12th ANKARA INTERNATIONAL AEROSPACE CONFERENCE AIAC-2023-103
13-15 September 2023 - Online, Ankara TURKIYE

IDENTIFICATION OF INERTIA PARAMETERS OF CAPTURED SPACE DEBRIS USING THE MOMENTUM-BASED APPROACH

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ABSTRACT

In space operations like Active Space-Debris Removal, it is necessary to grasp a tumbling object with unknown inertia properties using robotic arms. Having an estimation of the inertia-properties of the grasped object is crucial for stabilizing the space-robot and performing the removal operation. In this paper, the momentum conservation laws are used to develop the momentum-based generalized form of the estimation equation. The developed formulation is used then to extract a linear regressor form required for the estimation of unknown inertia-parameters of the grasped object. Despite the previous works the presented formulation can be used to calibrate the inertia-parameters of space-robots.

INTRODUCTION

Autonomous space robots offer the operational flexibility required for future space missions, encompassing tasks such as inspection, refueling, and manipulation. However, compared to ground robots, the dynamic coupling between the manipulator and its base introduces additional complexity to the dynamics modeling and motion planning [Xu, 2011]. These complexities arise not only from mathematical intricacies but also from uncertainties and variations in the Inertia Parameters (IPs). Uncertainties stem from the fact that IPs calculated based on CAD models can be subject to errors of up to 5 percent [Lampariello, 2005]. Additionally, fuel consumption and the capture of unknown objects, such as space debris, introduce further uncertainties associated with the IPs of a space manipulator throughout its lifecycle. In particular, these uncertainties impact the detumbling process during the capture of unknown objects like space debris [B. Dou, 2022]. Due to the strong coupling between the dynamics of the manipulator and its base, these uncertainties diminish the effectiveness of conventional reaction-free methods like Reaction Null Space (RNS) control, and may even result in instability of the spacecraft's base.

Generally, two different approaches are employed to address the stabilization and control problem of space robots in the presence of IP uncertainties. The first approach utilizes an adaptive control scheme to mitigate the sensitivity of the space robot's stability and control performance to model accuracy. References such as [Thai Chau, 2013] and [Shuanfeng, 2013] employ an identification approach to adapt the RNS control scheme (ARNS) during the capturing phase of space debris. Similarly, [Chu, 2018] proposes an integrated strategy for path planning and control by adapting the time-variable matrix of the momentum equation to construct a reactionless path planning algorithm. Furthermore, [Zhan 2022] develops an RNS-based adaptive law for detumbling the grasped debris, while also achieving control and stabilization of the base.

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Some researchers have adopted another approach to address these uncertainties, which involves the identification and reduction of such uncertainties [Zhang, 2023]. Despite the research conducted using the first approach, the main challenge in this alternative lies not only in identifying the IPs (Inertial Parameters) of the debris but also in identifying the IPs of the spacecraft's elements. This issue holds significant importance as the spacecraft itself is susceptible to IP uncertainties due to fuel consumption or CAD model estimation errors. References such as [Lampariello, 2000] and [Lampariello, 2005] have utilized the Newton-Euler formulation in conjunction with optimization techniques to identify the IPs of a space manipulator. However, their formulation lacks an explicit identification formula, and the utilization of optimization techniques affects the practicality of their proposed method for real-time applications like Active Space Debris Removal (ASDR). To overcome these challenges, [Nabavi, 2015] employed the Lagrange formulation of equations of motion and developed a generalized formulation for the identification of multi-body space systems, which exhibits linearity with respect to the mass and inertia matrices. The authors further extended their work to investigate the identifiability characteristics of a space manipulator and propose a method for identifying all IPs of the serially-linked space manipulator [Nabavi, 2017]. They discovered that in space-robotic applications, the IPs of the spacecraft appear in the dynamic equations in a combined form known as barycentric forms. These references adopt a Force-Based Approach (FBA), which utilizes equations of motion derived either through the Newton-Euler formulation or the Lagrange formulation to identify the IPs of space manipulators.

