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On Parameter Estimation of Space Manipulator Systems Using the Angular Momentum Conservation

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Abstract. To accomplish tasks with high accuracy, advanced control strategies that benefit from the knowledge of system parameters are required. However, during operation some of them may change, or be unknown. In this paper, a novel parameter estimation method is proposed, which is based on the conservation of the angular momentum of a space manipulator system in the free-floating mode. The estimated parameters are combinations of spacecraft, manipulator and payload parameters and render the system full dynamics identified and applicable to model-based control. The algorithm requires only measurements of joint angles and rates, and spacecraft attitude and angular velocity. No information about spacecraft and joint accelerations or joint torques, which include substantial noise, is required. Thus, in contrast to other methods using the equations of motion, the proposed method is insensitive to sensor noise. Moreover, it does not require the prior knowledge of any system parameters and can be applied to free-floating systems with more than one manipulators. The application of the proposed method is illustrated by a 3D example.

I. Introduction

On-Orbit Servicing (OOS) activities include missions, such as re-orbiting and de-orbiting, inspection and retrofit of orbiting structures, satellite maintenance, repair of damaged ones and removal of space debris. A cost-effective way to accomplish these is to use space manipulator systems (SMS) since space is too dangerous to human life, especially during EVA. SMS consist of one or more robotic manipulators, mounted on a satellite base equipped with thrusters, reaction wheels, antennas and sensors, see Fig. 1. The ETS-7 and the Orbital Express are two examples of such systems [1], [2].

To increase SMS life or avoid interactions with a target, the reaction wheels and the thrusters are turned off. This results in a free-floating operation, which is feasible when no external forces and torques act on the system. Then, motion of the uncontrolled satellite base results from manipulator(s) motions, due to dynamic coupling between them. To accomplish tasks at high accuracy, advanced model-based control strategies can be adopted; these require accurate knowledge of system parameters, [3].

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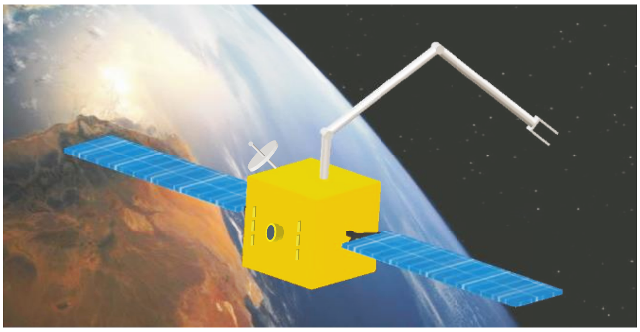

Fig. 1. A space manipulator system with a single manipulator.

However, very often, the dynamic parameters of an SMS may change on orbit for a number of reasons, such as fuel consumption, deployment of payload, docking to a spacecraft or object capture. To address this problem, many parameter estimation methods have been developed. Inspired by the methods for terrestrial fixed-base manipulators, [4], [5], some of them are based on the linearity of the equations of motion with respect to the dynamic properties, [6], [7]. However, these methods require measurements of spacecraft and joint accelerations, which contain undesirable noise.

To tackle this issue, some researchers have proposed estimation algorithms based on the momentum conservation. Yoshida and Abiko used the estimation errors for the reaction wheel momentum to compute the deviations of the parameters from the nominal ones [8]. The proposed estimation method fails to identify all the required parameters. Ma et al., used the angular momentum conservation to identify the spacecraft inertial parameters only, using complete knowledge of manipulator and payload parameters, [9].

Murotsu et al., have proposed and compared the two above-mentioned methods, of which one requires spacecraft and joint accelerations [10]. Both methods estimate only the inertia parameters of an unknown object handled by a free-flying manipulator. Xu et al. proposed a method, which uses both equations of motion and momentum equations, for identifying the inertia parameters of a space manipulator and the grasped target, [11]. The method requires measurements of spacecraft accelerations, which contain noise, and the use of thrusters for maneuvering, resulting in fuel consumption.

All past research either is based on equations of motion which require acceleration measurements and contain substantial noise, or on the momentum conservation, but then cannot estimate all the dynamic parameters. In this paper, a novel parameter estimation method is proposed, which is based on the conservation of the angular momentum of an

SMS in free-floating mode (FFSMS). The parameters to be identified are combinations of spacecraft, manipulator and payload parameters, and once available, they are enough to reconstruct the system full dynamics as required in model-based control. Only measurements of joint angles, rates, spacecraft attitude and angular velocity are employed; no spacecraft and joint accelerations or joint torques, which include substantial noise, are required. Hence, in contrast to equations of motion methods, the developed one is insensitive to sensor noise, while at the same time, it identifies a full set of SMS dynamic properties.

II. Dynamics of Free-Floating Space Manipulators

Advanced control strategies for FFSMS use the Generalized Jacobian matrix and the dynamic model of the system; hence they need knowledge of the system parameters, [12]. To this end, we briefly present the dynamics of an FFSMS with multiple manipulators and zero external forces and torques. We assume that the system has constant angular momentum, and without loss of generality, zero linear momentum, [13]. The FFSMS have an open chain kinematic configuration consist of n manipulators. The number of the links of the m-th manipulator is indicated by N_m. Under these conditions, the system Center of Mass (CM) remains fixed in inertial space, and hence the origin of an inertial frame, O, can be chosen to be the system CM, see Fig. 2.

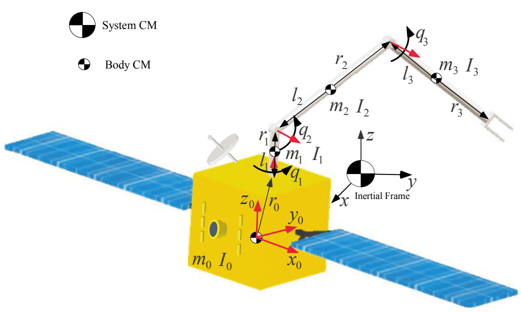

Fig. 2. A spatial FFSMS and the definition of its parameters.

