MOTION CAPABILITIES OF A PASSIVE OBJECT HANDLED BY FREE-FLOATING ROBOTIC SERVICERS

Georgios Rekleitis, Evangelos Papadopoulos

Control Systems Lab, School of Mechanical Engineering, National Technical University of Athens,
9 Heroon Polytechniou str, Zografou, Athens, Greece, email: georek@gmail.com, egpapado@central.ntua.gr

ABSTRACT

Robotic On-Orbit Servicing is a field that is constantly progressing over the last twenty years, with the task of handling of a passive object by manipulator equipped robotic servicers, being a significant one. Fuel, though, is a scarce commodity in space. Thus, in this paper, the motion capabilities of a passive object handled by a number of free-floating manipulator-equipped robotic servicers in space, is studied. Two different approaches are proposed in this initial study and a simple, characteristic case is demonstrating the approaches via simulations.

1. INTRODUCTION

As the exploitation and commercialization of space grows, the need for on-orbit tasks will increase, while space infrastructure will be in high demand. Systems capable of fulfilling On-Orbit Servicing (OOS) tasks such as construction, maintenance, astronaut assistance, or even orbital debris handling and disposal, will be required. Although some of these can be performed by astronauts in Extra Vehicular Activities (EVA) [1], they tend to be too dangerous, and subject to time, size, and effort limitations. To relieve astronauts from EVA, enhance and expand EVA performance, and introduce OOS capabilities even when astronauts are not present, autonomous robotic OOS is required.

Important OOS tasks, such as debris handling and orbital assembly, require the robotic manipulation of passive objects. The first step in the handling procedure is to secure the passive object (docking); this has been studied extensively during the last decades. Nevertheless, the actual handling of the secured passive object has not been studied adequately. Although several prototype robotic servicers have been introduced and studied since the 1990’s [2], only a few studies concern the dynamics and control during the autonomous handling of secured objects.

Orbital system thrusters are of an on-off control nature [3]. Thus, direct control of a passive object by firmly attached thruster equipped servicers, leads to limit cycles that reduce the accuracy and increase fuel consumption, compared to non on-off control [4]. To avoid this phenomenon, the authors have developed a control method for handling passive objects by single manipulator robotic servicers, in which the object itself is controlled by continuous forces / torques applied by the servicer manipulators, while the servicer thrusters are used to keep the servicer bases within their manipulator workspaces.

Nevertheless, since fuel is a scarce commodity in space, and since only manipulators can impose proportional control on passive objects, when handling such an object in space, it would be useful to maximize manipulator use and minimize thruster use. Along these lines, the first step is to derive the passive object motion workspace, when only servicer manipulators are used (i.e. no thrusters), and study how this is affected by system parameters and initial conditions.

In this work, the maximum passive object workspace that can be obtained using servicer manipulators only, is studied. Since all servicer thrusters are inactive and no external forces are applied to the system, the system centre of mass remains fixed. As the manipulators handle the passive object, the servicer bases move with respect to the passive object, thus limiting the duration of the exerted total force by the corresponding manipulator workspaces. Moreover, servicer momentum control devices are used to stabilize the servicer bases attitude only, allowing the use of simpler controllers. Thus, the passive object attitude bounds are also restricted by manipulator workspaces.

The inertial displacements are obtained as functions of the servicer and passive object masses, the position of the manipulator end-effectors contact / grasping points on the passive object, the initial relative distances between the passive object and the servicers, and the workspace of the manipulator of each servicer. Two approaches for the derivation of the passive object allowable motions are studied. One which provides the absolute maximum available workspace, beyond which no motion is possible, and another which provides the actual workspace of the allowed passive object motions.

A simplified example is used to demonstrate how the available motions are affected by the system parameters and the starting conditions, i.e. system masses, position of grasping points, initial relative positions and servicer manipulator workspaces, and the available passive object workspace, when handled by free-floating (i.e.

with deactivated thrusters) manipulator equipped servicers, is obtained.

