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Quaternion-Based Spacecraft Dynamic Modeling and Reorientation Control Using the Dynamically Equivalent Manipulator Approach

Elżbieta Jarzębowska and Marcin Kłak

Abstract

The chapter presents modification of a dynamically equivalent manipulator (DEM) method, which enables dynamic modeling of space robots and manipulators, including free-floating maneuvers, via their suitable substitution by ground-fixed manipulator models. DEM provides an attractive modeling and control design tool, since it enables conducting tests and experiments for space vehicles in earth laboratories. The modification of DEM method relies upon an introduction of quaternion-based modeling of manipulator attitude. Originally, DEM method was developed in Euler angles. The basic motivation for the presented DEM modification is to make dynamic and kinematic models more suitable for description of space robots and manipulator motions and their missions like debris removal, spacecraft servicing, space mining, and on-orbit docking and assemblies. It may also support control designs. The theoretical development is illustrated by an example of generation of spacecraft quaternion-based dynamics and simulation studies of its reorientation maneuvers.

Keywords: dynamically equivalent manipulator, quaternion-based dynamics, space robot attitude, free-floating maneuvers

1. Introduction

Possibilities of employing space robots and manipulators for variety of rescue, servicing, and reconnaissance missions have been addressed since the early 1980s (see, e.g., [1] and references there). A lot of research and theoretical studies address dynamic control and space missions for various space vehicles, but just a few experiments have been conducted on the orbit. Examples, from a very incomplete list, can be maintenance missions for the Hubble Space Telescope and the retrieval of the Space Flyer Unit as described in [2]. In these missions, however, the space crews manually operated manipulator arms. Autonomous target capture by an unmanned space robot can be another example of a challenging operation, first addressed theoretically through modeling and simulation studies by space robotic

researchers. A couple of milestones marked the human's way to autonomous space robot operations toward service and exploration of the universe. The examples are the Robot Technology Experiment (ROTEX) developed by the German Aerospace Center [3]. A multisensory robot was flown on space shuttle COLUMBIA (STS-55) in 1993. Although the robot worked inside a work cell on the shuttle, several key technologies such as a multisensory gripper, tele-operation from the ground, shared autonomy, and time delay compensation by a predictive graphic display were successfully tested. One more example is the Engineering Test Satellite VII, in the area of satellite servicing, which is an unmanned spacecraft developed and launched by the National Space Development Agency of Japan [4]. In 2005, Demonstration of Autonomous Rendezvous Technology (DART) experimented with rendezvous and docking to another satellite. The mission failed due to defective autonomous navigation system, but lessons were learnt, and the next mission Orbital Express in 2007 was a success and demonstrated free-flying capture and refueling by an autonomous servicing satellite (ASTRO) [5, 6]. Another example of a promising servicing mission is SMART-OLEV (orbital life extension vehicle) implemented for life extension of GEO communication satellites [7]. The space debris removal problem is another instance of a complex task that requires multistage space manipulator (SM) missions including tracking, capturing, and debris safe removal. The strong need of working out effective methods of debris removal from the space opened new research areas and mission planning for space manipulator-based missions that were traditionally focused on on-orbit servicing of satellites. An intensive review of space debris removal problems including dynamic modeling and control can be found in [8] and references there. One more emerging research and future mission area is space mining, which needs to get frames of the scientific and future mission visions.

Before any experiment can be carried out on the orbit and before any spacecraft is launched to the orbit, intensive research; theoretical tests in fields of dynamic modeling, motion control, navigation, sensors, and vision; and related field theories have to be completed and verified.