On the other hand, some references utilize a different approach known as the Momentum-Based Approach (MBA), which is based on the conservation of momentum law. MBA was initially introduced by [Murotsu, 1994] for identifying the IPs of an object captured by a space manipulator, achieved by moving one arm at each time instant. This approach has also been employed by [Ma, 2008] to identify the IPs of the space shuttle (as the base) when its robotic arms are in motion. These studies, including [Zhang, 2020] and [Zhang, 2020], primarily focus on the identification of IPs for individual bodies such as debris or the manipulator's base.

This paper focuses on research regarding the identification of all Inertia Parameters (IPs) of space manipulators using the Momentum-Based Approach (MBA). By employing mathematical manipulations, an explicit regressor form of the identification process is derived to facilitate the analysis of properties such as linearity and identifiability. This equation is particularly useful in the pre-capturing phase for calibrating the IPs of the space robot. Calibration is crucial to reduce model uncertainties during the capturing and post-capturing phases. It is observed that while the equations of motion exhibit linearity with respect to the masses and moments of inertia of the space robot, they are not linear with respect to the center of masses. However, it is demonstrated that if only the IPs of a single element of the space manipulator are unknown, a linearized form of the problem can be achieved. To validate the results, the dynamics of the space robots have been simulated in C#, and the results have been passed to the identification code (Figure 1). The accuracy of the simulation module has been further investigated for specific cases by comparing it to the results obtained using MSC-ADAMS, demonstrating the reliability of the process. The simulations show that the developed code can identify all the IPs of the space debris in less than 20 seconds, which is highly suitable for online applications such as Active Space Debris Removal (ASDR).

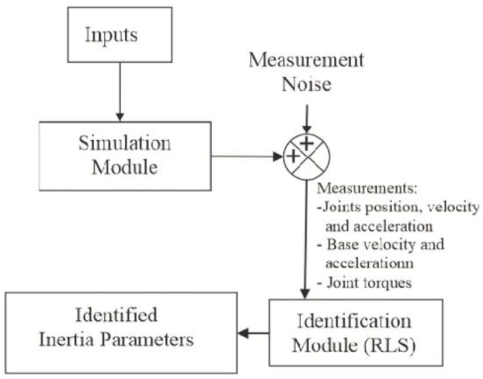

Fig. 1 – The simulation and identification process

MATHEMATICAL MODEL

Mathematical terms and definitions

In this section, some mathematical terms used in this paper for the mathematical modeling of the space-manipulator, are presented.

Definitions 1 – For a symmetric 3×3 matrix A, the vector $\underline{\vec{A}}$ is defined as

$$\underline{\vec{A}} = [a_{11}\ a_{12}\ a_{13}\ a_{22}\ a_{23}\ a_{33}\ ]^T$$

Definition 2 - Mass Vector of a space-manipulator:

$$\vec{m} = [m_0\ m_1\ \dots m_i \dots\ m_n\ ]^T$$

Definition 3 - Inertia vector of a space-manipulator is as

$$\vec{I} = \left[\underline{\vec{I_0}}^T\ \underline{\vec{I_1}}^T\ \dots\ \underline{\vec{I_n}}^T\ \right]^T$$

Definition 4 - First order moment vector is defined as

$$\overrightarrow{m r_c} = \left[m_0 \vec{r}_{c_0}^T\ \dots\ m_n \vec{r}_{c_n}^T\ \right]^T$$

Definition 5 – Skew-Symmetric Matrix of vector $\vec{r} = [r_1 \quad r_2 \quad r_3]^T$:

$$\tilde{\vec{r}} = \begin{bmatrix} 0 & -r_3 & r_2 \\ r_3 & 0 & -r_1 \\ -r_2 & r_1 & 0 \end{bmatrix}$$

Definition 6 – For vector $\vec{r} = [r_1 \quad r_2 \quad r_3]^T$:

$$[\underline{\vec{r}}] = \begin{bmatrix} r_1 & r_2 & r_3 & 0 & 0 & 0 \\ 0 & r_1 & 0 & r_2 & r_3 & 0 \\ 0 & 0 & r_1 & 0 & r_2 & r_3 \end{bmatrix}$$