The system angular momentum $\mathbf{h}_{CM}$ expressed in the inertial frame is given by:

$$\mathbf{h}_{CM} = \mathbf{R}_0 \, ({}^0\mathbf{D} \, {}^0\boldsymbol{\omega}_0 + {}^0\mathbf{D}_q \, \dot{\mathbf{q}}) \tag{1}$$

where ${}^0\boldsymbol{\omega}_0$ is the spacecraft angular velocity expressed in the spacecraft 0^{th} frame and the column-vector $\dot{\mathbf{q}}$ is:

$$\dot{\mathbf{q}} = [\dot{\mathbf{q}}^{(1)\mathrm{T}} \quad \cdots \quad \dot{\mathbf{q}}^{(m)\mathrm{T}} \quad \cdots \quad \dot{\mathbf{q}}^{(n)\mathrm{T}}]^{\mathrm{T}} \tag{2}$$

where the $N_m \times 1$ column-vector $\dot{\mathbf{q}}^{(m)}$ represents the joint rates of the m-th manipulator. The matrix $\mathbf{R}_0(\boldsymbol{\varepsilon}, \eta)$ is the rotation matrix between the spacecraft 0^{th} frame and the inertial frame, expressed as a function of the Euler parameters $\boldsymbol{\varepsilon}, \eta$, and the terms ${}^0\mathbf{D}$, ${}^0\mathbf{D}_q$ are inertia-type matrices of appropriate dimensions, given in Appendix A.

It has been shown that the equations of motion of a spatial FFSMS with nonzero initial angular momentum are [6]:

$$ {}^0\mathbf{D}(\mathbf{q}) \, {}^0\dot{\boldsymbol{\omega}}_0 + {}^0\mathbf{D}_q(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}_1({}^0\boldsymbol{\omega}_0, \mathbf{q}, \dot{\mathbf{q}}) = \mathbf{0} \tag{3}$$

$$ {}^0\mathbf{D}_q^{\mathrm{T}}(\mathbf{q}) \, {}^0\dot{\boldsymbol{\omega}}_0 + {}^0\mathbf{D}_{qq}(\mathbf{q}) \, \ddot{\mathbf{q}} + \mathbf{c}_2({}^0\boldsymbol{\omega}_0, \mathbf{q}, \dot{\mathbf{q}}) = \boldsymbol{\tau} \tag{4}$$

where the term ${}^0\mathbf{D}_{qq}$ is an inertia-type matrix and $\mathbf{c}_1$, $\mathbf{c}_2$ are column vectors containing the centrifugal and Coriolis torques, given in Appendix A. The 3×1 zero vector $\mathbf{0}$ corresponds to the zero moments acting on the spacecraft and $\boldsymbol{\tau}$ is the vector of the manipulator joint torques

$$\boldsymbol{\tau} = [\boldsymbol{\tau}^{(1)\mathrm{T}} \quad \cdots \quad \boldsymbol{\tau}^{(m)\mathrm{T}} \quad \cdots \quad \boldsymbol{\tau}^{(n)\mathrm{T}}]^{\mathrm{T}} \tag{5}$$

where the $N_m \times 1$ column-vector $\boldsymbol{\tau}^{(m)}$ represents the torques applied acting at the joints of the m-th manipulator.

Eq. (3) can be solved for ${}^0\dot{\boldsymbol{\omega}}_0$ and the result substituted to Eq. (4), yielding the reduced equations of motion:

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}\left({}^0\boldsymbol{\omega}_0, \mathbf{q}, \dot{\mathbf{q}}\right) = \boldsymbol{\tau} \tag{6}$$

where $\mathbf{H}$ and $\mathbf{c}$ are given in Appendix A.

III. Parameter Estimation Using Eqs. of Motion

In this section, we present a well-known estimation method based on the dynamic equations (*DE method*), [4]-[5]. In the case of FFSMS, the reduced equations of motion (6) cannot be written in a linear form with respect to the dynamic parameters. The non-linearity is caused by the presence of the term ${}^0\mathbf{D}^{-1}$ in $\mathbf{H}(\mathbf{q})$ and $\mathbf{c}$, see Appendix A. However, if Eqs. (3) and (4) are used, these can be expressed linearly with respect to the vector of the parameters to be estimated, $\boldsymbol{\pi}$:

$$\mathbf{0} = {}^0\mathbf{D} \, {}^0\dot{\boldsymbol{\omega}}_0 + {}^0\mathbf{D}_q \, \ddot{\mathbf{q}} + \mathbf{c}_1 = \mathbf{Y}_1(\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{q}, {}^0\dot{\boldsymbol{\omega}}_0, {}^0\boldsymbol{\omega}_0)\,\boldsymbol{\pi} \tag{7}$$

$$\boldsymbol{\tau} = {}^0\mathbf{D}_{qq} \, \ddot{\mathbf{q}} + {}^0\mathbf{D}_q^{\mathrm{T}} \, {}^0\dot{\boldsymbol{\omega}}_0 + \mathbf{c}_2 = \mathbf{Y}_2(\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{q}, {}^0\dot{\boldsymbol{\omega}}_0, {}^0\boldsymbol{\omega}_0)\,\boldsymbol{\pi} \tag{8}$$

Eqs. (7) and (8) can be combined into the following form:

$$\boldsymbol{\tau}^* = [\mathbf{0}^{\mathrm{T}} \quad \boldsymbol{\tau}^{\mathrm{T}}]^{\mathrm{T}} = \mathbf{Y}_\tau(\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{q}, {}^0\dot{\boldsymbol{\omega}}_0, {}^0\boldsymbol{\omega}_0)\,\boldsymbol{\pi} \tag{9}$$

where

$$\mathbf{Y}_\tau = [\mathbf{Y}_1^{\mathrm{T}} \quad \mathbf{Y}_2^{\mathrm{T}}]^{\mathrm{T}} \text{ of size } (3 + \sum_{m=1}^{n} N_m) \times k \tag{10}$$

is the regressor matrix, and k is the dimension of $\boldsymbol{\pi}$ (see Section IV.B).