This chapter focuses on dynamic modeling and reorientation of free-floating space manipulators dedicated to servicing tasks. The free-floating operation assumption requires the spacecraft thrusters to be turned off and the system linear and angular momentum to be conserved. This means that the spacecraft model is subjected to two constraints. One, the linear momentum conservation, generates the holonomic constraint equation, and the second, the angular momentum conservation, the nonholonomic constraints. Additionally, the uncontrolled space robot base makes the system underactuated, which means that there are less control inputs than degrees of freedom. Therefore, the free-floating space vehicles are classified as underactuated nonholonomic dynamical systems. The development of free-floating space manipulator mechanical models is then a complex task due to dynamic couplings, dynamic singularities, and nonholonomic constraints inherent to the system. There are many modeling methods, applied to a single spacecraft as well as to their formations that come from ground robotics and take advantage of the Lagrange approach and its modifications. However, space vehicles require more sophisticated modeling methods due to their specific properties and operation regimes. One of the recent modeling concepts was proposed by Liang et al. [9]. They proposed a new concept of a dynamically equivalent manipulator (DEM). In this formulation a free-floating space manipulator is substituted by a ground-fixed manipulator, whose first link is constrained by a spherical bearing. A proper scaling of physical parameters allows preserving kinematic and dynamic properties of the original space manipulator. In this original development, the attitude of the first DEM link is described by the Euler angles. Although this description is intuitive and well known in aviation, it is not suitable for dynamic modeling and control of space

systems. Unlike quaternions, Euler angles are subject of gimbal lock and ambiguity. Considering free space manipulator rotation in space, quaternions are the more suitable parameters for attitude description. Not only they do not share Euler angles' drawbacks, but they are also computationally more efficient. However, implementation of quaternions reveals other challenges due to complex relations with respect to space manipulator angular velocities and the constraint equation they have to satisfy as parameters. Introduction of quaternion parameterization to the Lagrange-based dynamics modeling can be found in Nikravesh et al. [10]. There, the derivation procedure was developed for ground manipulators subjected to position constraints only.

This chapter contributes to the modification of DEM method to enable space manipulators and other spacecraft kinematic and dynamic presentations in quaternions. The modification of DEM enables dynamic modeling of space robots and manipulators, including free-floating maneuvers, via their suitable substitution by ground-fixed manipulator models. The modified DEM may provide then an attractive modeling and control design tool, since it enables conducting tests and experiments for space vehicles in earth laboratories. This may contribute to mission failure reduction and mission cost reductions. The modification of DEM method relies upon an introduction of quaternion-based modeling of manipulator dynamics and attitude. The basic motivation for the DEM modification is to make dynamic and kinematic models more suitable for description of space robots and manipulator motions and their missions like debris removal, spacecraft servicing, space mining, and on-orbit docking and assemblies. It may also support control designs. The novelty of this modeling is in the modification of DEM to enable spacecraft kinematic and dynamic presentation in quaternions. The chapter also provides a short overview of the frequently used spacecraft dynamic modeling methods, advantages, and shortcomings of the resulted models with respect to their applications to descriptions of new mission scenarios and control demands. The theoretical development of the quaternion-based DEM method is illustrated by simulation studies of an example of space manipulator attitude dynamics. The study, presented for the first time, is designed as a comparative one with respect to other modeling methods and provides a confirmation of the right approach from the modeling and simulation point of view. Also, the modeling approach proved its effectiveness when the space manipulator is added additional links.

2. Dynamic modeling of spacecraft: the existing approaches, modeling using quaternions, and advantages of the quaternion description

Majority of space robot dynamic models uses the Lagrange approach and its modifications with the generalized coordinates, joint coordinates, Denavit-Hartenberg parameters, or others. For example, following the popular derivation of a space robot dynamics, presented in, e.g., [4, 11, 12] and references there, for a simple free-floating model that consists of a base and a serial manipulator, the Lagrange-based dynamics can be presented in the form

$$\begin{bmatrix} H_b & H_{bm} \\ H_{bm}^T & H_m \end{bmatrix} \begin{bmatrix} \ddot{x}_b \\ \ddot{\Theta} \end{bmatrix} + \begin{bmatrix} c_b \\ c_m \end{bmatrix} = \begin{bmatrix} F_b \\ \tau_m \end{bmatrix} \quad (1)$$

where:

$H_m \in R^{n \times n}$ is the inertia matrix of the manipulator arms.

