A Comparison of the Use of a Single Large vs a Number of Small Robots in On-Orbit Servicing

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ABSTRACT

The growing exploitation of space will require efficient techniques for on-orbit passive object manipulation. This paper presents initial work on the question of whether it is better to handle a passive object by a number of small robotic servicers or by a single one. A handling method developed previously by the authors is employed in comparing the two cases in the task of handling of a passive object. To this end, a number of characteristic trajectories are simulated. Three small, identical servicers are assumed in one case and a single, scaled-up servicer is assumed in the other. The total fuel consumption is used as a performance index, while the tracking motion error is kept the same in the two cases. It is found that the system comprising a large servicer has higher fuel consumption than the system with three small servicers.

1. INTRODUCTION

As man activities encompass space, opportunities for space tasks will increase while requirements for space structures will be on high demand. The exploitation of space and the growing number of orbital structures, will require systems capable of fulfilling tasks such as construction, maintenance, astronaut assistance, or even orbital debris handling and disposal. Some of these tasks can be performed by astronauts in Extra Vehicular Activities (EVA). These, however, are in general dangerous tasks, subject to limitations such as the magnitude of a force/torque an astronaut can apply, complexity of motions that can be performed, or even EVA time limitations. To relieve astronauts from EVA, enhance EVA performance and expand the EVA with tasks that astronauts cannot perform, robotic systems acting as orbital servicers will be required.

Important tasks requiring robotic EVAs, such as debris handling (e.g. the handling of an irreparable satellite, such as the Envisat), orbital assembly (e.g. the construction of another space station around the Earth or even around Mars), require manipulation of passive objects. Even though the first step in the handling procedure, i.e. securing the passive object or docking, has been studied extensively during the last decades, the actual handling of the secured passive object has not been studied adequately.

Robotic OOS has been discussed and a number of architectures have been proposed [1]. Although several prototype robotic servicers have been introduced and studied since the 1990's [2] - [6], only a few studies concern the dynamics and control during the autonomous handling of an already secured object. Dubowsky et al. proposed a control method for handling large flexible objects, aiming at flexibility-induced vibrations reduction. Robotic servicer thrusters are used as a low frequency control of a rigid body motion, while their manipulators are used as a high frequency control, cancelling out vibrations this motion causes on the flexible modes [7]. Nevertheless, in several cases, the handled object flexibilities can be neglected, due to size and low accelerations during the motion.

In orbital construction and in orbital debris handling, a wide variety of rigid bodies that need to be handled exists. Fitz-Coy and Hiramatsu presented a post-docking control approach based on game theory, minimizing interaction forces, and thus helping avoid the loss of firm grasp [8]. Moosavian et al. presented a passive object manipulation method by a single servicer with multiple manipulators, aiming at an object prescribed impedance behavior, in case of contact with the environment [9]. Everist et al. proposed a free-flying servicer concept for handling and assembling space construction rods, using proportional thrusters under PD control [10]. Orbital system thrusters, though, are of an on-off control nature, leading to limit cycles in the motion of the handled object that reduce the accuracy and increase fuel consumption, compared to non on-off control.

To tackle this problem, Rekleitis and Papadopoulos have proposed the use of a number of manipulator-equipped servicers, where both on-off thruster propulsion and manipulator continuous forces/ torques are used in object handling, [11], [12], see Fig. 1. It was shown that, since the relative motion between the servicers and the passive object only needs to be bounded, the servicers can be free to move in some envelope with respect to the passive object under scarce thruster firing, while their manipulators can apply continuous forces on the passive object, filtering the on-off thruster force effects on it and lowering fuel consumption and tracking errors [12]. The asymptotic stability of the motion of the passive object, subject to a total generalized force applied by the robotic servicers manipulators, and computed using to a model-based controller with PD action, was also proven in the same work.