Use of N measurements at time instants $t_1, t_2, \ldots, t_N$ of the variables $\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{q}, {}^0\dot{\boldsymbol{\omega}}_0, {}^0\boldsymbol{\omega}_0$, and $\boldsymbol{\tau}$, obtained during an appropriate trajectory, results in the following system of equations:

$$\hat{\boldsymbol{\tau}}^* = \begin{bmatrix} \boldsymbol{\tau}^*(t_1) \\ \boldsymbol{\tau}^*(t_2) \\ \vdots \\ \boldsymbol{\tau}^*(t_N) \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_\tau(t_1) \\ \mathbf{Y}_\tau(t_2) \\ \vdots \\ \mathbf{Y}_\tau(t_N) \end{bmatrix} \boldsymbol{\pi} = \hat{\mathbf{Y}}_\tau \boldsymbol{\pi} \tag{11}$$

To solve (11) for $\boldsymbol{\pi}$, the regressor matrix $\hat{\mathbf{Y}}_\tau$ must be of full rank. For this purpose, $\boldsymbol{\pi}$ must contain the minimum set of estimated parameters (see Section IV.B), appropriate exciting trajectories must be performed by the manipulators (see Section IV.C) and the number of the measurements N must be selected so that the number of rows of $\hat{\mathbf{Y}}_\tau$ is at least equal to the dimension of the vector $\boldsymbol{\pi}$,

$$(3 + \sum_{m=1}^{n} N_m) N \geq k \tag{12}$$

The system of Eq. (11) is over-determined and subject to the above conditions, it is solved using least-squares as,

$$\boldsymbol{\pi} = (\hat{\mathbf{Y}}_{\boldsymbol{\tau}}^{\mathrm{T}}\, \hat{\mathbf{Y}}_{\boldsymbol{\tau}})^{-1}\, \hat{\mathbf{Y}}_{\boldsymbol{\tau}}^{\mathrm{T}} \hat{\boldsymbol{\tau}}^{*} \tag{13}$$

It is important to note that the estimation method based on the equations of motion requires measurements of the spacecraft angular acceleration ${}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}$, the manipulator joint accelerations $\ddot{\mathbf{q}}$, and the applied torques $\boldsymbol{\tau}$. Joint accelerations are obtained essentially from encoder measurements and include substantial noise. The angular acceleration is obtained by angular velocity differentiation, again introducing noise to the estimation process. Finally, applied torques are hard to measure. They can be estimated using measurements or estimates of motor current. However, noise exists in motor current measurements and unmodeled joint friction and actuator dynamics limit the accuracy of applied torque estimation.

IV. Parameter Estimation Using the Angular Momentum Conservation

Methods which employ the momentum conservation cannot estimate all the required system inertia parameters without prior knowledge of some of them. However, in this paper, the estimated parameters are combinations of spacecraft, manipulator, and payload inertia parameters and can render the full system dynamics identified. A novel parameter estimation method for multi-arm FFSMS, based only on angular momentum conservation (*AMC method*), considering FFSMS with non-zero angular momentum, is developed. The desired non-zero angular momentum can be applied using momentum control devices such as reaction wheels.

A. Estimation Method

To use Eq. (1) for parameter estimation, the angular momentum $\mathbf{h}_{\mathbf{CM}}$, must be expressed linearly with respect to the vector of the estimated parameters $\boldsymbol{\pi}$. First, the terms ${}^{\mathbf{0}}\mathbf{D}_{\mathbf{ij}}^{(m)}$, derived in Appendix A, are expressed in sums of terms, where each term is the product of a constant and a measured quantity. A similar procedure has to be followed for all other terms of ${}^{\mathbf{0}}\mathbf{D}_{\mathbf{j}}^{(m)}$ and ${}^{\mathbf{0}}\mathbf{D}_{\mathbf{0}}$, shown in Appendix A. Thus, the angular momentum can be expressed as:

$$\mathbf{h}_{\mathbf{CM}} = \mathbf{Y}_{\mathbf{h}}(\dot{\mathbf{q}}, \mathbf{q}, {}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}, \boldsymbol{\varepsilon}, \eta)\, \boldsymbol{\pi} \tag{14}$$

where the $3\times k$ matrix $\mathbf{Y}_{\mathbf{h}}$ is the regressor matrix. Note that this regressor does not require acceleration measurements.

Assuming constant angular momentum $\mathbf{h}_{\mathbf{CM},0}$, and N measurements of the variables $\dot{\mathbf{q}}, \mathbf{q}, {}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}$ and $\boldsymbol{\varepsilon}, \eta$ obtained at time instants $t_1, t_2, ..., t_N$ during an appropriate trajectory, results in the following system of equations:

$$\hat{\mathbf{h}}_{\mathbf{CM}} = \begin{bmatrix} \mathbf{h}_{\mathbf{CM},0} \\ \mathbf{h}_{\mathbf{CM},0} \\ \vdots \\ \mathbf{h}_{\mathbf{CM},0} \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{\mathbf{h}}(t_1) \\ \mathbf{Y}_{\mathbf{h}}(t_2) \\ \vdots \\ \mathbf{Y}_{\mathbf{h}}(t_N) \end{bmatrix} \boldsymbol{\pi} = \hat{\mathbf{Y}}_{\mathbf{h}} \boldsymbol{\pi} \tag{15}$$

where $\boldsymbol{\pi}$ is the parameter vector same for both methods.