$H_b \in R^{6 \times 6}$ is the inertia matrix of the base.

$H_{bm} \in R^{6 \times n}$ is the coupling inertia matrix.

$c_b \in R^6$ is the velocity-dependent term for the base.

$c_m \in R^n$ is the velocity-dependent term for the arms.

$F_b \in R^6$ is the force and torque vector on the base mass center.

$\tau_m \in R^n$ is the torque on the manipulator joints.

The linear and angular velocities of the base are equal to $\dot{x}_b = [v_b^T \ \omega_b^T]^T$, the velocities of the end effector are equal to $\dot{x}_e = [v_e^T \ \omega_e^T]^T$, and the joint vector is $\Theta = [\theta_1 \ \dots \ \theta_n]$. Then, the kinematics of the space robot can be presented as

$$\begin{bmatrix} v_e \\ \omega_e \end{bmatrix} = J_b \begin{bmatrix} v_b \\ \omega_b \end{bmatrix} + J_m \dot{\Theta} \quad (2)$$

where J_b and J_m are the Jacobian matrices that depend upon the base and the manipulator arms, respectively.

If there are no external forces and torques acting on a free-floating space system, the linear and angular momenta are conserved. If to assume that both of their initial values are equal to zeros, the momentum conservation equation yields

$$H_b \begin{bmatrix} v_b \\ \omega_b \end{bmatrix} + H_{bm} \dot{\Theta} = 0 \quad (3)$$

H_b is always non-singular, so (3) can be solved for the base velocities as

$$\begin{bmatrix} v_b \\ \omega_b \end{bmatrix} = -H_b^{-1} H_{bm} \dot{\Theta} = J_{bm} \dot{\Theta} \quad (4)$$

Inserting then Eq. (4) to Eq. (2), one can get the so-called generalized Jacobian matrix (GJM) of the form $\dot{x}_e = (J_m - J_b H_b^{-1} H_{bm}) \dot{\Theta} = J^* \dot{\Theta}$. It can be used to control the manipulator end effector by the resolved motion rate in the inertial space. Notice that the relation (3) is generally non-integrable and its structure is the same as for the nonholonomic kinematic constraint that comes from the no-slip wheel condition for wheeled vehicle dynamics and control. This is the reason for which Eq. (3) is called the nonholonomic constraint equation and the space robots are sometimes considered nonholonomic control systems and control designs for them follow nonlinear control technique methods. More details toward control of the space manipulator can be found in, e.g., [4, 13, 14].

Another modeling method, using the generalized coordinates is adopted in [13, 14]. It is based upon the generalized programmed motion equations (GPME) that enable incorporation of holonomic or nonholonomic constraints to the system dynamics. The GPME yield the smallest system of equations, i.e., the constraint reaction forces are eliminated during derivation. The GPME enable adding a desired trajectory for the end effector, written as a position constraint, and get the so-called reference dynamics that serves as a motion planner for a dynamic control model, which is also developed using the GPME. For more details about the use of the GPME for space manipulator dynamics and control, see [15].

Consider, as the GPME application illustrating example, a two-arm plane model of a space robot, as presented in **Figure 1**. The robot orientation is denoted by an angle θ and joint angles by a vector $q = [q_1 \ q_2]^T$. The joint angles are not independent in the sense that they are counted from one link to another, but they do not add any position constraint equations.

