4. A passive (center) body handled by servicers with manipulators.

Note that, since here the motion is one-dimensional, **C** in (1) is zero. The generalized forces vector **Q**, consists of the thruster (u_1 and u_2) and manipulator (u_{10} and u_{02}) forces, where the later are the ones acting on the robotic servicers. Thus, the forces $-u_{10}$ and $-u_{02}$, are the only ones acting on the body, filtering the on-off thruster force effects on it. Using (1), the error-dynamics equations of motion are

$$\ddot{\mathbf{e}}=\begin{bmatrix}\ddot{e}_0\\ \ddot{e}_1\\ \ddot{e}_2\end{bmatrix}=\underbrace{\begin{bmatrix}0 & \frac{-1}{m_0} & \frac{-1}{m_0} & 0\\ \frac{-1}{m_1} & \frac{m_0+m_1}{m_0 m_1} & \frac{-1}{m_0} & 0\\ 0 & \frac{1}{m_0} & \frac{m_0+m_2}{m_0 m_2} & \frac{1}{m_2}\end{bmatrix}}_{\mathbf{H}^{-1}\mathbf{J}^T}\underbrace{\begin{bmatrix}u_1\\ u_{10}\\ u_{02}\\ u_2\end{bmatrix}}_{\mathbf{Q}}-\begin{bmatrix}\ddot{x}_{0\_des}\\ 0\\ 0\end{bmatrix} \tag{5}$$

with $u_1 > 0$, $u_2 < 0$ in on-off mode, while e_i are defined as

$$\begin{aligned} e_0 &= x_0 - x_{0\_des}\\ e_1 &= x_0 - x_1 - x_m/2\\ e_1 &= x_2 - x_0 - x_m/2 \end{aligned} \tag{6}$$

where x_{0_des} is the desired value for the passive body to be controlled and x_m is the manipulator reach. It is important to point out that, by trying, with the appropriate control, to set these error variables to zero, the passive body is forced to follow its desired trajectory, while the free-flying robots are forced to stay at a distance from the passive body, as close as possible to half the maximum manipulator length.

IV. CONTROL DESIGN

In order to derive the desired controller we use a *backstepping* methodology [13]. According to this method, we "step back" at each iteration, in order to create the control inputs from the simple subsystems of a more complex dynamic model. By transforming into new variables at each iteration, a nonlinear system can be lead to display linear behavior, if there are no uncertainties on the modeling of the dynamic system. A very important characteristic of backstepping is that, in the process of variable transformation, it avoids the elimination of nonlinear quantities, important for stability and trajectory tracking, as opposed to feedback linearization. Thus, it ensures stability of the controlled system and assists trajectory tracking algorithms. Other control approaches like optimal or H^{∞} control can also be used. Nevertheless, a more realistic 3D system is highly nonlinear, with joint friction and actuator nonlinearities. In those cases, backstepping is easier to implement. By applying this method to (5), the following control is obtained

$$\begin{aligned} u_{10} &= \frac{m_0}{2}K_0\left(\dot{e}_0+K_0e_0\right)+m_1K_1\left(\dot{e}_1+K_1e_1\right)+\\ &\quad +m_2K_2\left(\dot{e}_2+K_2e_2\right)-\frac{m_0}{2}\ddot{x}_{0\_des}\\ u_{02} &= \frac{m_0}{2}K_0\left(\dot{e}_0+K_0e_0\right)-m_1K_1\left(\dot{e}_1+K_1e_1\right)-\\ &\quad -m_2K_2\left(\dot{e}_2+K_2e_2\right)-\frac{m_0}{2}\ddot{x}_{0\_des} \end{aligned} \tag{7}$$

$$\begin{aligned} u_1 &= \frac{m_0}{2}\ddot{x}_{0\_des}-m_2K_2\left(\dot{e}_2+K_2e_2\right)-\left(\frac{m_0}{2}+m_1\right)K_0\left(\dot{e}_0+K_0e_0\right)\\ u_2 &= \frac{m_0}{2}\ddot{x}_{0\_des}+m_1K_1\left(\dot{e}_1+K_1e_1\right)-\left(\frac{m_0}{2}+m_2\right)K_0\left(\dot{e}_0+K_0e_0\right) \end{aligned} \tag{8}$$

where K_i (i = 0, 1, 2) are the controller gains, and u_1 and u_2 are assumed to be proportional forces. In our case, though, u_1 and u_2 are thruster unidirectional on-off forces. Thus, a switching strategy must be derived, based on (8). A possible strategy is to turn each thruster on when the backstepping derived proportional value exceeds a threshold value f_t. Thus, the final control algorithm is given by (7), and (9).