As with the DE method, appropriate exciting trajectories must be followed by the manipulators. The number of the measurements N should satisfy Eqs. (16)-(17) for spatial and planar free-floating space robots, respectively,

$$3N \geq k \tag{16}$$

$$N \geq k \tag{17}$$

The system of equations, given by Eq. (15), is over-determined and the least-squares solution is,

$$\boldsymbol{\pi} = (\hat{\mathbf{Y}}_{\mathbf{h}}^{\mathrm{T}}\, \hat{\mathbf{Y}}_{\mathbf{h}})^{-1}\, \hat{\mathbf{Y}}_{\mathbf{h}}^{\mathrm{T}}\, \hat{\mathbf{h}}_{\mathbf{CM}} \tag{18}$$

B. Minimum Set of Estimated Parameters

The vector $\boldsymbol{\pi}$ should contain the minimum set of estimated parameters so that the regressor $\hat{\mathbf{Y}}$ ($\hat{\mathbf{Y}}_{\boldsymbol{\tau}}$ for DE and $\hat{\mathbf{Y}}_{\mathbf{h}}$ for the AMC method), is of full rank. Therefore, a case-by-case analysis is required. Suppose that initially the $\mathbf{Y}$ and $\boldsymbol{\pi}$ are:

$$\mathbf{Y} = [\mathbf{e_1} \;\; \cdots \;\; \mathbf{e_i} \;\; \cdots \;\; \mathbf{e_k}] \tag{19}$$

and

$$\boldsymbol{\pi} = [\pi_1 \;\; \cdots \;\; \pi_i \;\; \cdots \;\; \pi_k]^{\mathrm{T}} \tag{20}$$

where $\mathbf{e_i}$ is the i^{th} column of matrix $\mathbf{Y}$ and π_i is the i^{th} element of column vector $\boldsymbol{\pi}$.

To find the minimum set of parameters, one must examine if a column $\mathbf{e_i}$ can be written as a linear combination of the other columns, i.e.,

$$\mathbf{e_i} = \sum_{j=1,\, j\neq i}^{k} \lambda_j \mathbf{e_j} \tag{21}$$

where λ_j are constants. If this is the case, $\mathbf{e}_i$ and π_i are removed from $\mathbf{Y}$ and $\boldsymbol{\pi}$, respectively, to obtain a new $\boldsymbol{\pi}$:

$$\boldsymbol{\pi} = \left[\pi_1\,(1+\lambda_1) \cdots \pi_{i-1}\,(1+\lambda_{i-1})\pi_{i+1}\,(1+\lambda_{i+1}) \cdots \pi_k\,(1+\lambda_k)\right]^{\mathrm{T}} \tag{22}$$

This is an iterative procedure that terminates when no column $\mathbf{e_i}$ of $\mathbf{Y}$ can be written in the form of (21). Then, the final $\boldsymbol{\pi}$ contains the minimum set of estimated parameters.

C. Exciting Trajectories

Appropriate exciting trajectories are required that result in $\mathbf{Y}$ being of full rank and with a small condition number. A small condition number is needed so that the estimation is relatively insensitive to measurement noise. The developed exciting trajectories are based on truncated Fourier series. To satisfy desired initial and final conditions, a fifth-order polynomial is added to the truncated Fourier series:

$$q_i^{(m)} = \sum_{l=1}^{N_f} \frac{a_l^{i(m)}}{\omega_f l} \sin(\omega_f l t) - \frac{b_l^{i(m)}}{\omega_f l} \cos(\omega_f l t) + \sum_{j=0}^{5} c_j^{i(m)} t^j \tag{23}$$

where $m = 1,...n$, $i = 1,..., N_m$, N_f is the number of the harmonics employed, $a_l^{i(m)}$ and $b_l^{i(m)}$ are free coefficients and $\omega_f = 2\pi / t_f$ with t_f the motion duration.

The free coefficients of the Fourier series are found by minimizing the condition number of the regressor matrix. The optimization algorithm is implemented using the Global Search Solver provided by the Global Optimization Toolbox (MathWorks Inc.) taking into account mechanical constraints on joint positions, velocities and accelerations.

D. *Noise Modeling*

To identify the desired identified parameters the measurements obtained by the system sensors are required. Here, it is assumed that an Inertial Measurement Unit (IMU) and joint encoders are available on an SMS.

The model of the IMU is given by, [14]:

$$ {}^{0}\tilde{\boldsymbol{\omega}}_0 = {}^{0}\boldsymbol{\omega}_0 + \mathbf{b}_\omega + \mathbf{n}_\omega \quad (24)$$

$$ \dot{\mathbf{b}}_\omega = \mathbf{n}_{b\omega} \quad (25)$$

where ${}^{0}\boldsymbol{\omega}_0$ is the true angular velocity whereas ${}^{0}\tilde{\boldsymbol{\omega}}_0$ is the corresponding measurement of the angular velocity. Additionally, the term $\mathbf{b}_\omega$ is the gyroscope bias, considered to be a "Brownian" motion process, while the terms $\mathbf{n}_\omega$ and $\mathbf{n}_{b\omega}$ represent white Gaussian noise with zero mean and standard deviations σ_ω and $\sigma_{b\omega}$, respectively.

The output of the motor encoder is also noisy, [15]:

$$ \tilde{\mathbf{q}} = \mathbf{q} + \mathbf{n}_q \quad (26)$$

where $\mathbf{q}$ is the true joint angle and $\tilde{\mathbf{q}}$ is the corresponding measurement; the term $\mathbf{n}_q$ represents Gaussian noise with zero mean and standard deviation σ_q.