Space-Manipulator Modeling and Kinematics

In this work the model presented in Fig. 2 is used to model the Space-Manipulator. The model consists of N elements, indexed from 0 (base) to n (outmost arm), all hinged sequentially with revolute joints. We assume that all elements are rigid, and gravity gradient torque, joints friction, and other external disturbances have negligible effects. The model of each element of the space manipulator is presented in Fig. 3. In this model a body frame Σ_0, positioned at its joint position to the element 1, is attached to the base. All other elements ($i = \{1 \dots n\}$) have their own body frames Σ_i, attached to their hinge point to their previous element ($i-1$). The body frames (Σ_i 's) are such that the joint to the next element is on the x axis of the Σ_i and the rotation of the element i happens around the z axis. The position of the center of mass for each element i in inertia frame is considered as $\vec{r}_i$ and in body frame (Σ_i) is presented as $\vec{r}_{c_i}$. Also, the position joints in inertia frame are presented as $\vec{p}_i$.

Assuming that the $\vec{\mathrm{X}}$ as the state vector of the spacecraft, the kinematic constraints of space manipulator's elements can be presented mathematically by (1):

$$\vec{\mathrm{v}}_\mathrm{i} = \mathrm{J}_{\mathrm{v_i}} \vec{\mathrm{X}}, \qquad \vec{\omega}_\mathrm{i} = \mathrm{J}_{\omega_\mathrm{i}} \vec{\mathrm{X}} \tag{1}$$

Where $\vec{\mathrm{v}}_\mathrm{i}$ and $\vec{\omega}_\mathrm{i}$ are, respectively, the linear and rotational velocities of the i^{th} element of the spacecraft and, $\mathrm{J}_{\mathrm{v_i}}$ and $\mathrm{J}_{\omega_\mathrm{i}}$ are the Jacobians. Using the model presented in Fig. 3, the CoM position of the i^{th} element of the space-manipulator ($\vec{r}_i$) can be presented as

$$\vec{r}_i = \vec{p}_i + R_i \vec{r}_{c_i} \tag{2}$$

The time derivative of (2) is:

$$\vec{\mathrm{v}}_\mathrm{i} = \dot{\vec{\mathrm{p}}}_\mathrm{i} + \mathrm{R_i} \dot{\vec{r}}_{\mathrm{c_i}} + \dot{R}_i \vec{r}_{c_i} \tag{3}$$

The time derivative of pin position ($\dot{\vec{\mathrm{p}}}_\mathrm{i}$) depends on the pin positions of elements and position of base but it is not dependent on CoMs of the space-manipulator. On the other hand, $\dot{\vec{r}}_{\mathrm{c_i}}$ is zero while last term dependent to the CoM of element i. So, by comparing (3) and (1), the J_{v_i} can be divided into CoM dependent term (CoM of the element i) and CoM free term:

$$J_{v_i} = J_{p_i} + L(\vec{r}_{c_i}) \qquad (4$$

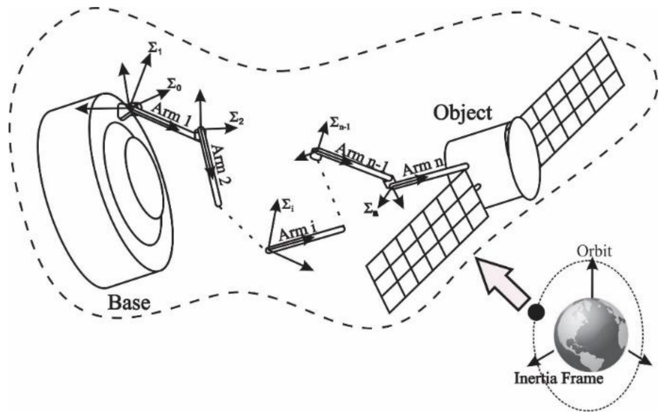

Figure 2 - Schematic of a space-manipulator capturing an object

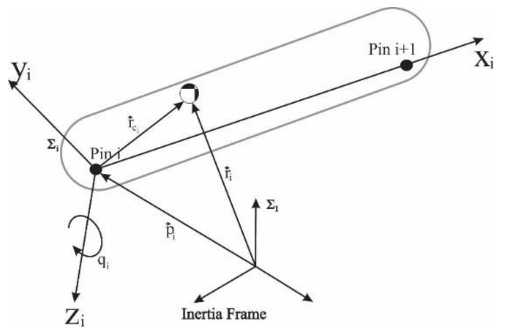

Figure 3 - Schematic of each element of space-manipulator

Using (1) the linear momentum of a multi-body system like space-manipulators can be written as:

$$\vec{P} = \sum_{i=0}^{n} m_i V_i = \sum_{i=0}^{n} m_i J_{v_i} \dot{\vec{X}} \quad (5)$$

$$\vec{L} = \sum_{i=0}^{n} (I_i \omega_i + m_i \vec{r}_{\mathrm{i}} \times \vec{v}_{\mathrm{i}})$$

Formulation of All IPs Identification Problem

As an identification problem, it is desired to present the MBA-based dynamic equations in the regressor form (6) which is appropriate for Least-Square based algorithms like Recursive Least Squares (RLS).

$$\begin{bmatrix}\Phi_{1\mathrm{u}}\\ \Phi_{2\mathrm{u}}\end{bmatrix} \vec{\theta}_{\mathrm{u}} = \vec{\tau} - \begin{bmatrix}\Phi_{1\mathrm{k}}\\ \Phi_{2\mathrm{k}}\end{bmatrix} \vec{\theta}_{\mathrm{k}} \quad (6)$$

In this equation, $\Phi_{1\mathrm{u}}$ and $\Phi_{2\mathrm{u}}$ are the regressor terms related to unknown IPs and $\Phi_{1\mathrm{k}}$ and $\Phi_{2\mathrm{k}}$ are the regressor terms related to unknown IPs. $\vec{\theta}_{\mathrm{k}}$ and $\vec{\theta}_{\mathrm{u}}$ presents known and unknown IPs respectively.

Where $\vec{P}$ denotes the linear momentum. Using (4), The linear momentum term in (5) can be written as

$$\vec{P} = \sum_{i=0}^{n} m_i \left(J_{p_i} + L(\vec{r}_{c_i})\right) \dot{\vec{X}} \quad (7)$$

For a serially linked manipulator [7] showed that

$$L(\vec{r}_{c_i}) \dot{\vec{X}} = B_i' \left(\dot{\vec{X}}\right) \vec{r}_{c_i} \quad (8)$$

So, Eq. 7 can be rewritten as:

$$\vec{P} = \sum_{i=0}^{n} m_i J_{p_i} \dot{\vec{X}} + \sum_{i=0}^{n} B_i{}' \overrightarrow{m_\iota r_{c_i}} \quad (9)$$

This equation is linear w.r.t mass vector and first moment vector.

For the angular momentum term ($\vec{L}$), it is necessary to transfer the In a similar fashion, the angular momentum of the space-manipulators can be written as:

$$\vec{L} = \sum_{i=0}^{n} I_i \omega_i + m_i \vec{r}_{\mathrm{i}} \times \vec{v}_{\mathrm{i}} = \sum_{i=0}^{n} I_i J_{\omega_i} \dot{\vec{X}} + \sum_{i=0}^{n} m_i \tilde{r}_i J_{v_i} \dot{\vec{X}} \quad (10)$$

Using definitions 3 and 6, the first part of (10) can be presented in a linear form w.r.t the inertia matrix of the elements of the space-manipulator as

$$I_i J_{\omega_i} \dot{\vec{X}} = \left[\underline{J_{\omega_i} \dot{\vec{X}}}\right] \underline{\vec{I_\iota}} \quad (11)$$

Considering (4), the second part of (10) can be written as:

$$m_i \tilde{r}_i J_{v_i} \dot{\vec{X}} = m_i \tilde{r}_i J_{p_i} \dot{\vec{X}} + m_i \tilde{r}_i L(\vec{r}_{c_i}) \dot{\vec{X}} \quad (12)$$