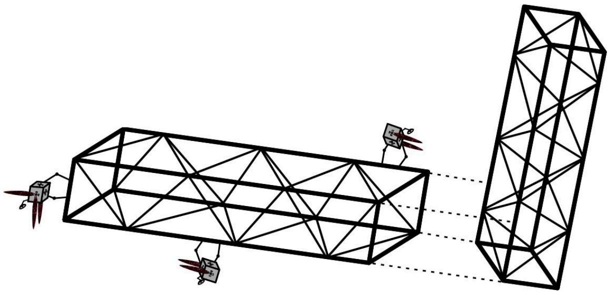

Figure 1. Handling of a rigid passive body by a number of cooperating free-flyers equipped with manipulators, during a space structure assembly.

In that work, the authors suggested single manipulator servicers and, via simulations, they demonstrated the superiority of the proposed control method over the pure on-off control that would result from firmly attaching free-flyers on the passive object and using their on-off thruster to control it, both in terms of fuel consumption and in terms of accuracy of the passive object trajectory tracking.

This paper presents initial work on the question of whether it is better to handle a passive object by a number of small servicers or by a single large one. The abovementioned method is used to compare the two cases in the handling of the same passive object. To this end, a number of characteristic trajectories is simulated, while for simplicity, single-manipulator servicers are assumed in both cases. Each of the free-flying servicers is equipped with reaction wheels that provide proportional torques, pairs of on-off thrusters that provide additional on-off torques and on-off thrusters that provide pure force. The comparison is done in terms of total fuel consumption, for the same trajectory tracking motion accuracy for the passive object.

2. DYNAMICS AND CONTROL OF THE SYSTEM

Assume a passive object of mass m_0 and inertia matrix ${}^0\mathbf{I}_0$. For the remaining of the paper, a subscript of zero refers to the passive object. The zero superscript in ${}^0\mathbf{I}_0$ means that the inertia matrix is defined in the passive object body-fixed frame. On the object, a generalized force $\mathbf{Q}_0$ is acting by the end-effectors of a number of robotic servicers, as also described in [12]. Then, the equation of motion of the object, is

$$\mathbf{H}_0\ddot{\mathbf{q}}_0 + \mathbf{C}_0\left(\mathbf{q}_0, \dot{\mathbf{q}}_0\right) = \mathbf{Q}_0 \tag{1}$$

where $\mathbf{q}_0$ are the generalized coordinates for the passive object,

$$\mathbf{q}_0^T = \left[\mathbf{r}_0^T, \boldsymbol{\theta}_0^T\right]^T = \left[x_0, y_0, z_0, \theta_0, \varphi_0, \psi_0\right]^T \tag{2}$$

where, $[x_0 \; y_0 \; z_0]^T$ is the position vector $\mathbf{r}_0$ and the row vector $[\theta_0 \; \varphi_0 \; \psi_0]^T$ denotes the Euler angles $\boldsymbol{\theta}_0$ of the passive object. $\mathbf{H}_0$ is the 6×6 mass matrix of the passive object, with

$$\mathbf{H}_0 = \begin{bmatrix} \mathrm{diag}(m_0, m_0, m_0) & \mathbf{0}_{3x3} \\ \mathbf{0}_{3x3} & \mathbf{E}_0^T\mathbf{R}_0\,{}^0\mathbf{I}_0\mathbf{R}_0^T\mathbf{E}_0 \end{bmatrix} \tag{3}$$

where $\mathbf{I}_{3x3}$ is the 3×3 identity matrix, $\mathbf{R}_0$ is the rotation matrix transforming vectors from the frame of the passive object to the inertial frame and $\mathbf{E}_0$ is a 3×3 matrix mapping the Euler rates $\dot{\boldsymbol{\theta}}_0$ of the passive object to its angular velocity $\boldsymbol{\omega}_0$:

$$\boldsymbol{\omega}_0 = \mathbf{E}_0\dot{\boldsymbol{\theta}}_0 \tag{4}$$

$\mathbf{C}_0$ is a 6×1 vector containing the nonlinear velocity terms,

$$\mathbf{C}_0 = \left[\mathbf{0}_{1x3}, \left(\mathbf{E}_0^T\left(\mathbf{R}_0\,{}^0\mathbf{I}_0\mathbf{R}_0^T\dot{\mathbf{E}}_0\dot{\boldsymbol{\theta}}_0 + \mathbf{E}_0\dot{\boldsymbol{\theta}}_0 \times \mathbf{R}_0\,{}^0\mathbf{I}_0\mathbf{R}_0^T\mathbf{E}_0\dot{\boldsymbol{\theta}}_0\right)\right)^T\right]^T \tag{5}$$