$$u_1 = \begin{cases} f_m \text{ if } \frac{m_0}{2}\ddot{x}_{0\_des} - m_2 K_2(\dot{e}_2 + K_2 e_2) - \\ \quad -\left(\frac{m_0}{2} + m_1\right) K_0(\dot{e}_0 + K_0 e_0) \geq f_t \\ 0 \text{ if } \frac{m_0}{2}\ddot{x}_{0\_des} - m_2 K_2(\dot{e}_2 + K_2 e_2) - \\ \quad -\left(\frac{m_0}{2} + m_1\right) K_0(\dot{e}_0 + K_0 e_0) < f_t \end{cases}$$

$$u_2 = \begin{cases} -f_m \text{ if } \frac{m_0}{2}\ddot{x}_{0\_des} + m_1 K_1(\dot{e}_1 + K_1 e_1) - \\ \quad -\left(\frac{m_0}{2} + m_2\right) K_0(\dot{e}_0 + K_0 e_0) \geq -f_t \\ 0 \text{ if } \frac{m_0}{2}\ddot{x}_{0\_des} + m_1 K_1(\dot{e}_1 + K_1 e_1) - \\ \quad -\left(\frac{m_0}{2} + m_2\right) K_0(\dot{e}_0 + K_0 e_0) < -f_t \end{cases} \tag{9}$$

Since the only force exerted on the passive body is the sum of the manipulators forces, this controller leads to a simple PD control on the tracking error. In addition to that, each manipulator controller takes into account the requirement to stay within each manipulator's reach.

We study next the stability of the control system. Backstepping generally ensures the stability of the controller. In the current case, though, it is used to provide a switching strategy for the on-off forces that facilitates the stability proof, as will be shown next.

The passive body moves under proportional forces and no on-off force is acting on it. Hence, the stability of its motion can easily be proven by using Lyapunovs' global stability theorem, with the following Lyapunov function

$$V_0 = \frac{1}{2}\left(\dot{e}_0^2 + K_0^2 e_0^2\right) > 0 \tag{10}$$

Then, from (10), the following is obtained

$$\lim_{e \to \pm\infty} V_0 = \pm\infty \tag{11}$$

Differentiating (10) and using (5) and (7), we obtain

$$\dot{V}_0 < 0 \tag{12}$$

According to Lyapunovs' global stability theorem, (10), (11) and (12) ensure global asymptotic stability of the passive body motion and therefore e_0 tends to zero.

For the relative motion between the robots and the passive body, asymptotic stability with respect to a specific position is not of interest. However, it is important to ensure that the values of the relative distances are bounded. What makes the analysis harder, is that some of the forces are continuous (i.e. (7)), while the rest are switched (i.e. (9)), resulting in a controller. Using proof by contradiction, we have proved that at each phase of this switched control, the relative motions are bounded, independent of the previous phases, or the state of the system at the initial time of the current phase. The proof is omitted here for brevity.

V. Simulation Results

To display the stable performance of the controller and verify the soundness of the proposed method, a series of simulations was run. To this end we assume a rigid passive body of 400 kg mass, manipulated by two free-flying robots of 90 kg each. Each robot has a thruster pointing away from the controlled body, which, when fired, delivers a force of 50 N. The triggering value f_t for the thrusters' initiation is set to 40 N. Both robots manipulators have a 3 m reach.

First, a simple forward motion is simulated, where the passive body has to follow a trapezoidal profile on its velocity. The body accelerates with constant acceleration of 0.05 m/s^2 for 10 s. Then, its desired velocity remains constant at 0.5 m/s for 40 s. Finally, it decelerates till zero velocity for 10 s, and then it remains still. The gains of the controller for this simulation were set to K_0 = 1.5, K_1 = 0.8 and K_2 = 0.8. Fig. 5 shows the motion of the three bodies, the tracking error of the passive body and the distances between the two robots and the passive body. Fig. 6 shows the manipulator applied forces and the on-off thruster forces.