2. PASSIVE OBJECT MOTION WORKSPACE

Initially, the case of the maximum passive object translational motion that can be obtained by using only the servicer manipulators, is studied. A typical case for the initial state of the system is as shown in Figure 1. Note that, for simplicity, single-manipulator servicers are assumed, and that, in order to keep the servicers in contact with the passive object, the following analysis is done assuming that the manipulator end effectors have firmly grasped the passive object by appropriate handles/appendages and that all the servicer thrusters are inactive and no external force is applied to the system. Thus, the system center of mass state remains constant. The manipulators can be used to exert a non-zero total force and/or total moment on the passive object, leading to pure translation or a general translation and rotation. The servicer bases would then move with respect to the passive object, thus limiting the duration of the exerted total force by the corresponding manipulator workspaces. Note that the manipulator links masses are assumed very small compared to the passive object and the servicer bases ones, so as to assume insignificant contribution for the calculation of the system center of mass (CM). Without loss of generality, the system CM (x_{cm}, y_{cm}, z_{cm}) is assumed to coincide with the origin of the inertial frame, thus leading to

$$x_{cm} = y_{cm} = z_{cm} = 0 \tag{1}$$

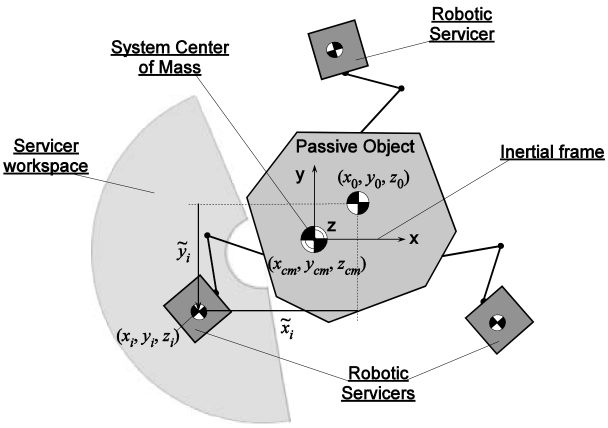

Figure 1. Spatial handling of the passive object by use of manipulator forces only.

Moreover, x_{cm} is obtained as:

$$x_{cm} = \frac{\sum_{i=0}^{3} x_i m_i}{m_0 + m_1 + m_2 + m_3} \tag{2}$$

where x_i are the coordinates along the inertial x-axis of the CM of the passive object (i = 0) and the servicer bases (i = 1, 2, 3), see also Figure 1.

2.1. First Approach

By denoting the relative distances between the passive object and the servicers as

$$\tilde{x}_i = x_i - x_0 \qquad \text{for } i = 1,2,3 \tag{3}$$

and using Eq. (1), Eq. (2) becomes

$$x_{cm} = \frac{m_0 x_0 + \sum_{i=1}^{3} \left(x_0 + \tilde{x}_i \right) m_i}{m_0 + m_1 + m_2 + m_3} = 0 \tag{4}$$

By denoting x_{i_in} and x_{i_f} the initial and final values of x_i respectively, Eq. (1) leads to

$$x_{cm\_in} = x_{cm\_f} = 0 \tag{5}$$

Then, Eqs. (4) and (5) yields:

$$\begin{aligned} &\frac{m_0 x_{0\_in} + \sum_{i=1}^{3} \left(x_{0\_in} + \tilde{x}_{i\_in} \right) m_i}{m_0 + m_1 + m_2 + m_3} = \\ &= \frac{m_0 x_{0\_f} + \sum_{i=1}^{3} \left(x_{0\_f} + \tilde{x}_{i\_f} \right) m_i}{m_0 + m_1 + m_2 + m_3} \end{aligned} \tag{6}$$

or, equally,

$$\begin{aligned} &\left(m_0 + m_1 + m_2 + m_3 \right) x_{0\_in} + \sum_{i=1}^{3} \tilde{x}_{i\_in} m_i = \\ &= \left(m_0 + m_1 + m_2 + m_3 \right) x_{0\_f} + \sum_{i=1}^{3} \tilde{x}_{i\_f} m_i \end{aligned} \tag{7}$$