V. SIMULATION RESULTS

The proposed identification method is illustrated by a spatial 3-DOF FFSMS. Although the method can be easily applied in multi-arm FFSMS, here a single arm manipulator, shown in Fig. 2, is studied. The kinematic and inertia parameters of the FFSMS are given in Table I.

The angular momentum of the system is set by the reaction wheels to $\mathbf{h}_{cm} = [68 \quad 66 \quad 65]^T$ Nms and the initial spacecraft attitude is $[\boldsymbol{\varepsilon}_{in}^T \quad \eta_{in}]^T = [0.2 \quad 0.1 \quad 0.3 \quad 0.9274]^T$.

Table I. Parameters of the system shown in Fig. 2.

i	l_i (m)	r_i (m)	m_i (kg)	I_{xx} (kg m^2)	I_{yy} (kg m^2)	I_{zz} (kg m^2)
0	-	$[0.1, 0.2, 1]^T$	2000	1500	1500	1500
1	0.25	0.25	10	0.21	0.21	0.01
2	1.0	1.0	50	0.05	16.69	16.69
3	1.0	1.0	50	0.05	16.69	16.69

The exciting trajectories are given by Eq. (23) where $t_f = 30s$ and $N_f = 3$. The desired initial and final conditions correspond to zero joint angles, rates and accelerations. The number of measurements is taken equal to $N = 20$. Regressors $\hat{\mathbf{Y}}_\tau$ and $\hat{\mathbf{Y}}_h$ differ, therefore different optimized trajectories are derived, which correspond to different minimum condition numbers. Since the DE method is more sensitive in measurement noise than the proposed AMC method, the exciting trajectory used in identification with both methods corresponds to that with minimum condition number of the regressor $\hat{\mathbf{Y}}_\tau$, which is 28. The coefficients a_l^i and b_l^i of the exciting trajectory are shown in Table II.

The gyro measurements are simulated using Eqs. (24) and (25) with standard deviations $\sigma_\omega = 3.1623 \cdot 10^{-4}\ \mu\text{rad}/\text{s}^{3/2}$ and $\sigma_{b\omega} = 0.31623\ \mu\text{rad}/\text{s}^{1/2}$, respectively, and with initial bias on each axis $b_{\omega,0} = 0.1\ \text{deg}/\text{hr}$, [14]. The joint angle standard deviation is $\sigma_q = 10^{-5}$ rad. The time histories of joint angles, rates and accelerations including noise, are shown in Fig. 3.

Table II. Trajectory coefficients for minimum condition number.

a_1^1	0.0411	b_1^1	0.0533
a_2^1	-0.0622	b_2^1	-0.1269
a_3^1	0.0002	b_3^1	0.0171
a_1^2	0.0435	b_1^2	-0.0393
a_2^2	-0.0407	b_2^2	0.0596
a_3^2	-0.1253	b_3^2	-0.0444
a_1^3	0.0516	b_1^3	-0.0153
a_2^3	-0.0423	b_2^3	0.0449
a_3^3	0.1343	b_3^3	0.0463

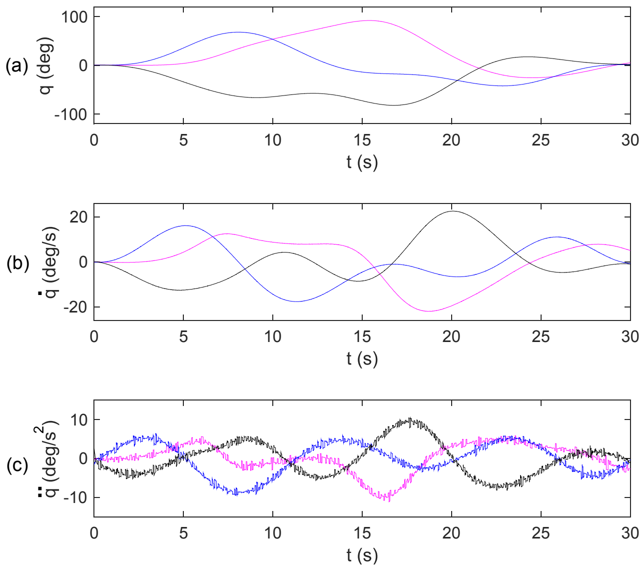

Fig. 3 (a) Joint angles, (b) joint rates and (c) joint accelerations of the spatial FFSMS in Table I, for the trajectories described in Table II, considering noisy measurements.

For the spatial 3-DOF manipulator, shown in Fig. 2, the minimum set of estimated parameters is presented in Appendix B. The results of the identification methods DE and AMC, using measurements with and without noise, are displayed in Table III. As shown in this table, if no noise exists in the measurements, (second and third column in Table III), both methods estimate the required parameters practically exactly.

However, when noisy measurements are introduced, the DE method fails to identify the parameters, displaying errors between 19 and 140%. In contrast to these results, the developed AMC method, (fourth and fifth column in Table III) exhibits errors which are 25-1800 times smaller than those obtained with the DE method. The main reason for this spectacular difference is that the developed method does not require noisy acceleration measurements.

Note that for these results no joint torque noise or unmodeled friction was added; if such terms are added, it is expected that the results of the DE method will be even worse. Therefore, the AMC method yields much better results, and in addition it does not require torque measurements, which are difficult to obtain.

Table III. Results from DE & AMC methods with & without noise.