A free-floating operation assumption requires the spacecraft thrusters to be turned off and the system linear and angular momentum to be zero. The condition

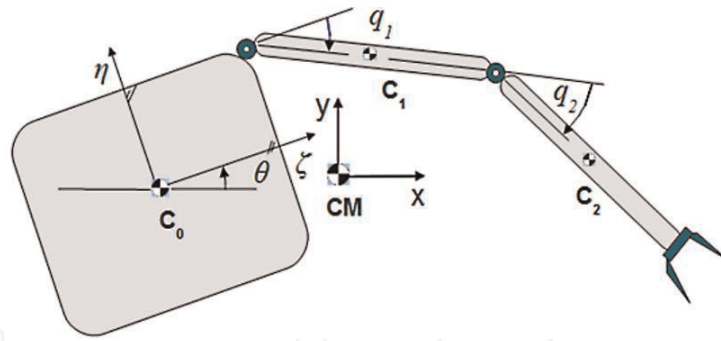


Figure 1.
 Free-floating space manipulator [13].

of zero linear momentum is a holonomic constraint that can be integrated, and it is satisfied in this example by pinning the spacecraft at its mass center C_0 . The space manipulator angular momentum is equal to.

$$K = M(\dot{x}_0 \dot{y}_0 - \dot{x}_0 \dot{y}_0) + I_0 \dot{\theta} + m_1(x_1 \dot{y}_1 - \dot{x}_1 y_1) + I_1(\dot{\theta} + \dot{q}_1) + m_2(x_2 \dot{y}_2 - \dot{x}_2 y_2) + I_2(\dot{\theta} + \dot{q}_1 + \dot{q}_2). \quad (5)$$

This equation is the constraint equation on the space robot motion, and it is nonholonomic. The second constraint equation may come from a desired trajectory for the end effector E, e.g.,

$$X_d = \begin{bmatrix} x_E(t) \\ y_E(t) \end{bmatrix} = \begin{bmatrix} 1.11 - 0.3 \cos(2\pi t/15) \\ 0.032 + 0.3 \sin(2\pi t/15) \end{bmatrix} \quad (6)$$

as it is presented in [14]. The angular velocity of the base $\dot{\theta}$ can be determined from Eq. (5) for control purposes. The GPME enable deriving the constrained dynamics for a space robot subjected to the constraint Eqs. (5) and (6), and the Lagrange multipliers are eliminated at the equation derivation level. This constrained dynamics is referred to as the reference dynamics, and it serves as motion planner for a controller design.

Based upon the GPME, the robot dynamics described in the joint space is of the form

$$M(q, \theta) \ddot{q} + C(q, \theta, \dot{q}) = \tau \quad (7)$$

$$\dot{\theta} = D(q, \theta) \dot{q}$$

where the second equation is the transformed angular momentum conservation Eq. (5). Notice, that the constraint reaction forces, i.e., Lagrange multipliers in the classical approach, are eliminated from Eq. (7). Eq. (7), being a dynamic control model, can be applied to design a tracking controller for the space robot, e.g., to track desired motion by the end effector Eq. (6).

Attitude dynamics of a space robot is of a special interest due to its reorientation maneuvers inherent to most of its operations. Attitude can be described in various ways. The most popular representations are rotation matrices, Euler angles, and quaternions. The quaternion originates in Euler's rotation theorem, and it describes attitude as a single rotation about a vector in 3D space.

A unit quaternion consists of four elements constrained by its norm. Thus, a quaternion has 3 degrees of freedom, and it is not the minimum representation, as, for instance, in the case of Euler angles. Quaternions come in different conventions, and in this chapter the Hamilton convention is adopted (see [16] for details). Specifically, the quaternion is represented as

$$\mathbf{q} = \begin{bmatrix} q_0 \\ \mathbf{q}_v \end{bmatrix} = [q_0 \quad q_1 \quad q_2 \quad q_3]^T \quad (8)$$

The scalar part of the quaternion is a function of rotation magnitude only. The latter elements describe direction of the rotation axis, preserving the unit norm. Describing the rotation magnitude as Θ and the vector of the rotation axis as \bar{e} , the formula for the quaternion yields

$$\mathbf{q} = \begin{bmatrix} \cos\left(\frac{\theta}{2}\right) \\ \bar{e} \sin\left(\frac{\theta}{2}\right) \end{bmatrix} \quad (9)$$