Using (2), Eq. (12) can be rewritten as

$$m_i\tilde{r}_i J_{v_i}\dot{\vec{X}} = \left(\tilde{\vec{p}}_i J_{p_i}\dot{\vec{X}}\right)m_i + \left(\left[\widetilde{J_{p_i}\dot{\vec{X}}}\right]^T \mathrm{R_i} + \tilde{\vec{p}}_i B_i{}'\right)m_i\vec{r}_{c_i} + m_i\widetilde{R_i r_{c_i}}B_i{}'\vec{r}_{c_i} \tag{13}$$

Combining (10), (11) and (13) the angular momentum of space-manipulator can be written as:

$$\vec{L} = \sum_{i=0}^{n}\left(\left(\tilde{\vec{p}}_i J_{p_i}\dot{\vec{X}}\right)m_i + \left(\left[\widetilde{J_{p_i}\dot{\vec{X}}}\right]^T \mathrm{R_i} + \tilde{\vec{p}}_i B_i' + \widetilde{R_i r_{c_i}}B_i{}'\right)m_i\vec{r}_{c_i} + \left[\underline{J_{\omega_i}\dot{\vec{X}}}\right]\underline{\vec{I_i}}\right) \tag{14}$$

This equation is linear with respect the masses (m_i) and inertias (I_i) of all elements of the spacecraft. However, appearance of $\vec{r}_{c_i}$ in the coefficient of term $m_i\vec{r}_{c_i}$ makes (14), nonlinear with respect to the first moment vector of the elements of the spacecraft.

Equation (14) can be helpful in the process of the calibration of IPs of the spacecraft to remove the uncertainties related to on-ground measurements or IPs changes during the space operations. However, during the capturing of the space-debris it can be assumed that calibration is performed in pre-capture phase and identification of IPs of the debris is the focus of the identification process.

Special form of IPs Identification Problem – One Unknown Element

In this section, it will be shown that if just one element of the space-manipulator has unknown IPs, it is possible to find a linear form of equations of motion w.r.t unknown IPs.

Without loss of generality, assume that the last element of space-manipulator has unknown IPs. Then (9) can be used to calculate the linear momentum of the last arm ($\vec{P}'$) as:

$$\vec{P}' = \vec{P} - \sum_{i=0}^{n-1} m_i J_{p_i}\dot{\vec{X}} - \sum_{i=0}^{n-1} B_i{}'\overrightarrow{m_i r_{c_i}} = J_{p_n}\dot{\vec{X}}m_n + B_n{}'\overrightarrow{m_n r_{c_n}} \tag{15}$$

Similarly, the angular momentum of the last arm ($\vec{L}'$) can be shown as:

$$\vec{L}' = \vec{L} - \sum_{i=0}^{n-1}\left(\left(\tilde{\vec{p}}_i J_{p_i}\dot{\vec{X}}\right)m_i + \left(\left[\widetilde{J_{p_i}\dot{\vec{X}}}\right]^T \mathrm{R_i} + \tilde{\vec{p}}_i B_i' + \widetilde{R_i r_{c_i}}B_i{}'\right)m_i\vec{r}_{c_i} + \left[\underline{J_{\omega_i}\dot{\vec{X}}}\right]\underline{\vec{I_i}}\right)$$

$$= \left(\tilde{\vec{p}}_n J_{p_n}\dot{\vec{X}}\right)m_n + \left(\left[\widetilde{J_{p_n}\dot{\vec{X}}}\right]^T \mathrm{R_n} + \tilde{\vec{p}}_n B_n' + \widetilde{R_n r_{c_n}}B_n{}'\right)m_n\vec{r}_{c_n} + \left[\underline{J_{\omega_n}\dot{\vec{X}}}\right]\underline{\vec{I_n}} \tag{16}$$

From (15) it can be shown that

$$B_n'\overrightarrow{m_n r_{c_n}} = \vec{P}' - J_{p_n}\dot{\vec{X}}m_n \tag{17}$$