π	π True value	No noise		With noise	
		Relative Error (%) (DE)	Relative Error (%) (AMC)	Relative Error (%) (DE)	Relative Error (%) (AMC)
π_1	1832.5	0.0214	0.0008	30.85	-0.017
π_2	-104.2	-0.0042	-0.0371	139.48	-0.898
π_3	-154.0	-0.0972	-0.0146	73.54	-0.681
π_4	1832.5	0.0324	0.0035	38.27	-0.066
π_5	-154.0	-0.0121	-0.0519	97.86	-0.470
π_6	1708.5	0.0158	0.0108	34.29	-0.147
π_7	321.5	0.0581	0.0787	50.47	0.603
π_8	321.5	0.0043	0.0353	29.89	0.290
π_9	255.9	-0.0074	-0.0471	29.75	0.166
π_{10}	256.0	0.0381	0.0040	25.96	0.038
π_{11}	-65.4	-0.0087	-0.0568	60.89	1.451
π_{12}	65.5	0.0834	0.0318	18.33	-0.674
π_{13}	142.1	0.0042	0.0179	78.23	-0.466
π_{14}	213.4	0.0024	0.0171	39.80	0.345
π_{15}	142.1	0.0289	0.0303	85.82	-0.645
π_{16}	47.4	0.0959	0.0476	25.49	-0.999
π_{17}	71.1	0.0271	0.0843	44.99	0.309
π_{18}	47.39	0.0121	0.0976	119.23	-0.564
π_{19}	96.4	0.0064	0.0333	26.01	0.745

VI. CONCLUSIONS

In this paper, a novel parameter estimation method was developed, based on the conservation of the angular momentum of FFSMS. Combinations of spacecraft, manipulator and payload parameters are identified that allow full reconstruction of the system dynamics, and therefore can be used in model-based control algorithms. Only measurements of joint angles, rates, and spacecraft attitude and angular velocity are needed; noisy and hard to obtain spacecraft and manipulator joint accelerations or joint torques, are not required. Thus, in contrast to methods based on equations of motion, the developed method is insensitive to sensor noise while it identifies the full parameter set. Moreover, it does not require prior knowledge of any parameter and can be applied to free-floating systems with more than one manipulators. The developed method was illustrated by a 3D example.

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APPENDIX A

The matrices ${}^{0}\mathbf{D}$, ${}^{0}\mathbf{D}_{\mathbf{q}}$ and ${}^{0}\mathbf{D}_{\mathbf{qq}}$, expressed in the spacecraft frame, are presented.

First, the term ${}^{0}\mathbf{D}$ is given by,

$$
{}^{0}\mathbf{D} = {}^{0}\mathbf{D}_{0} + \sum_{m=1}^{n}\sum_{j=1}^{N_m} {}^{0}\mathbf{D}_{\mathbf{j}}^{(m)} \tag{A1}
$$

where

$$
\begin{aligned}
{}^{0}\mathbf{D}_{0} = {}^{0}\mathbf{I}_{0} &+ \sum_{m=1}^{n}\sum_{i=1}^{Nm} {}^{0}\mathbf{D}_{\mathbf{i0}}^{(m)} + \sum_{m=1}^{n} \frac{M\sum_{k=1}^{Nm} m_k^{(m)}}{M-\sum_{k=1}^{N_m} m_k^{(m)}} [{}^{0}\tilde{\mathbf{r}}_{\mathbf{0}}^{(m)}, {}^{0}\tilde{\mathbf{r}}_{\mathbf{0}}^{(m)}] \\
&- \sum_{m=1}^{n}\sum_{\substack{q=1\\ q\neq m}}^{n} \frac{M\sum_{k=1}^{Nm} m_k^{(m)} \sum_{k=1}^{Nq} m_k^{(q)}}{\left(M-\sum_{k=1}^{N_m} m_k^{(m)}\right)\left(M-\sum_{k=1}^{Nq} m_k^{(q)}\right)} [{}^{0}\tilde{\mathbf{r}}_{\mathbf{0}}^{(m)}, {}^{0}\tilde{\mathbf{r}}_{\mathbf{0}}^{(q)}] \\
&+ \sum_{m=1}^{n}\sum_{\substack{q=1\\ q\neq m}}^{n}\sum_{i=1}^{N_q} \frac{M\sum_{k=1}^{Nm} m_k^{(m)}}{M-\sum_{k=1}^{N_m} m_k^{(m)}} [{}^{0}\tilde{\mathbf{r}}_{\mathbf{0}}^{(m)}, {}^{0}\tilde{\mathbf{l}}_{\mathbf{i}}^{(q)}]
\end{aligned} \tag{A2}
$$

and

$$ {}^{0}\mathbf{D}_{\mathbf{j}}^{(m)} = \sum_{i=0}^{N_m} {}^{0}\mathbf{D}_{\mathbf{ij}}^{(m)} - \sum_{\substack{q=1 \\ q\neq m}}^{n} \sum_{k=1}^{N_q} M\,[\,{}^{0}\tilde{\mathbf{l}}_{\mathbf{j}}^{(m)},\ {}^{0}\tilde{\mathbf{l}}_{\mathbf{k}}^{(q)}] + \sum_{\substack{q=1 \\ q\neq m}}^{n} \frac{M \sum_{k=1}^{N_q} m_k^{(q)}}{M - \sum_{k=1}^{N_q} m_k^{(q)}} [\,{}^{0}\tilde{\mathbf{l}}_{\mathbf{j}}^{(m)},\ {}^{0}\tilde{\mathbf{r}}_{\mathbf{0}}^{(q)}] \tag{A3} $$