By denoting,

$$\begin{aligned} &\delta x_0 = x_{0\_f} - x_{0\_\text{in}} \\ &\delta \tilde{x}_i = \tilde{x}_{i\_f} - \tilde{x}_{i\_\text{in}} \quad \text{for } i = 1,2,3 \end{aligned} \tag{8}$$

then Eq. (7) leads to

$$\delta x_0 = - \frac{\sum_{i=1}^{3} \delta \tilde{x}_i m_i}{m_0 + m_1 + m_2 + m_3} \tag{9}$$

Equation (9) provides the motion of the passive object $\delta x0$, along the inertial x-axis, with respect to the relative motions $\delta \tilde{x}_i$ between the servicers and the passive object, without the use of the thrusters. The maximum passive object motion that can be achieved without thruster firing depends on the maximum relative motions $\delta\tilde{x}_i$, which are functions of the initial relative distances $\tilde{x}_{i\_in}$ and the workspace of each servicer.

Next, a simplified example is used to illustrate the method of obtaining the maximum passive object displacement without thruster firing, with specific workspace limits. In this example, it is assumed that the system center of mass velocity is zero, and that the motion studied is along the passive object fixed frame x-axis (coinciding with the inertial x-axis in this case), as seen in Figure 2. For i = 1 or 2, δ_i denotes the distance from the i^{th} servicer center of mass to its manipulator base, while d_i denotes the projection of δ_i along the passive object x-axis. Note that, while δ_i is fixed, d_i^* is a function of the relative orientation between the corresponding servicer and the passive object. Moreover, δ_{0i} denotes the constant distance from the passive object center of mass to the contact point with the i^{th} servicer manipulator, along the passive object x-axis, δx_i denotes the distance of the i^{th} servicer base from the passive object, i.e. the current manipulator reach of the i^{th} servicer, again along the passive object x-axis and x_{00} denotes the initial distance from the passive object center of mass to the system center of mass, along the passive object x-axis.

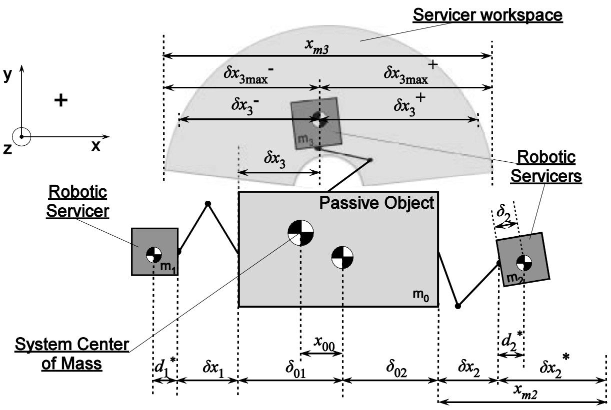

Figure 2. Spatial handling of the passive object by use of manipulator forces only, in simple motion.

Note also that δx_i^* (in Figure 2 only δx_2^* is shown) denotes the additional reach the i^{th} servicer manipulator can have on top of δx_i, in order to reach its maximum manipulator reach x_{mi}, i.e.

$$\delta x_i + \delta x_i^* = x_{mi}, \qquad i = 1,2 \tag{10}$$

Moreover, taking into account Figure 2, $\tilde{x}_i$, which was defined in Eq. (3), becomes

$$\begin{aligned} \tilde{x}_1 &= -d_1^* - \delta x_1 - \delta_{01} \\ \tilde{x}_2 &= d_2^* + \delta x_2 + \delta_{02} \end{aligned} \tag{11}$$

while, since δ_{0i} is constant, $\delta\tilde{x}_i$ defined in Eq. (8), becomes

$$\begin{aligned} \delta x_0 &= x_{0\_f} - x_{0\_\text{in}} \\ \delta\tilde{x}_i &= \tilde{x}_{i\_f} - \tilde{x}_{i\_\text{in}} \quad \text{for } i = 1,2,3 \end{aligned} \tag{12}$$