Eqs. (1) to (5) also describe the robotic servicers, after substituting subscript 0 by i, where $i = 1,\ldots, n$ (for the case of n small servicers) or $i = 1$ (for the case of a single large servicer).

The model-based controller with PD action that was chosen for the passive object is given by,

$$\mathbf{Q}_0 = \mathbf{C}_0 + \mathbf{H}_0\left(\ddot{\mathbf{q}}_{0d} + \mathbf{K}_{P0}\mathbf{e}_0 + \mathbf{K}_{D0}\dot{\mathbf{e}}_0\right) \tag{6}$$

where $\mathbf{e}_0 = \mathbf{q}_{0d} - \mathbf{q}_0$ and $\mathbf{q}_{0d}$ is the desired trajectory for the passive object and $\mathbf{K}_{P0}$ and $\mathbf{K}_{D0}$ are control gains. Use of controller (6) leads to asymptotically stable motion of the passive object, as can be easily proven using Lyapunov stability theory [12].

Although (6) dictates the force and torque that must be applied to the object, the end-effector forces, in the case of a number of small servicers, cannot be calculated by (6) due to redundancy and to the existence of constraints. Therefore, in this case and at each moment t of the motion of the system, we resort to the use of a constrained nonlinear optimization, as a force distribution method, with the components of the end-effector generalized forces as the design parameters.

Planning the desired free-flying servicer trajectory is complex, for both cases, as the manipulator servicer will have to apply the required generalized force on the passive object while maintaining a desired position and attitude of its base that takes into account workspace and collision avoidance requirements. To this end, appropriate initial servicer base position and orientation with respect to the passive object are selected.

In more detail, it is desired that the base relative position and orientation are maintained within certain safety limits, throughout the object motion. Hence, the desired servicer base trajectory $\mathbf{q}_{id}$ is computed based on the object trajectory and sent to its motion controller. The servicer motion controller takes as feedback the position and attitude of the servicer base and uses it to compute the motion tracking errors, based on its desired trajectory. Then, a model-based PD controller, like the one in Eq. (6), is employed to provide the control generalized forces on the servicer base. Those forces, though, are continuous, whereas the thrusters that are on the servicer base are on-off. Therefore, a switching strategy is chosen in order to provide the final control input for the servicer. Note that, for the motion of the servicers, we do not require asymptotic stability. We only need the relative motion (position/ orientation) between each servicer and the passive object to be bounded within the workspace on the corresponding manipulator. For a more detailed description of the controller, both for the passive object and for the servicers, please refer to [12].

3. ONE LARGE VS THREE SMALL SERVICERS

As seen in [12], for the case of a number of small servicers, each servicer has the thrusters that face the passive object deactivated for safety reasons. Thus, the only force that can repel a thruster from the passive object can come from its manipulator. For that reason, an extra force is added, when needed, to the manipulator force required for the control of the passive object. This extra force would act as a disturbance to the passive object motion, but its effect is cancelled out by appropriate counter forces applied by the other servicer manipulators.

In the case of a single, large robotic servicer, this approach cannot be applied, since there are no additional servicers whose manipulators would cancel out the effect the extra repulsive force would have on the passive object. In order to overcome this problem, we assume that in the case of a single robotic servicer, the servicer controller would orient its base (relative to the passive object) such, that there would always exist pairs of thrusters with forces $\mathbf{f}_{1j}$ along lines that do not pass through the passive object, but would have components $\mathbf{f}_{1jr}$ along the desired direction, as can be seen in Fig. 2. Moreover, the other components of the thruster forces ($\mathbf{f}_{1jp}$), would roughly cancel out each other, leaving a small remaining force acting as a disturbance in that direction. The freedom the servicer has to move within its manipulator workspace, makes it easier to deal with this small disturbance. For example, if $\mathbf{f}_{11p}$ is larger than $\mathbf{f}_{12p}$ (Fig. 2), then the servicer base will start moving mainly away from the passive object, but also a bit to the side. The thruster that delivers a force opposite to $\mathbf{f}_{11}$ along with $\mathbf{f}_{12}$ can be used to cancel the side motion, when its deemed necessary by the controller of the servicer base, in order to keep it within the manipulator workspace.