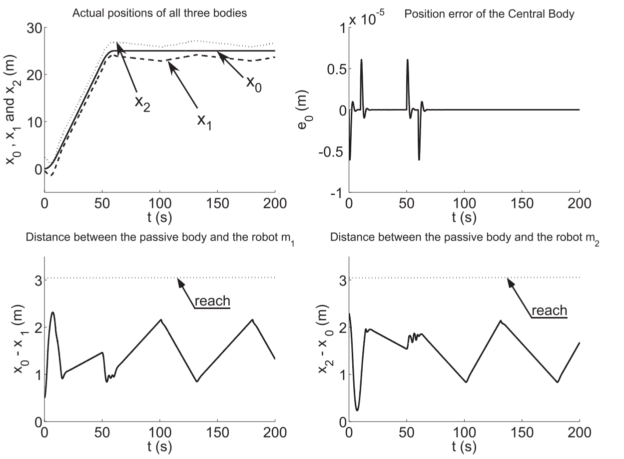

Figure 5. Response of the system with manipulators, for a trapezoidal profile desired velocity.

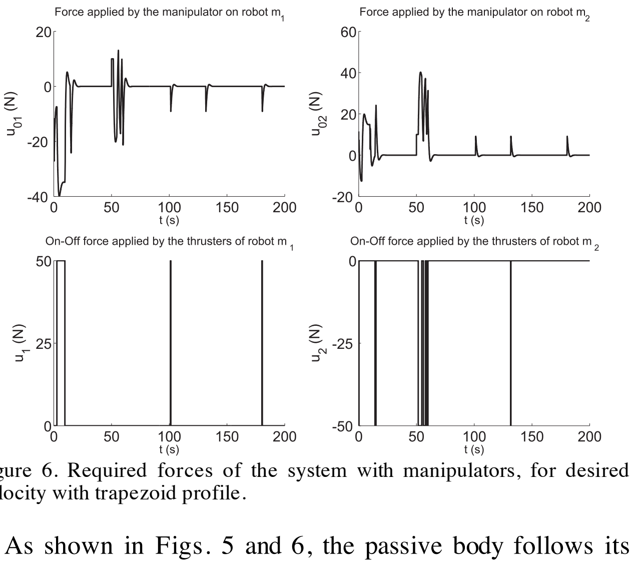

Figure 6. Required forces of the system with manipulators, for desired velocity with trapezoid profile.

As shown in Figs. 5 and 6, the passive body follows its desired trajectory very well, while the distances between the robots and the body remain within the workspace limits. Another important issue shown in these plots is that, even in this case, there is a very small limit-cycle effect remaining, at the steady state part of the simulation. This is happening because, in order to keep the passive body inactive with ever diminishing position error, manipulators apply a small remaining force. Due to this reason, a small remaining relative motion between each robot and the passive body, forces the robots to move slowly towards the boundary distances from the body. When they move too close to these distances, the controller briefly activates the thrusters setting this small motion towards the opposite direction. However, this effect, as will be shown later, is far less intense than the classic limit-cycle occurring on pure on-off controlled systems.

The next simulation corresponds to a more demanding passive body trajectory, since it corresponds to a sinusoidal motion with a 5 m amplitude and a 0.07 rad/s frequency. Fig. 7, 8 display the same features as those in Figs. 5, 6.

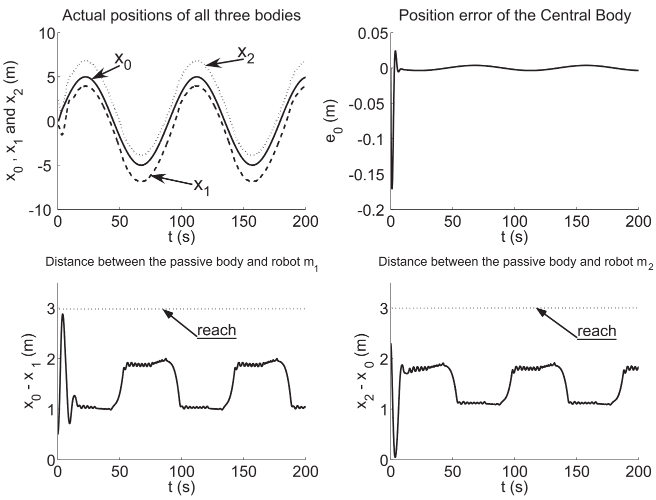

Figure 7. Response of the system with manipulators, for sinusoidal position.