Quaternions can be easily related to the more intuitive space robot angular velocity vector $\boldsymbol{\omega}$ expressed in its body frame (x,y,z) . These relations yield

$$\dot{\mathbf{q}} = \frac{1}{2} \mathbf{q} \otimes \begin{bmatrix} 0 \\ \boldsymbol{\omega} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \mathbf{0} & -\omega_x & -\omega_y & -\omega_z \\ \omega_x & \mathbf{0} & \omega_z & -\omega_y \\ \omega_y & -\omega_z & \mathbf{0} & \omega_x \\ \omega_z & \omega_y & -\omega_x & \mathbf{0} \end{bmatrix} \mathbf{q} \quad (10)$$

Eq. (10) applies the quaternion product described with the operator \otimes , and zero is appended to the velocity vector to form the so-called pure quaternion making the multiplication possible. However, a matrix multiplication form is also applicable.

In comparison to other representations, quaternions possess a couple of advantages:

- They are intuitive, unlike Euler angles where the sequential nature is more difficult to comprehend than a single rotation.
- The representation is not susceptible to gimbal lock as for the Euler angles.
- Any rotation can be presented as a continuous trajectory of quaternions.
- Quaternion algebra does not use trigonometric functions, just basic operations on numbers, and thus is usually more computationally efficient than Euler angles.
- Any rotation represented by quaternions can be linearly interpolated by efficient methods [16].
- Four elements construct a more compact representation than the nine-element rotation matrix.

There are also some disadvantages of adopting quaternion description, e.g.,

- The attitude is not represented uniquely; in particular \mathbf{q} and $-\mathbf{q}$ describe the same rotation.
- Algebra behind quaternions requires some preprocessing work to start with this representation.

been researched. The first attempt was to develop the Lagrange equations using quaternions and then derive space robot equations of motion. This approach, however, occurred to be inefficient for an increasing number of manipulator links. Due to poor scalability, authors decided to model the space robot as a set of links, which for modeling purposes, are considered separate bodies subjected to position constraints. In this formulation each link has 6 degrees of freedom, and its state is described by the following 13-element state vector (time dependency is omitted for clarity):

$$\mathbf{x}_i = [\mathbf{r}_i^T \mathbf{v}_i^T \mathbf{q}_i^T \boldsymbol{\omega}_i^T]^T \quad (12)$$

where:

\mathbf{r}_i are global, translational coordinates of the center of mass of a body i .

$\mathbf{v}_i = \dot{\mathbf{r}}_i$ is global translational velocity.

$\mathbf{q}_i = \mathbf{q}_{iB}^I$ is a quaternion rotating from the body to the inertial frame according to the formula:

$$\mathbf{p}^I = \mathbf{q}_B^I \otimes \mathbf{p}^B \otimes \mathbf{q}_B^{I*} \quad (13)$$

$\boldsymbol{\omega}_i$ is the angular velocity determined in the body frame.

The Lagrange multipliers method is adopted due to the position constraints in the system. The equations governing DEM composed of b rigid bodies are of the following form:

$$\begin{bmatrix} \mathbf{M} & \mathbf{B}^T \\ \mathbf{B} & \mathbf{O} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{x}} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \boldsymbol{\mu} \end{bmatrix} \quad (14)$$

In Eq. (14) $\mathbf{M} = \text{diag}[m_1 \quad \mathbf{I}_1 \quad \dots \quad m_b \quad \mathbf{I}_b]$ is a mass matrix, and \mathbf{B} is a matrix satisfying the equation

$$\dot{\boldsymbol{\phi}} = \mathbf{B}\mathbf{w} + \boldsymbol{\phi}_t = \mathbf{O}, \quad (15)$$

where:

$\boldsymbol{\phi}$ represents the position constraint equation.

$$\mathbf{w} = [\mathbf{v}_i^T \boldsymbol{\omega}_i^T]^T.$$

$\boldsymbol{\lambda}$ is a vector of Lagrange multipliers.