For the third servicer (m_3) the notation is different, since different values are important for this motion. Thus, δx_3 is the distance from the m_3 servicer center of mass to the passive object left side, along the passive object x-axis, as seen in Figure 2. The allowed relative motion between this servicer and the passive object along the passive object x-axis, starting from this initial relative position, is limited by motion δx_0 of the passive object center of mass *without* the use of thrusters, is obtained,

$$\delta x_0 = \frac{-\sum_{i=1}^{2}\left[\left(d_{i\_f}^* - d_{i\_in}^* + \delta x_{i\_f} - \delta x_{i\_in}\right)m_i\right]}{m_0 + m_1 + m_2 + m_3} - \frac{\left(\delta x_{3\_f} - \delta x_{3\_in}\right)m_3}{m_0 + m_1 + m_2 + m_3} \tag{13}$$

Using a similar approach, the passive object displacements along the y-axis (δy_0) and z-axis (δz_0), when using manipulators only, can also be obtained.

To obtain the maximum value of δx_0, δy_0 and δz_0 (i.e. $\delta x_{0\text{-max}}$, $\delta y_{0\text{-max}}$ and $\delta z_{0\text{-max}}$ respectively), the maximum allowable servicer base displacements in the corresponding axes, in the Inertial frame, should be obtained, a task which is not trivial, since it is affected by the simultaneous motion of the passive object itself.

Next, the limits of the servicer bases motions are further analysed. The magnitude of the position vector of each servicer base (recall that the inertial frame is assumed to coincide with the unmoving system frame) can be obtained as a function of all the link vectors $\boldsymbol{l}_{ij}$, as [5]:

$$\left\|\boldsymbol{\rho}_i\right\| = \left\| \frac{\mathbf{d}_i \sum_{\substack{j=1 \\ j\neq i}}^{3} m_j + \left(\boldsymbol{l}_{i1} + \boldsymbol{l}_{i2} + \mathbf{r}_i\right)\left(m_0 + \sum_{\substack{j=1 \\ j\neq i}}^{3} m_j\right)}{\sum_{j=0}^{3} m_j} - \frac{\sum_{\substack{j=1 \\ j\neq i}}^{3}\left(\mathbf{d}_j\left(m_0 + m_j\right) + m_j\left(\boldsymbol{l}_{j1} + \boldsymbol{l}_{j2} + \mathbf{r}_j\right)\right)}{\sum_{j=0}^{3} m_j} \right\| \tag{14}$$

In Figure 3, the link vectors, as well as vectors $\mathbf{d}_i$, from the passive object CM to the i^{th} grasping point, and vectors $\mathbf{r}_i$, from the manipulator base on the i^{th} servicer to the corresponding servicer base CM, are also shown. Note that all those vectors are expressed in the passive object frame, thus no knowledge of the passive object or servicer bases attitude is required in order to obtain $\|\boldsymbol{\rho}_i\|$, which is, nevertheless, a function of all the manipulator joint angles. For the allowed range of the manipulator joint angles (geometric constraints), the maximum and minimum values of each $\|\boldsymbol{\rho}_i\|$ can be obtained numerically, by using an optimization process with the joint angle constraints as the optimization constraints and $\|\boldsymbol{\rho}_i\|$ as the objective function to be minimized or maximized. Thus, the corresponding servicer base is bounded between two concentric spheres with center at the system CM and radii $\|\boldsymbol{\rho}_i\|_{\min}$ and $\|\boldsymbol{\rho}_i\|_{\max}$. Those absolute maximum allowed motions provide the maximum δx_{i_f} required in Eq. (13). Moreover, by assuming that the servicer reaction wheels are capable of maintaining their attitude, d_i^* remain unchanged, resulting in:

$$d^*_{i\_f} - d^*_{i\_in} = 0 \qquad (15)$$

Nevertheless, it should be noted that this analysis provides the absolute maximum reach of each servicer and consecutively of the passive object by means of Eq. (13), beyond which it definitely cannot reach at any direction. It does not provide, though, what the passive object **can** reach at a given direction, since there is no way of telling whether each servicer base can reach its $\|\boldsymbol{\rho}_i\|_{\max}$ distance from the system CM, at the specific direction.