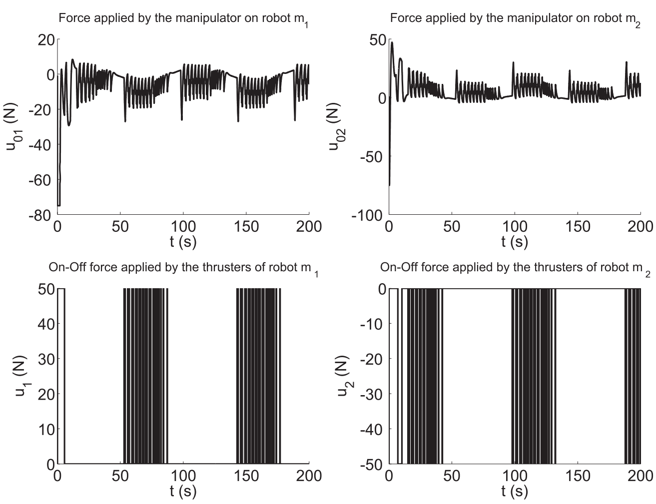

Figure 8. Required forces of the system with manipulators, for sinusoidal desired position.

Even this demanding trajectory is followed easily, with the distances between the robots and the controlled body remaining within limits. As expected, the fuel consumption is now greater since the desired motion is time varying.

Having demonstrated the stable performance of the controller, we examine next its robustness. Several tests with inaccurate parameter estimations and measurements were conducted. Again, the same trapezoidal profile on the desired passive body velocity was used.

In Fig. 9 and 10, the same variables as in Fig. 5 and 6 respectively, are displayed. However, here inaccurate estimation of the three masses is assumed, at a rate of 15% for the passive body, 10% for one robot and 5% for the other. Besides that, the measurement of all three velocities is assumed to include Gaussian noise, with variance 0.04. Moreover, one thruster is assumed to have a lag of 0.3 s. Finally, one manipulator is assumed to be flawed and to always apply 10% less of the required force.

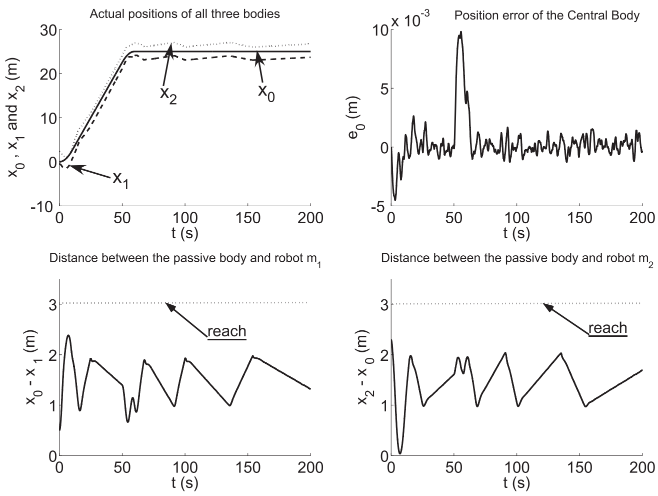

Figure 9. Response of the system with manipulators, for desired velocity with trapezoid profile, with inaccurate parameters estimation.

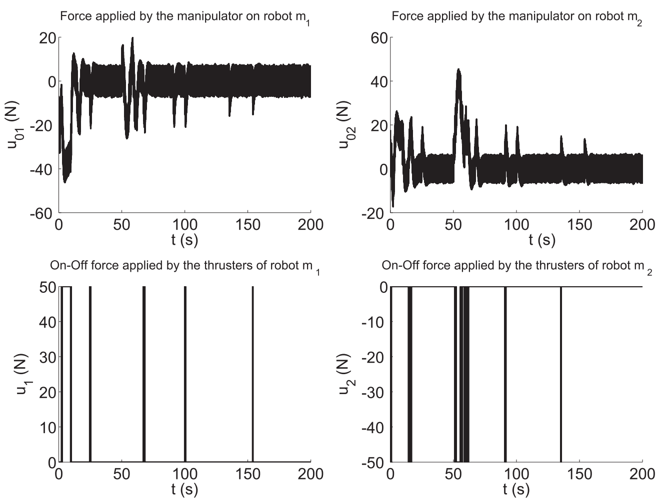

Figure 10. Required forces of the system with manipulators, for desired velocity with trapezoid profile, with inaccurate parameters estimation.