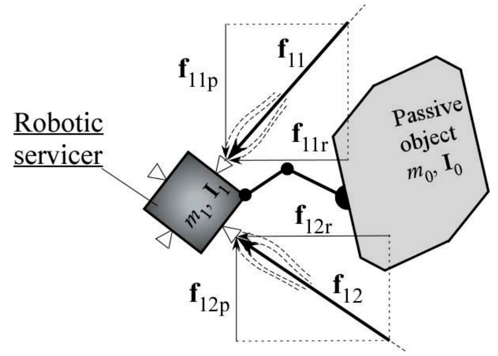

Figure 2. Pushing the servicer away from the passive object, in the case of one, large servicer.

This type of control is simpler than the one opted for the case with three servicers, as the latter is described above and in more detail in [12]. Nevertheless, the use of pairs of forces like $\mathbf{f}_{11}$ and $\mathbf{f}_{12}$ in Fig. 2, leads to extra fuel consumption, because of the simultaneous existence of opposing forces like $\mathbf{f}_{11p}$ and $\mathbf{f}_{12p}$. Fuel consumption depends heavily on the existence of forces in the null space of the servicer base. Thus, in order to mitigate this effect, another switching strategy is opted.

As already mentioned, the first step in deriving the servicer base controller, is to use a model-based PD control, like the one in Eq. (6), to provide the continuous generalized control force, and then use a switching strategy to provide the thrusters control inputs. This continuous control force of the servicer is first recalculated at the servicer base frame, whose axes coincide with the thruster firing lines. Then, the new switching strategy is to turn each thruster on whenever the corresponding force component exceeds a pre-set threshold. This method leads to lower fuel consumption, since it mitigates the appearance of forces in the null space of the servicer base motion. Nevertheless, the existence of a number of servicers, as opposed to one, makes the system more flexible in terms of gain and servicer positioning tuning, a fact that can further lower fuel consumption as will also be demonstrated in the Simulations section.

Another difference between the system with a number of small servicers and the system with a single large servicer lies on the required type of contact between the manipulator end-effector and the passive object. In the case of one large servicer, firm grasping of the passive object is required. In the case of a number of small servicers, firm grasping of the passive object is still an option, but point contact is another viable one, for whenever firm grasp is not feasible. For example, this is the case of orbital debris handling, where appropriate appendages for firm grasping may not exist, or may not be available.

An additional difference between the two cases stems from the fact that there is a limit in the maximum size of the servicers, due to the limit in the payload capacities of the launchers. Thus, the option of several small servicers in order to handle large passive objects, in some cases it may be the only one.

A final difference between the two cases is that, in the case of a single and large robotic servicer, a failure in the performance of the servicer would result in the failure of the trajectory tracking motion of the passive object. In the case of a number of small robotic servicers, failure in the performance of one of them may not have catastrophic results on the trajectory tracking motion of the passive object, since the remaining servicers may be able to adequately control the passive object, depending on the type of the failure and on the type of the desired motion.

4. SIMULATIONS

The two cases to be compared include (a) three single-manipulator servicers, firmly grasping a passive object and (b) a single, scaled-up, single-manipulator servicer, firmly grasping the same passive object. Each servicer base has thrusters capable of producing forces or moments, (in the case of three servicers, thrusters facing the object are deactivated), reaction wheels, and a single PUMA-type manipulator.

A series of simulations is run, with realistic parameters in terms of force and torque capabilities of thrusters and reaction wheels. The rigid passive body to be handled has mass of 180 kg in the shape of a 2m×3m×2m orthogonal parallelepiped.