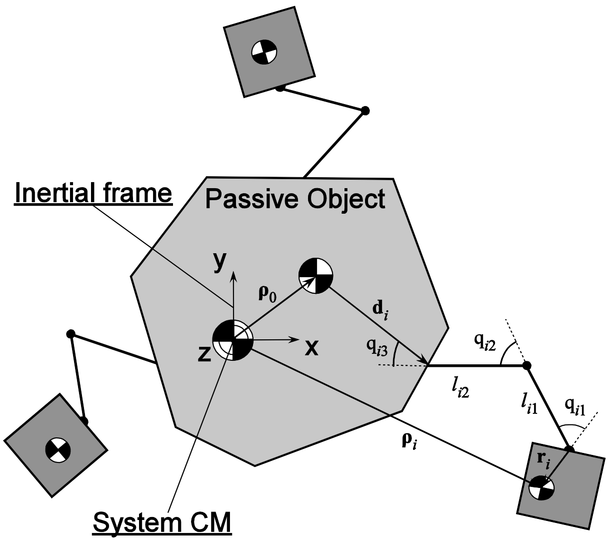

Figure 3. Position vectors of passive object and servicers.

Another drawback of the above analysis is that it does **not** mean that the space in which the passive object can move when using only manipulator forces, is a rectangular box of sides $\delta x_{0\text{-max}}$, $\delta y_{0\text{-max}}$ and $\delta z_{0\text{-max}}$. As already mentioned, the maximum allowed motion for the passive object is a function of the initial servicer configurations (see Eq. (13)), and what Eq. (14) provides are the absolute maximum bounds of the servicer base motions, which, along with Eq. (13), provide the maximum bounds of the passive object. For a given set of initial state of the system and in order to check if a desired final passive object position is feasible without the use of thrusters, the following approach can be used:

1. First, the feasibility of the motion to the desired position along its x-axis, by using only manipulator forces is checked. To do so the desired x-position is checked with respect to the maximum feasible one given by Eq. (13), for the given initial conditions. If the desired x-position is feasible, the passive object is moved to this desired position along its x-axis. Note that the coupling of translational and rotational motions may result in a different final system state.

2. This state is used as initial configuration for the next step, in which the feasibility of the desired y-position is checked, given this initial configuration. If the motion to the desired y-position is feasible, the passive object is moved there and again the coupling of the translational and rotational motions would result in a different final system state.

3. This final state is used as an initial configuration for the final step, which checks the feasibility of the passive object motion to the desired z-position, using the same strategy as in the previous steps.

2.2. Second Approach

The presented first approach, although it provides an initial estimation of the allowable passive object motion, has the abovementioned two significant drawbacks. In order to avoid the limitations of the first approach, the concept of finding the (inertial) workspace of a servicer base by use of its inertial position vector, is further exploited in order to deliver directly the displacement workspace of the passive object. Since we have assumed that the inertial frame coincides with the (fixed) system CM, by denoting as $\boldsymbol{\rho}_i$ the position vectors of each body CM with respect to the system CM (with $i = 0$ for the passive object and $i = 1, \ldots, n$ for the n servicer bases, see also Figure 3 for planar case and for two-link manipulators), it can be obtained that:

$$\sum_{i=0}^{n} m_i \boldsymbol{\rho}_i = 0 \qquad (16)$$

with $\boldsymbol{\rho}_i$ for $i = 1,\ldots,n$ obtained as a function of $\boldsymbol{\rho}_0$, as:

$$\begin{bmatrix} \boldsymbol{\rho}_i \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{\rho}_0 \\ 1 \end{bmatrix} + \begin{bmatrix} \mathbf{R}_0 & \mathbf{0}_{3\times1} \\ \mathbf{0}_{1\times3} & 1 \end{bmatrix} \left\{ \begin{bmatrix} \mathbf{d}_i \\ 1 \end{bmatrix} + \begin{bmatrix} {}^{0}\mathbf{R}_i & \mathbf{0}_{3\times1} \\ \mathbf{0}_{1\times3} & 1 \end{bmatrix} * \right.$$
$$\left. * \underbrace{\left(\sum_{j=1}^{m_i} \left(\prod_{k=1}^{j} \left({}^{k-1}_{\ \ k}\mathbf{T}_i \right) \begin{bmatrix} l_{ij} \\ 0 \\ 0 \\ 1 \end{bmatrix} \right) + \prod_{k=1}^{m_i+1} \left({}^{k-1}_{\ \ k}\mathbf{T}_i \right) \begin{bmatrix} \|\mathbf{r}_i\| \\ 0 \\ 0 \\ 1 \end{bmatrix} \right)}_{\mathbf{C}_i} \right\} \qquad (17)$$

In Eq. (17), $\mathbf{R}_0$ is the passive object rotation matrix with respect to the inertial frame, fixed at the system CM, ${}^{0}\mathbf{R}_i$ is the (known and fixed) rotation matrix between the i^{th} servicer grasping point frame and the passive object frame, ${}^{k-1}_{\ \ k}\mathbf{T}_i$ are the transformation matrices between consecutive links of the i^{th} servicer manipulator (including the manipulator Denavit-Hartenberg parameters) [6], l_{ij} is the length of the j^{th} link of the i^{th} servicer manipulator and $\mathbf{d}_i$ and $\mathbf{r}_i$ are defined in Figure 3, in a simple, planar case. By substituting $\boldsymbol{\rho}_i$ from Eq. (17) in Eq. (16) and by denoting the upper three elements of $\mathbf{C}_i$ in Eq. (17) as $\mathbf{C}_i^*$, the passive object position vector can be obtained:

$$\boldsymbol{\rho}_0 = \frac{-\mathbf{R}_0 \sum_{i=1}^{n} m_i \left(\mathbf{d}_i + {}^{0}\mathbf{R}_i \mathbf{C}_i^* \right)}{\sum_{i=0}^{n} m_i} \qquad (18)$$

or

$$\|\boldsymbol{\rho}_0\| = \frac{\left\| \sum_{i=1}^{n} m_i \left(\mathbf{d}_i + {}^{0}\mathbf{R}_i \mathbf{C}_i^* \right) \right\|}{\sum_{i=0}^{n} m_i} \qquad (19)$$

Note that the manipulator joint angles are embedded in ${}^{k-1}_{\ \ k}\mathbf{T}_i$ in Eq. (17) and thus in $\mathbf{C}_i^*$ in Eq. (19). Thus the bounds of $\boldsymbol{\rho}_0$, as functions of the joint angles, and can be obtained numerically, using Eq. (19), and taking into account the geometrical limitations on the joint angles.

It can be shown that if the passive object CM can reach a point with position vector $\boldsymbol{\rho}_0$ (recall that the inertial frame is assumed to coincide with the unmoving system CM), then, without any servicer thruster use, it can reach any point at a distance of $\|\boldsymbol{\rho}_0\|$ from the system CM. This can be achieved by fixing all servicer manipulators, after reaching $\boldsymbol{\rho}_0$, and using the servicer reaction wheels to exert pure torque on the rigid system. Thus, the system rotates around the unmoving system CM, without any of the bodies CM (i.e. passive object and servicer bases) changing its distance from the system CM, since the manipulator configuration is fixed and the whole system forms a rigid body.

The bounds of the magnitude of $\boldsymbol{\rho}_0$ obtained by Eq. (19) determine that the passive object CM displacement, at a specific (but unknown) direction, can reach a maximum distance from the system CM, defined by $\|\boldsymbol{\rho}_0\|_{max}$, and a minimum distance from the system CM, defined by $\|\boldsymbol{\rho}_0\|_{min}$. Thus, based on the abovementioned analysis, the passive object CM can reach any point on the surfaces of the two concentric spheres, with center at the fixed system CM and radii $\|\boldsymbol{\rho}_0\|_{min}$ and $\|\boldsymbol{\rho}_0\|_{min}$, and any point between those spheres, defining directly the passive object CM displacement workspace, without the use of the servicer thrusters.