where

$$ {}^{0}\mathbf{D}_{\mathbf{ij}}^{(m)} = \begin{cases} -M\,[\,{}^{0}\tilde{\mathbf{l}}_{\mathbf{j}}^{(m)},\ {}^{0}\tilde{\mathbf{r}}_{\mathbf{i}}^{(m)}] & i<j \\ {}^{0}\mathbf{I}_{\mathbf{i}}^{(m)} + m_i^{(m)}[\,{}^{0}\tilde{\mathbf{e}}_{\mathbf{i}}^{(m)},\ {}^{0}\tilde{\mathbf{e}}_{\mathbf{i}}^{(m)}] + m_0[\,{}^{0}\tilde{\mathbf{l}}_{\mathbf{i}}^{(m)},\ {}^{0}\tilde{\mathbf{l}}_{\mathbf{i}}^{(m)}] \\ \quad + (\sum_{\substack{q=1 \\ q\neq m}}^{n} \sum_{k=1}^{N_q} m_k^{(q)} + m_1^{(m)} + \ldots + m_{i-1}^{(m)})[\,{}^{0}\tilde{\mathbf{l}}_{\mathbf{i}}^{(m)},\ {}^{0}\tilde{\mathbf{l}}_{\mathbf{i}}^{(m)}] & i=j \\ \quad + (m_{i+1}^{(m)} + \ldots + m_{N_m}^{(m)})[\,{}^{0}\tilde{\mathbf{r}}_{\mathbf{i}}^{(m)},\ {}^{0}\tilde{\mathbf{r}}_{\mathbf{i}}^{(m)}] \\ -M\,[\,{}^{0}\tilde{\mathbf{r}}_{\mathbf{j}}^{(m)},\ {}^{0}\tilde{\mathbf{l}}_{\mathbf{i}}^{(m)}] & i>j \end{cases} \tag{A4} $$

The term ${}^{0}\mathbf{D}_{\mathbf{q}}$ is given by,

$$ {}^{0}\mathbf{D}_{\mathbf{q}} = \begin{bmatrix} {}^{0}\mathbf{D}_{\mathbf{q}}^{(1)} & \cdots & {}^{0}\mathbf{D}_{\mathbf{q}}^{(m)} & \cdots & {}^{0}\mathbf{D}_{\mathbf{q}}^{(n)} \end{bmatrix} \tag{A5} $$

where

$$ {}^{0}\mathbf{D}_{\mathbf{q}}^{(m)} = \sum_{j=1}^{N_m} {}^{0}\mathbf{D}_{\mathbf{j}}^{(m)}\ {}^{0}\mathbf{F}_{\mathbf{j}}^{(m)} \tag{A6} $$

and

$$ {}^{0}\mathbf{F}_{\mathbf{j}}^{(m)} = \begin{bmatrix} {}^{0}\mathbf{z}_{\mathbf{1}}^{(m)} & \cdots & {}^{0}\mathbf{z}_{\mathbf{j}}^{(m)} & \cdots & \mathbf{0}_{3\times(\mathrm{N}_m-\mathrm{j})} \end{bmatrix} \tag{A7} $$

where ${}^{0}\mathbf{z}_{\mathbf{j}}^{(m)}$ is the unit vector along the j-th joint's axis of the m-th manipulator expressed in spacecraft frame and $\mathbf{0}$ is the zero matrix.

The $\sum_{m=1}^{n} N_m \times \sum_{m=1}^{n} N_m$ matrix ${}^{0}\mathbf{D}_{\mathbf{qq}}$ is given by,

$$ {}^{0}\mathbf{D}_{\mathbf{qq}}(m,q) = \begin{cases} -M \sum_{i=1}^{N_m} \sum_{j=1}^{N_q} {}^{0}\mathbf{F}_{\mathbf{i}}^{(m)\mathrm{T}} [\,{}^{0}\mathbf{l}_{\mathbf{i}}^{(m)},\ {}^{0}\mathbf{l}_{\mathbf{j}}^{(q)}]\ {}^{0}\mathbf{F}_{\mathbf{j}}^{(q)} & m\neq q \\ \sum_{j=1}^{N_m} \sum_{i=1}^{N_m} {}^{0}\mathbf{F}_{\mathbf{i}}^{(m)\mathrm{T}}\ {}^{0}\mathbf{D}_{\mathbf{ij}}^{(m)}\ {}^{0}\mathbf{F}_{\mathbf{j}}^{(m)} & m=q \end{cases} \tag{A8} $$

In Eqs. (A2)–(A4) and Eq. (A8), the body-fixed barycentric vectors ${}^{0}\tilde{\mathbf{l}}_{\mathbf{k}}^{(m)}$, ${}^{0}\tilde{\mathbf{r}}_{\mathbf{k}}^{(m)}$ and ${}^{0}\tilde{\mathbf{e}}_{\mathbf{k}}^{(m)}$ are given in [16] and

$$ [\mathbf{a}\,,\mathbf{b}] = (\mathbf{a}\cdot\mathbf{b})\mathbf{1} - \mathbf{ab} \tag{A9} $$

where $\mathbf{1}$ is the unit dyadic.

The column vectors $\mathbf{c_1}$ and $\mathbf{c_2}$ in Eqs. (3) and (4) are given by, [13]:

$$ \mathbf{c_1} = {}^{0}\boldsymbol{\omega}_{\mathbf{0}}^{\times}\ {}^{0}\mathbf{D}\ {}^{0}\boldsymbol{\omega}_{\mathbf{0}} + \left({}^{0}\boldsymbol{\omega}_{\mathbf{0}}^{\times}\ {}^{0}\mathbf{D}_{\mathbf{q}} + \frac{\partial\left({}^{0}\mathbf{D}\ {}^{0}\boldsymbol{\omega}_{\mathbf{0}}\right)}{\partial\mathbf{q}} + \frac{\partial\left({}^{0}\mathbf{D}_{\mathbf{q}}\dot{\mathbf{q}}\right)}{\partial\mathbf{q}} \right)\dot{\mathbf{q}} \tag{A10} $$