Inserting (17) in (16) yields in

$$\vec{L}' = \left(\tilde{\vec{p}}_n J_{p_n}\dot{\vec{X}}\right)m_n + \left(\left[\widetilde{J_{p_n}\dot{\vec{X}}}\right]^T\right)R_n m_n\vec{r}_{c_n} + \left(\tilde{\vec{p}}_n + \widetilde{R_n r_{c_n}}\right)\left(\vec{P}' - J_{p_n}\dot{\vec{X}}m_n\right) + \left[\underline{J_{\omega_n}\dot{\vec{X}}}\right]\underline{\vec{I_n}} \tag{18}$$

Considering that for two arbitrary 3×1 vectors $\vec{r}$ and $\vec{u}$

$$\tilde{\vec{r}}\vec{u} = \tilde{\vec{u}}^T\vec{r} \tag{19}$$

Equation (18) can be simplified to

$$\vec{L}' - \tilde{\vec{p}}_n\vec{P}' = \widetilde{\vec{P}'}^T R_n\vec{r}_{c_n} + \left[\underline{J_{\omega_n}\dot{\vec{X}}}\right]\underline{\vec{I_n}} \tag{20}$$

Equation (17) can be rewritten as

$$\vec{P}'\left(\frac{1}{m_n}\right) - B_n'\vec{r}_{c_n} = J_{p_n}\dot{\vec{X}} \tag{21}$$

Equations (20) and (21) can be combined in the regressor form of

$$\begin{bmatrix} \vec{P}'R_n & -B_n' & 0 \\ 0 & \widetilde{\vec{P}'}^T & \left[\underline{J_{\omega_n}\dot{\vec{X}}}\right] \end{bmatrix}\begin{Bmatrix} \frac{1}{m_n} \\ \vec{r}_{c_n} \\ \underline{\vec{I_n}} \end{Bmatrix} = \begin{Bmatrix} J_{p_n}\dot{\vec{X}} \\ \vec{L}' - \tilde{\vec{p}}_n\vec{P}' \end{Bmatrix} \tag{22}$$

In a planar case, the (22) consisting three equations while, in a spatial case, this includes six equations. Mathematically, this form is appropriate for identification as it is linear with respect to the IPs. On the other hand, the implementation of (22) requires to measuring or estimating the inertial position and the linear and angular velocities of the base. It also needs the angular state and the angular velocity vector of the space manipulator elements. The drawback of using these equations to identify the IPs of the debris is its reliance on the measurement or estimation of the linear and angular velocities of the last arm ($\vec{L}'$, $\vec{P}'$).

Analysis of the presented identification formulation

Equation 22 shows a linear form of linear and angular momentums with respect to the IPs of the spacecraft that makes it appropriate to be used in conjunction of well-known methods like Least-Square based method (LS, RLS, WRLS) to identify unknown IPs of the space debris. The case studies presented in the following section show that using the presented formulation, the IPs of the space-manipulator can be estimated very fast using reliable methods like RLS.

Practically, there are some parameters in the the presented formulation that cannot be measured or estimated. Examination of the right-hand side of Eq. 22 shows that the regressor matrix depends on angular Jacobian (J_{ω_n}), B_n', R_n, and linear momentum of the last arm $\vec{P}'$. The terms J_{ω_n} , R_n and B_n' require the measurement of rotational angles and angular rates of the arms of the manipulator that can be measured using available sensors. On the other hand, the linear momentum of the last arm ($\vec{P}'$) is a parameter that cannot be measured or calculated as it relates to the unknown IPs of the last arm.

The left-hand side of Eq. 22 depends on J_{p_n} and the pin position of the last arm ($\tilde{\vec{p}}_n$) which can be calculated using the rotation angles of the arms of the manipulator. It also requires angular velocities of the arms ($\dot{\vec{X}}$) that generally the sensors of the manipulators are measuring them. However, the RHS of equation depends on linear and angular momentums of the spacecraft that are not measurable.