It can be observed that the method displays a very robust behavior, even though four very important inaccuracies occur simultaneously. The position error of the passive body motion is obviously larger, but still remains quite small.

As mentioned in the previous sections, the proposed controller, even reaching a type of a small limit-cycle, is greatly improved over the simple on-off control. This is illustrated in Fig. 11 in which the motion of a system without manipulators Fig. 11(a), (c) is compared to a system with manipulators Fig. 11(b), (d).

The one-dimensional motion of the system without manipulators is modeled as shown in (2) and the controller is the one shown in (3) and (4). Using the same backstepping approach as we used to derive the controller for the system with manipulators, the same PD on-off controller as the one shown in (3) and (4) is obtained. According to backstepping stability requirements, the control gains K_p and K_D should satisfy the following condition,

$$K_D = K_P^2 \tag{13}$$

Trapezoidal velocity profiles for the passive object were selected for both systems. Fig. 11 displays the position errors on the motion of the passive body, as well as the energy consumption for both cases. The latter is computed as the integral of the work produced by both thruster forces (chemical energy) and manipulator forces (electrical energy). Note that, depending on motor drives, it may be possible to recuperate the electric energy supplied to the motors when the applied force of a manipulator is opposing the relative motion of the passive body and the corresponding free-flyer. If this possibility does not exist, then the brake energy is dissipated to heat. The energy for both of these cases is displayed in Fig. 11d.

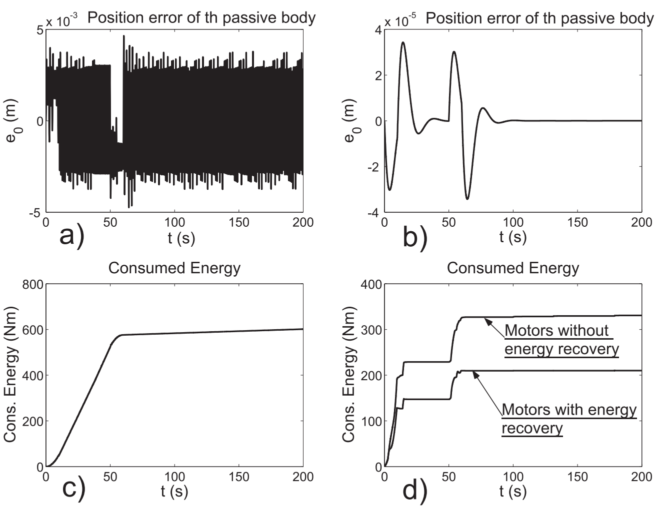

Figure 11. Position error as a function of time and corresponding consumed energy (a), (c) without manipulators, and (b), (d) with.

To reduce the position error without manipulators, the control gains must be increased, or equivalently, f_t must be decreased. This results in an even larger fuel consumption, since the thrusters fire more frequently. Note, though, that the system with the manipulators yields a passive body position error which is two orders of magnitude smaller than the one of the system without them. Moreover, it also uses far less fuel, making the introduction of manipulators a significant improvement, over the simple PD on-off control. When the desired trajectory for the passive body is more demanding, the comparison is even more in favor of employing manipulators in controlling the passive object.

VI. Conclusions

The concept of cooperative manipulation of a rigid passive body, via manipulators based on a number of free-flying robots in zero-g environment, was introduced in this paper. The system dynamics arising from the unilateral constraints and the on-off thrusting were discussed and the manipulation concept was illustrated using a simplified one-dimensional model. A novel controller was presented, based on backstepping and Lyapunov stability theories. It was shown that the introduction of manipulators in the handling of a passive body is a vast improvement over the simple on-off control, currently used in the control of orbital systems, both in terms of errors and in terms of fuel consumption.

Although the motion of an actual 3D system is far more complex, the proposed concept can assist in the design and control of novel orbital robotic servicers required in future space projects and in the exploitation of space.

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