For the case of three, small free-flying servicers, each one has mass of 70 kg, and their base is of cubic shape with a 0.7 m side. The three contact points lie on the object surfaces with normal vectors parallel to the $\hat{\mathbf{x}}_0$, $-\hat{\mathbf{x}}_0$ and $\hat{\mathbf{y}}_0$ unit vectors of the object body-fixed axes. The servicer thrusters develop per axis a pure force of 20 N, while their trigger threshold is set to f_t =10 N.

For attitude control, the servicers have additional pairs of thrusters that develop pure torque of 2 Nm per axis, and reaction wheels that can develop proportional torques up to n_t =1 Nm per axis. The manipulator on each robot has a maximum reach of 3 m.

For the case of a single, large servicer, the servicer mass is 210 kg, and its base is of cubic shape with a 1 m side. The contact point lies on the object surface with normal vector parallel to the $-\hat{\mathbf{x}}_0$ unit vector of the object body-fixed axes. The servicer thrusters develop per axis a pure force of 60 N, while their trigger threshold is set to f_t =25 N. For attitude control, the servicers have additional pairs of thrusters that develop pure torque of 6 Nm per axis, and reaction wheels that can develop proportional torques up to n_t =3 Nm per axis. The servicer manipulator has again a maximum reach of 3 m.

Several sets of simulations were run for both cases, in which all bodies were involved in 3D motions. Here we present two characteristic simulation runs, one with a simple 2D passive object desired trajectory and one with a realistic 3D passive object desired trajectory. For both simulation sets, the servicer position control task is to keep the manipulator base at a distance equal to 1.5 m, measured along the object surface normal vector passing from the end-effector contact point.

The servicer attitude control task is to keep the surface of the servicer that the manipulator is mounted on, parallel to the corresponding contact surface of the passive object in the case with the three servicers or, in the single servicer case, to keep two adjusting surfaces of the servicer on angles of $-\pi/4$ and $\pi/4$ respectively, with respect to the corresponding contact surface, so that the thrusters on those servicer surfaces, will be able to fire without harming the passive object. The simulations are run on the Matlab/ Simulink package. To obtain the required contact forces in the case of three servicers, the *fmincon* non-linear constrained optimization process is employed.

First, a 3D motion of all bodies is simulated in which the desired trajectory for the passive object is a 2D motion along the inertial a-axis, as seen at the first two lines of Table I, along with the last line (x_{0d}, y_{0d} and ψ_{0d}).

For the three-servicers system, the control gains in Eq. (6) are K_{P0} = 25, K_{D0} = 5 (for all passive object *translational* dof), K_{P0} = 9, K_{D0} = 3 (for all passive object *rotational* dof). The corresponding gains for the servicer model-based PD control are K_{Pi} = 0.16, K_{Di} = 0.4 (for all servicer bases *translational* dof, with i = 1, 2, 3), except for K_{Piz} = 0.09, K_{Diz} = 0.3, K_{P1y} = K_{P2y} = 0.1225 and K_{D1y} = K_{D2y} = 0.35. For all the *rotational* dof of the servicer bases, we have K_{Pi} = 25, K_{Di} = 5, with i = 1,2,3.

For the single-servicer system, the control gains are K_{P0} = 0.01, K_{D0} = 0.1 (for all passive object *translational* dof), K_{P0} = 0.25, K_{D0} = 0.5 (for all passive object *rotational* dof). The corresponding gains for the servicer model-based PD control are K_{P1} = 0.16, K_{D1} = 0.4 (for all servicer bases *translational* dof) and K_{P1} = 4, K_{D1} = 2 (for all the *rotational* dof of the servicer bases).