\mathbf{f} is a vector of forces and torques.

$\boldsymbol{\mu}$ satisfies the equation.

$$\ddot{\boldsymbol{\phi}} = \mathbf{B}\ddot{\mathbf{w}} - \boldsymbol{\mu} = \mathbf{O} \quad (16)$$

Further details related to the presented derivation can be found in [17].

The links of the space manipulator are connected by a pair of constraints that simulate a revolute joint. A position constraint of the form

$$\boldsymbol{\phi}_1 = \mathbf{r}_i + \mathbf{s}_{1i}^B - \mathbf{r}_j - \mathbf{s}_{1j}^B = \mathbf{O} \quad (17)$$

is needed to connect extremities of links i and j . \mathbf{s}_1^B denotes a vector from the center of mass to the joint location, and it is expressed in the local coordinates.

Another equation is required to constrain the rotational motion to a single axis. This equation has the form

$$\phi_2 = s_{2i}^B \times s_{2j}^B = O \tag{18}$$

In Eq. (18) the vector s_{2k}^B governs the selected joint rotation vectors in their body frames. Eq. (18) preserves that those axes are parallel.

Constrained mechanical system models, when solved numerically, tend to exhibit unstable solutions, and instabilities increase with simulation time. To stabilize the solutions, a numerical stabilization method is welcome. One of them is the Baumgarte numerical stabilization method [18]. It requires that the differentiated constraint Eq. (16) is augmented as follows:

$$\ddot{\phi} + 2\alpha\dot{\phi} + \beta^2\phi = O \tag{19}$$

In Eq. (19) α and β are gains which have to be selected. The constraint Eq. (19) is numerically stable securing the constraint equation satisfaction during the system model motion. With the Baumgarte method introduced, Eq. (14) turns into

$$\begin{bmatrix} M & B^T \\ B & O \end{bmatrix} \begin{bmatrix} \dot{x} \\ \lambda \end{bmatrix} = \begin{bmatrix} f \\ \mu - 2\alpha\dot{\phi} - \beta^2\phi \end{bmatrix} \tag{20}$$

Eq. (20) is the final form of the space robot motion equations. They are to be solved in the numerical simulation study.

4. Example: spacecraft dynamic simulation studies

An experimental simulation study has been performed to verify, evaluate, and compare the correctness and possible applicability of the modified, quaternion-based DEM method. An example of a planar manipulator model using the original DEM method is presented in [9]. However, it is meaningless to verify a quaternion-based dynamic model on a plane. Thus, a spatial model is prepared for the simulation experiment. A space two-link manipulator model has been selected. Firstly, the properties of the space manipulator must be mapped to DEM. These are presented in **Tables 1** and **2**.

The model of a space manipulator (SM) serving as a reference one has been developed in MATLAB Simscape. An open-loop torque applied to joints with the initial angular velocity vector in the direction perpendicular to joints' axes is supposed to reveal any potential inconsistency. The open-loop torque applied to the first joint J_2 is of the form of a sinusoidal signal of an amplitude of 0.5 Nm and period of 1 s, while the torque applied to the second joint J_3 is sinusoidal of an amplitude of 0.2 Nm and period of 1 s. The base of the space manipulator is not actuated and in the case of DEM joint J_1 remains passive. In the initial configuration,

Link number	$L_i[m]$	$R_i[m]$	$m_i[kg]$	$I_i[kg\ m^2]$
1	—	0.75	4	$1 * I_3$
2	0.75	0.75	1	$0.2 * I_3$
3	0.75	0.75	1	$0.2 * I_3$

Table 1.
Space manipulator properties.

the manipulator arms are straightened, i.e., all angles as in **Figure 1** are equal to zeros. The angular velocity of 0.1 rad/s is applied around the initial links' axes. To verify the correctness of the quaternion-based DEM modified method, joint angles and the end effector position in the inertial reference frame are compared. The results are presented in **Figures 3** and **4**.