To tackle this problem, a specific feature that space environment provides us is used in this research. If the spacecraft remains in free-floating state during the estimation period, then the linear and angular momentums of the spacecraft will not change. Additionally, considering the fixed relative position of the spacecraft and the debris before the capturing process, the linear momentum resulted from their relative motion can be set to zero (before and after the grasping):

$$\vec{P} = \sum_{i=0}^{n} m_i v_i = \sum_{i=0}^{n-1} m_i v_i + \vec{P}' = \sum_{i=0}^{n-1} m_i J_{v_i} \dot{\vec{X}} + \vec{P}' = 0 \tag{23}$$

So,

$$\vec{P}' = -\sum_{i=0}^{n-1} m_i J_{v_i} \dot{\vec{X}} \tag{24}$$

Despite total linear momentum, the total angular momentum is not zero as the debris generally have unknown angular momentums. However, as the free-floating flight suggests, the total angular momentum remains unchanged during the estimation process. We employed this property by using the difference form of the angular-momentum-related terms in (22) to substitute the unknown angular momentum of the last arm with their known difference value:

$$\begin{bmatrix} \vec{P}' R_n & -B_n' & 0 \\ 0 & \overrightarrow{\Delta \widetilde{P}'}^{T} & \Delta \left[\underline{J_{\omega_n} \dot{\vec{X}}} \right] \end{bmatrix} \begin{Bmatrix} \frac{1}{m_n} \\ \vec{r}_{c_n} \\ \underline{\overrightarrow{I_n}} \end{Bmatrix} = \begin{Bmatrix} J_{p_n} \Delta \dot{\vec{X}} \\ \Delta \vec{L}' - \Delta\left(\tilde{\vec{p}}_n \vec{P}' \right) \end{Bmatrix} \tag{25}$$

In the following sections Eq. 25 is recognized as “difference form” of identification equation to distinguish it from the “main form” (Eq. (22)).

Table 1– Space-Manipulator parameters

Element Number	Mass (Kg)	Inertia around CoM (Kg.m2)	X_{cg}(m)	Y_{cg}(m)	l_p(m)	$q(t=0)$ (Deg)	$\dot{q}(t=0)$ (Deg/s)
0	2552	7087	-1.75	0.75	--	0	2
1	180	245	1.8	-0.06	4	60	1
2	180	245	1.95	0.02	4	-60	-2
3	180	245	1.9	-0.03	4	-60	1
4	934.45	3435	2.3	0.9	--	60	2

Case Study

A space manipulator consisting of a base spacecraft equipped with a four serially linked arms manipulator is simulated and its results are used for the verification of the identification developed formulation and algorithm (Fig. 1). The parameters of the simulated space manipulator are presented in Table 1. It is assumed that after grasping the debris by the last arm, they will bond to each other and form a new unique element. The IPs of this new element are a combination of the IPs of the debris and the last arm. Additionally, after grasping the space debris its angular momentum will be transferred to the space manipulator elements. The angular velocities of these elements after grasping the debris are assumed to be known as presented in Table 1.

The RLS algorithm with the initial covariance matrix of $P_0 = 10^6\boldsymbol{I}$ and forgetting factor of $\lambda = 0.99$ has been employed to identify the IPs of the last arm (including debris). To see how the “difference form” affects the identification performance compared to the “main form”, both forms have been used to identify the IPs of the last arm (including Debris).

The time variation of the identification of IPs of the last arm using the 'main form' is presented in Fig. 4. It is evident that the proposed algorithm successfully identifies all of the IPs of the captured debris in parallel in less than 10 seconds. On the other hand, the identification results using the difference form (Fig. 5) demonstrate that the difference form reduces the excitation level of terms related to the identification of the moment of inertia. This reduction can be attributed to the fact that the coefficients of mass and CoM in Eq. (25) are the same as in Eq. (22), and the difference form is only applied to the terms related to the moment of inertia. Consequently, the mass and CoM are identified first in less than 20 seconds, after which the inertia matrix is identified. It can be observed that the identification of the inertia term begins approximately after 15 seconds, when the mass and CoM identification converge to their final values. Once the identification of the inertia terms begins, it converges relatively quickly in about 5 seconds.