Table I. Passive object desired motion parameters.

dof	const. accel. (m/s^2) or (rad/s^2)	up to (s)	const. vel. (m/s) or (rad/s)	up to (s)	const. deccel. (m/s^2) or (rad/s^2)	up to (s)
x_{0d}	0.0003	56	0.0168	84	-0.0003	140
y_{0d}	-0.00036	50	-0.018	90	0.00036	140
z_{0d}	0.0002	59	0.0118	81	-0.0002	140
θ_{0d}	$5*10^{-5}$	60	0.003	80	$-5*10^{-5}$	140
φ_{0d}	$7*10^{-5}$	55	0.00385	85	$-7*10^{-5}$	140
ψ_{0d}	10^{-4}	65	0.0065	75	-10^{-4}	140

In Fig. 3, the passive object tracking errors (a and b) and the total fuel consumption (c and d) are shown, both for the case of three servicers (a and c) and the single-servicer case (b and c). The fuel consumption was obtained as the integral of all thruster absolute forces. As can be seen in Fig. 3, in the three-servicer case we have not only lower maximum passive object tracking errors than the single-servicer case, but also about 41% lower fuel consumption (from 453 to 320).

Note that lowering the control gains for the passive object motion in the single-servicer case would result in a lower need for manipulator force/ torque application and thus lower disturbances on the servicer base, and lower fuel consumption in order to keep it within the manipulator workspace. This though, would result in increasing the passive object tracking errors. Note also that the control gains for the servicers (for both cases) were chosen so as to keep the servicer base within the corresponding manipulator workspace (plots not shown here for brevity).

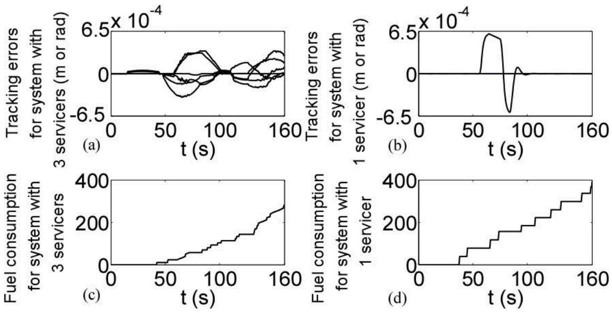

Figure 3. Passive object tracking errors (a, b) and fuel consumption (c, d), for the case of three servicers (a, c) and single-servicer (b, c).

Also, a general, 3D motion of all bodies is simulated, in which each of the six degrees-of-freedom (dof) of the passive object follow a trapezoidal profile for the linear velocity or Euler angles rate for both cases, see Table I.

For the three-servicers system, the control gains in Eq. (6) are K_{P0} = 3.24, K_{D0} = 1.8 (for all passive object *translational* dof), K_{P0} = 0.49, K_{D0} = 0.7 (for all passive object *rotational* dof). The corresponding gains for the servicer model-based PD control are K_{Pi} = 0.09, K_{Di} = 0.3 for all servicer bases *translational* dof, except K_{P1x} = K_{P2x} = 0.16, K_{D1x} = K_{D2x} = 0.04, K_{P3y} = 0.2025 and K_{D3y} = 0.45. Also, K_{Pi} = 9, K_{Di} = 3 for all the *rotational* dof of the servicer bases, with i = 1, 2, 3.

For the single-servicer system, the control gains are K_{P0} = 3.24, K_{D0} = 1.8 (for all passive object *translational* dof), K_{P0} = 0.49, K_{D0} = 0.7 (for all passive object *rotational* dof). The corresponding gains for the servicer model-based PD control are K_{P1} = 0.09, K_{D1} = 0.3 (for all servicer bases *translational* dof) and K_{P1} = 9, K_{D1} = 3 (for all the *rotational* dof of the servicer bases).

In Fig. 4, the passive object tracking errors (a and b) and the total fuel consumption (c and d) are shown, both for the case of three servicers (a and c) and the single-servicer case (b and c). As can be seen in Fig. 4, for the same maximum passive object tracking errors, we have about 40% higher fuel consumption in the single-servicer case (from 350 to 350).

In Fig. 5, the reach of each servicer manipulator is shown throughout the simulation, both for the three-servicer (a) and single-servicer (b) case. As can be seen, all manipulators in both cases have approximately the same minimum and maximum reach throughout the simulation.