$$ \mathbf{c_2} = \left(\frac{\partial\left({}^{0}\mathbf{D}_{\mathbf{q}}^{\mathrm{T}}\ {}^{0}\boldsymbol{\omega}_{\mathbf{0}}\right)}{\partial\mathbf{q}} + \frac{\partial\left({}^{0}\mathbf{D}_{\mathbf{qq}}\dot{\mathbf{q}}\right)}{\partial\mathbf{q}} - \frac{1}{2}\frac{\partial\left(\dot{\mathbf{q}}^{\mathrm{T}}\ {}^{0}\mathbf{D}_{\mathbf{qq}}\right)}{\partial\mathbf{q}} \right)\dot{\mathbf{q}} - \frac{\partial\left({}^{0}\boldsymbol{\omega}_{\mathbf{0}}^{\mathrm{T}}\ {}^{0}\mathbf{D}_{\mathbf{q}}\right)}{\partial\mathbf{q}}\dot{\mathbf{q}} - \frac{1}{2}\frac{\partial\left({}^{0}\boldsymbol{\omega}_{\mathbf{0}}^{\mathrm{T}}\ {}^{0}\mathbf{D}\right)}{\partial\mathbf{q}}\ {}^{0}\boldsymbol{\omega}_{\mathbf{0}} \tag{A11} $$

where ${}^{0}\boldsymbol{\omega}_{\mathbf{0}}$ is given by Eq. (1).

The inertia matrix in Eq. (6) is given by:

$$ \mathbf{H}(\mathbf{q}) = {}^{0}\mathbf{D}_{\mathbf{qq}} - {}^{0}\mathbf{D}_{\mathbf{q}}^{\mathrm{T}}\ {}^{0}\mathbf{D}^{-1}\ {}^{0}\mathbf{D}_{\mathbf{q}} \tag{A12} $$

The vector $\mathbf{c}$ in Eq. (6) is given by:

$$ \mathbf{c} = \mathbf{c_2} - {}^{0}\mathbf{D}_{\mathbf{q}}^{\mathrm{T}}\ {}^{0}\mathbf{D}^{-1}\ \mathbf{c_1} \tag{A13} $$

APPENDIX B

The minimum set of parameters of the FFSMS in Fig. 2, i.e. the elements of the $\boldsymbol{\pi}$ vector are shown below:

$$ \pi_1 = I_{0x} + I_{1y} + A\left(r_{0y}^2 + r_{0z}^2 + 2r_{0z}l_1 + l_1^2\right)\left(2Br_1\left(r_{0z}+l_1\right) + Cr_1^2\right) \tag{B1} $$

$$ \pi_2 = -Ar_{0x}r_{0y} \tag{B2} $$

$$ \pi_3 = -(Ar_{0x}(r_{0z}+l_1) + Br_{0x}r_1) \tag{B3} $$

$$ \pi_4 = I_{0y} + I_{1y} + A\left(r_{0x}^2 + r_{0z}^2 + 2r_{0z}l_1 + l_1^2\right)\left(2Br_1\left(r_{0z}+l_1\right) + Cr_1^2\right) \tag{B4} $$

$$ \pi_5 = -(Ar_{0y}\left(r_{0z}+l_1\right) + Br_{0y}r_1) \tag{B5} $$

$$ \pi_6 = I_{0z} + A\left(r_{0x}^2 + r_{0y}^2\right) \tag{B6} $$

$$ \pi_7 = I_{1x} - I_{1y} + I_{2y} + I_{3y} + Cl_2^2 + D\left(l_3^2 + r_2^2\right) + 2El_2r_2 \tag{B7} $$

$$ \pi_8 = I_{1z} + I_{2y} + I_{3y} + Cl_2^2 + D\left(l_3^2 + r_2^2\right) + 2El_2r_2 \tag{B8} $$

$$ \pi_9 = I_{2x} - I_{2y} - \left(Cl_2^2 + Dr_2^2 + 2El_2r_2\right) \tag{B9} $$

$$ \pi_{10} = I_{2z} + Cl_2^2 + Dr_2^2 + 2El_2r_2 \tag{B10} $$

$$ \pi_{11} = I_{3x} - I_{3y} - Dl_3^2 \tag{B11} $$

$$ \pi_{12} = I_{3z} + Dl_3^2 \tag{B12} $$

$$ \pi_{13} = r_{0y}\left(Bl_2 + Fr_2\right) \tag{B13} $$

$$ \pi_{14} = Bl_2\left(r_{0z}+l_1\right) + Cl_2r_1 + Er_1r_2 + Fr_2\left(r_{0z}+l_1\right) \tag{B14} $$

$$ \pi_{15} = r_{0x}\left(Bl_2 + Fr_2\right) \tag{B15} $$

$$ \pi_{16} = Fl_3r_{0y} \tag{B16} $$

$$ \pi_{17} = El_3r_1 + Fl_3\left(r_{0z}+l_1\right) \tag{B17} $$

$$ \pi_{18} = Fl_3r_{0x} \tag{B18} $$

$$ \pi_{19} = Dl_3r_2 + El_2l_3 \tag{B19} $$

where,

$$ A = m_0\left(m_1 + m_2 + m_3\right)/M \tag{B20} $$

$$ B = m_0\left(m_2 + m_3\right)/M \tag{B21} $$

$$ C = \left(m_0 + m_1\right)\left(m_2 + m_3\right)/M \tag{B22} $$

$$ D = m_3\left(m_0 + m_1 + m_2\right)/M \tag{B23} $$

$$ E = m_3\left(m_0 + m_1\right)/M \tag{B24} $$

$$ F = m_0m_3/M \tag{B25} $$

$$ M = m_0 + m_1 + m_2 + m_3 \tag{B26} $$