One way to numerically obtain $\|\boldsymbol{\rho}_0\|_{min}$ and $\|\boldsymbol{\rho}_0\|_{min}$ is to use an optimization process, with $\|\boldsymbol{\rho}_0\|$ being the objective function, as:

$$\|\boldsymbol{\rho}_0\|_{\min} = \min_{q_{ij}} \left\{ \|\boldsymbol{\rho}_0\| \right\} \qquad (20)$$

and

$$\|\boldsymbol{\rho}_0\|_{\max} = \max_{q_{ij}} \left\{ \|\boldsymbol{\rho}_0\| \right\} = -\min_{q_{ij}} \left\{ -\|\boldsymbol{\rho}_0\| \right\} \qquad (21)$$

respectively, taking also into account the geometric constraints (collision avoidance constraints) on the manipulator joint angles q_{ij}.

2.3. Attitude correction capabilities

As already mentioned, the translation of the passive object, as it is handled by a number of free-floating robotic servicers, results also is the passive object reorientation. After the passive object has reached its destination point (if this is feasible), its attitude can be rearranged to the desired one, by implementing a simple strategy, that also does not affect the passive object final position.

Assume that the passive object must rotate along a specific axis, in order to reach its desired attitude. To achieve this, the servicers can move their bases (using their manipulators) in small circles around that axis, always returning at their initial point in the Cartesian space. After a full circular motion, the position of each servicer base is the same as the initial one and, since the system CM also remains stationary (no thrusters, thus no external forces used), the passive object CM also returns at its initial place.

Those circular motions, though, result in the passive object reorienting itself around said axis. This motion has also another result: since the passive object reorients but the servicer bases return at their initial position, the servicer manipulators configuration changes. This side effect provides the only limitation in the achievable attitude change of the passive object, since the reconfiguration of the servicer manipulators should be kept from violating geometrical constraints.

3. ILLUSTRATIVE EXAMPLE

In order to illustrate the proposed method, a simple, planar example is presented next. Assume the system of Figure 2 with system parameters as seen in Table 1 (see also Figure 3). Note that, for simplicity and without loss of generality, each body CM is assumed to coincide with the corresponding geometric centre.

Table 1. System parameters.

m_0 (kg)	m_i (kg)	l_{i1} (m)	l_{i2} (m)	Passive object size	Servicer size
600	250	1.5	1.5	5 × 2 × 2 (m)	1 m (cube side)

The system initial conditions are shown in Table 2. Note that for all three servicers, q_{i3} corresponds to a wrist joint (almost) at the grasping point. Moreover, the grasping point coordinates seen in Table 2 are obtained with respect to the inertial frame, that coincides with the unmoving system CM frame, leading to $\delta_{02} = -\delta_{01} = 2.5$ m and $d_2 = -d_1 = 0.5$ m (see also Figure 2 and Figure 4).

Table 2. Grasping and initial conditions.

q_{i1}, q_{i3}	q_{i2}	1st grasp point (m)	2nd grasp point (m)	3rd grasp point (m)
45°	-45°	(-2.5, -0.3, 0)	(2.5, -0.3, 0)	(0, 0.7, 0)

These initial conditions result in the two servicer CM, the passive object CM and the corresponding grasping points to be on the same line, parallel to the inertial x-axis, while the third servicer CM along with the passive object CM, the system CM and the corresponding grasping point form a second line, parallel to the inertial y-axis, see also Figure 4.