In Fig. 6, all thruster forces are displayed, both for the three-servicers (a) and the single servicer (b) case. Moreover, the reaction wheel torques, as well as the thruster pure torques, are also displayed for both cases (c and d). As can be seen, the three servicers together have more frequent thruster firing, since there are three of them to be kept within their manipulator workspaces, but the single, large servicer has far more powerful thrusting, resulting in higher fuel consumption, as seen in Fig. 4. In Fig. 6c the reaction wheel torques for the three-servicer case are displayed.

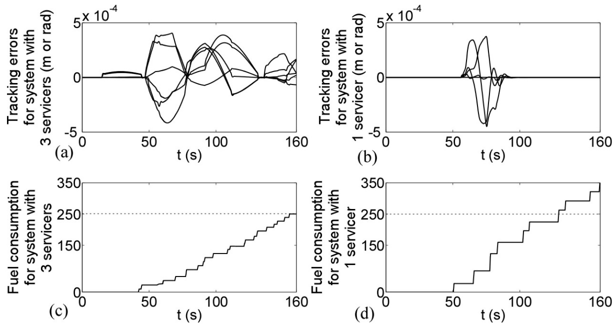

Figure 4. Passive object tracking errors (a, b) and fuel consumption (c, d), for the case of three servicers (a, c) and single-servicer (b, c).

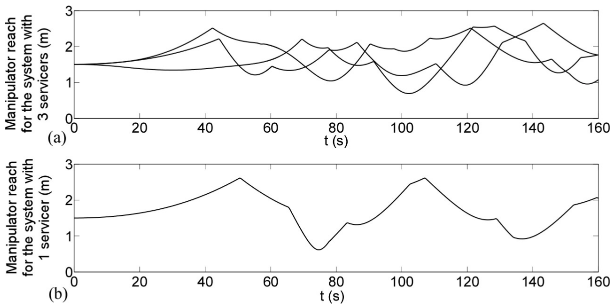

Figure 5. Manipulator reach for the three-servicers case (a), as well as the single-servicer case (b).

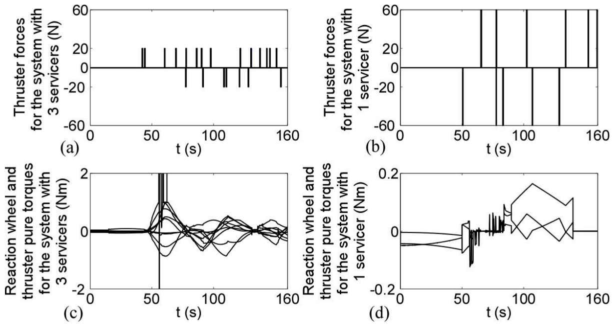

Figure 6. Thruster firing (a, b) and reaction wheel and thruster torque (c, d), for the three-servicers case (a, c), as well as the single-servicer case (b, d).

As can be seen, these torques were not adequate and the pure-torque thrusters had to ignite briefly for one of the servicers, a little bit after 50 s. On the contrary, for the single-servicer system, no such thruster firing was necessary, as can be seen in Fig. 3d. Nevertheless, the three-servicer system still has lower fuel consumption.

5. CONCLUSIONS

This paper presents initial work on the question of whether it is better to handle a passive object by a number of small robotic servicers or by a single one. A method for handling the passive object, previously developed by the authors, is employed in comparing the two cases in the task at hand. To this end, a number of characteristic trajectories are simulated, while for simplicity, single-manipulator servicers are assumed in both cases. In one case, three small, identical servicers are assumed and a single, scaled-up servicer is assumed in the other. The total fuel consumption is used as a performance index, while the tracking motion error is kept the same in the two cases. It is found that the system comprising a large servicer has higher fuel consumption than the system with three small servicers. Moreover, the three-servicer system has some further advantages, such as higher flexibility in gain tuning and servicer initial positioning, higher robustness in servicer failures, higher payload capabilities and more versatility in acceptable types of contact between the passive object and the servicer end-effectors.

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