Conclusion

In this paper, the simultaneous identification of IPs for all elements of spacecraft equipped with space manipulators is formulated using the MBA approach. The formulation of the problem utilizes the conservation laws of linear and angular momentum. As a result, an equation is derived that is linear with respect to the masses and inertia matrices of the spacecraft's elements. However, due to the presence of center of masses in the regressor matrix, the equation is not linear with respect to the center of masses. Nevertheless, it has been demonstrated that for space systems with only one element having unknown IPs, a linear form of the equation with respect to all IPs can be obtained when the system operates in the free-floating mode. To address the requirement of measuring the angular and linear momenta of the debris, a difference form of the identification equation is developed. Simulation results indicate that both the main form and the difference form are capable of identifying IPs. However, due to the reduced excitation level in the difference form, the identification process takes longer to converge.

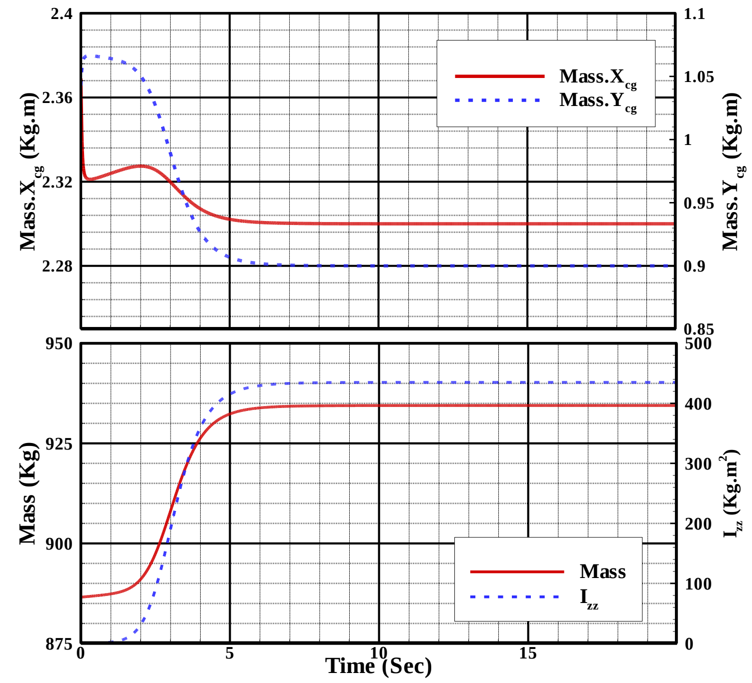

Figure 4 – Results of identification of mass and CG position assuming known angular momentum

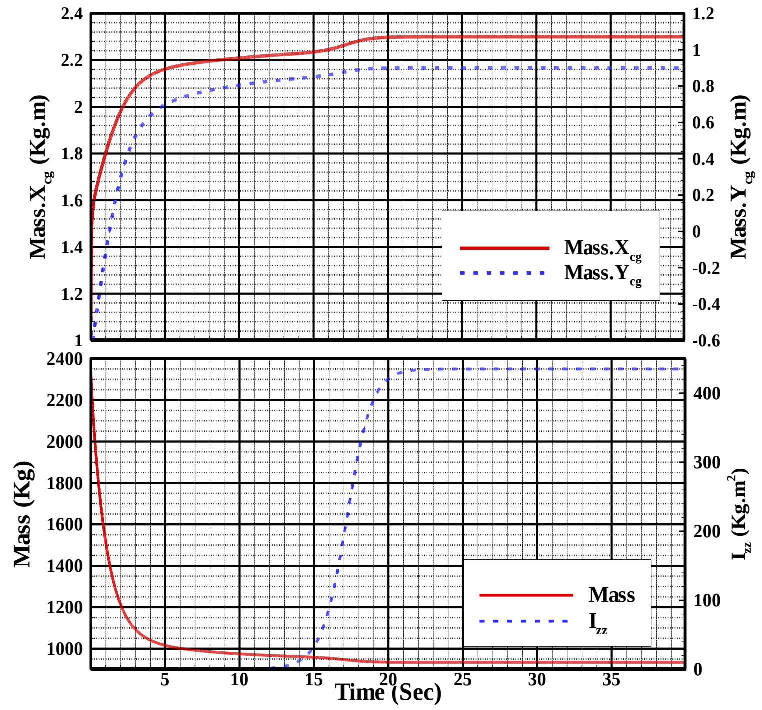

Figure 4 – Results of identification of mass and CG position using the difference form

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