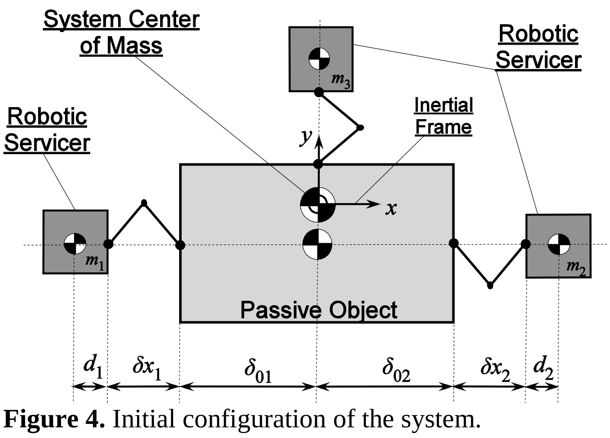

Figure 4. Initial configuration of the system.

Thus, the joint angle limits are

$$-\frac{\pi}{2} \le q_{i1}, q_{i3} \le \frac{\pi}{2} \tag{22}$$

while angle q_{i2} is thus restricted so as to avoid collision of the i^{th} servicer base with the passive object (omitted here for brevity). The specific initial configuration also yields

$$\delta x_{2\_in} = -\delta x_{1\_in} = 1.5\sqrt{2} \tag{23}$$

while $\delta x_{3\_in} = 0$.

The optimization with $\|\boldsymbol{\rho}_i\|$ as the objective function, resulted in

$$\begin{aligned} \|\boldsymbol{\rho}_1\|_{\max} &= \|\boldsymbol{\rho}_2\|_{\max} = 6.094m \\ \|\boldsymbol{\rho}_3\|_{\max} &= 4.47m \end{aligned} \tag{24}$$

Thus, using $\delta x_{3\_in} = 0$ and Eqs. (15), (21) and (19), Eq. (13) finally yields

$$\delta x_{0\_\max} = \pm 3.085m \tag{25}$$

Equation (25) means that the passive object cannot be placed on the x-axis more than 3.085 m away from its initial position, without the use of the servicer thrusters. Note that, a displacement of 3.085 m on the x-axis, means a final distance from the (unmoving) system CM of 3.1 m, since the system CM does not coincide with the passive object initial position, but is at a distance of +0.3 m on the y-axis, from the initial passive object position.

In order to obtain the actual displacement workspace of the passive object (where it can actually reach), as it is handled by free-floating robotic servicers, the second approach is implemented. By use of the parameters and initial conditions of Table 1 and Table 2 and of Eq. (19), the optimization described in Eqs. (20) and (21) yields

$$\begin{aligned} \|\boldsymbol{\rho}_0\|_{\min} &= 0.045m \\ \|\boldsymbol{\rho}_0\|_{\max} &= 2.102m \end{aligned} \tag{26}$$

Thus, the passive object displacement that can be achieved when handled by free-floating robotic servicers as seen in Figure 4 is defined by the space between two concentric spheres, with center at the unmoving system CM and radii as seen in Eq. (24). Note that the maximum distance from the system CM (i.e. $\|\boldsymbol{\rho}_0\|_{\max}$ in Eq. (24)) is less than the absolute maximum obtained by the first approach, indicating that the second approach can accurately provide the allowed passive object displacements.

4. CONCLUSIONS

The task of handling a passive object by manipulator equipped robotic servicers, without the use of thrusters (free-floating mode), was studied in this paper. The inertial displacements were obtained as functions of the servicer and passive object masses, the position of the manipulator end-effectors contact / grasping points on the passive object, the initial relative distances between the passive object and the servicers, and the workspace of the manipulator of each servicer.

Two different approaches were proposed in this initial study. In the first approach, the absolute maximum available workspace of a passive object is obtained, providing a space beyond which the passive object cannot reach without the servicer thrusters firing. In the second approach, the actual passive object displacement workspace is obtained as a function of the system parameters and initial conditions, when handled by free-floating, manipulator equipped servicers. The passive object attitude handling, without disturbing the passive object position, is also discussed.

The validity of the proposed methods was demonstrated by a simplified example, via simulations. Both approaches work as they were supposed, with the second one providing the actual passive object displacement workspace.

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