In **Figure 3(a)** the joint angles are compared. The obtained values of the angles overlap for the space manipulator (SM) and quaternion-based DEM. Both, space

Link number	$W_i[m]$	$l_{ci}[m]$	$m_i[kg]$	$I_i[kg\ m^2]$
1	0.5	0	4	$1 * I_3$
2	1.125	0.5	1.8	$0.2 * I_3$
3	1.375	0.625	1.2	$0.2 * I_3$

Table 2.
DEM properties.

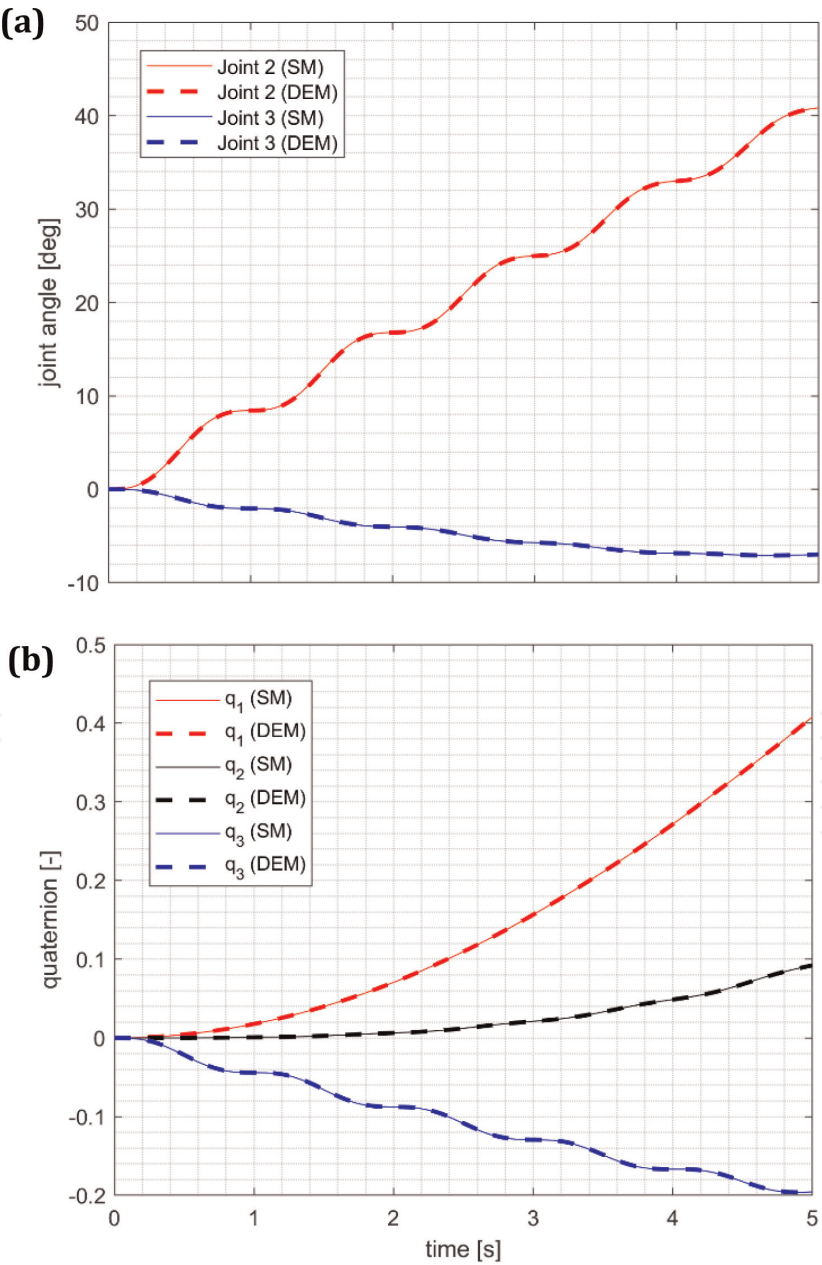


Figure 3.
(a) Comparison of joint angles for the space manipulator model and DEM quaternion-based model and
(b) comparison of the quaternions of the space manipulator (SM) base and the equivalent first link of DEM.

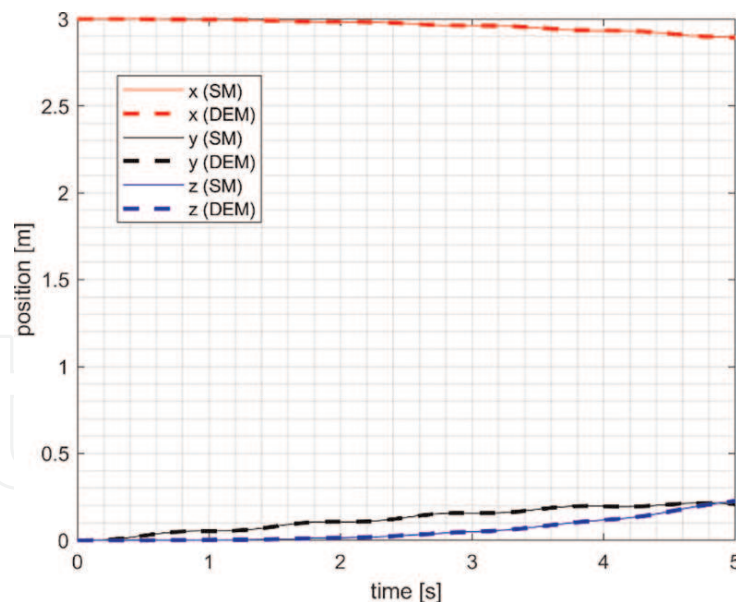


Figure 4.
 Comparison of end effector positions for SM and DEM models.

manipulator's base and the corresponding first link of the DEM model have the same attitude through the entire simulation. Vector parts of quaternions representing their attitude are shown in **Figure 3(b)**. The positions in the inertial frame for both end effectors are presented in **Figure 4**. The quaternion-based DEM end effector achieves the same positions as the reference space manipulator one in the simulation run.

The numerical experiment demonstrated correctness of application of the modified quaternion-based dynamic DEM method. The base quaternion, joint angles, and the end effector positions are consistent between the reference (SM) and the developed (DEM) models. It may be concluded that the quaternion-based modified DEM is the good modeling tool, it is numerically efficient, and it is promising to be applied to study guidance algorithms, control systems, and design experimental setups for free-floating space manipulators.

5. Conclusions and future research prospects

The chapter presents a dynamics modeling method dedicated to free-floating spacecraft, specifically manipulators, based on a modified method of a dynamically equivalent manipulator. DEM enables dynamic modeling of space manipulators, e.g., free-floating maneuvers, via their suitable substitution by ground-fixed manipulator models. As a result, the space manipulator dynamics is equivalent to the ground one. This provides attractive modeling and control design tools, since it enables conducting tests and experiments for space manipulators in earth laboratories. The basic motivation for the DEM modification is to make dynamic and kinematic models suitable for description of arbitrary space manipulators maneuvers and their missions like debris removal, servicing, space mining, and on-orbit docking and assemblies. It may also support space manipulators attitude controller designs. The chapter contribution is the modification of DEM to enable space manipulator kinematic and dynamic representation in quaternions. The modified DEM method delivers a tool for conducting reliable simulation studies and tests for various maneuvers and mission scenarios for SM, and it offers a promising control design tool. The theoretical development of DEM method in quaternions is

illustrated by a simulation study of a two-link space manipulator model. The space manipulator attitude dynamics has been compared to the results reported in the literature. The satisfactory results enhance the next studies to apply the quaternion-based DEM to design guidance algorithms and control systems for space manipulator missions.

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