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Guidance and control system design for a free-flying space manipulator based on a dynamically equivalent manipulator

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Abstract: The paper presents a new approach to guidance and control systems design for a free-flying space manipulator. It takes advantage of a dynamically equivalent manipulator (DEM) model, which is a fixed manipulator representation of a free-floating or a free-flying one and it can be successfully used to handle the guidance problem that is very complex for a non-fixed space manipulator. Also, the free-flying manipulator model includes constraints resulting from linear and angular momentum conservation and its attitude is a function of an actual state and of a path. Since the position of the end effector, joints and base angles are the same in the DEM and in the space manipulator, the fixed representation of a space robot allows for simpler joint and work space transformations and results in simpler path planning and guidance systems design. The novelty is also in the attitude presented in the quaternion description that prevents singularities during computation. The presented design of the guidance and control system allows for effective space manipulators mission design and execution.

Keywords: free-flying manipulator, dynamically equivalent manipulator, quaternion dynamics, control, guidance

1. Introduction

An effective guidance and control design of a space manipulator is challenging and its control can be performed in free-floating or free- flying approaches [1]. The first design allows for control of only the manipulator joints while in the latter the base of the spacecraft is also actuated. A free-floating regime is more power efficient and in case of spacecraft's base actuated with reaction wheels, there is no saturation problem. However, the free-flying approach facilitates use of guidance and control methods developed for a ground-based robotic arms. Stabilized manipulator's base attenuates influence of the arm dynamic coupling on the space robot's attitude but the impact on manipulator's base position still must be considered. Translation of the spacecraft's base could be stabilized by a reaction control system, but it implies some difficulties, e.g. the spacecraft must take additional propellant. Also, a fault of propulsion system can cause a collision. For these reasons, a free-flying control approach is chosen as a baseline for the design. The paper focuses on applying a concept of dynamically equivalent manipulator (DEM) to design an efficient guidance and control system for a free-flying space manipulator. The concept of mapping a free-floating space manipulator into equivalent fixed base manipulator is introduced in [2]. DEM preserves both kinematic and dynamic properties of a space manipulator and allows modeling using classical methods. It is also more suitable for experimental validation of guidance and control algorithms. To map a free-floating space manipulator into a fixed-base robotic one, the base is reproduced by a spherical joint. It can be passive or active responding to free-floating or free-flying space manipulator, respectively. In [3] the quaternion representation to the DEM approach is introduced. Since DEM maintains the position of manipulator's end-effector the model can be applied to facilitate the guidance and control design.

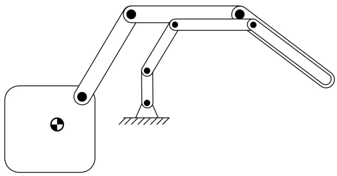

Fig. 1. The space manipulator and its corresponding DEM – end effector's position is maintained

Mapping the free-flying manipulator to a fixed one allows to efficiently apply guidance and control algorithms developed for ground-based manipulators and mitigate complex dynamic coupling between motion of the robotic arm and translation of the base.

2. Results and Discussion

The use of DEM dynamics in the design allowed for a stable and effective guidance and control system. From the DEM dynamics model of the form

$$\begin{bmatrix} \boldsymbol{M} & \boldsymbol{B}^T \\ \boldsymbol{B} & \boldsymbol{O} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{x}} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{\mu} \end{bmatrix} \tag{1}$$

where: **M** – mass matrix, **B** – matrix of position constraints, $\boldsymbol{x} = [\boldsymbol{q} \quad \dot{\boldsymbol{q}}]^T$ – state vector, **λ** – vector of Lagrange multipliers, **f -** vector of forces and torques, **μ** – term from the extended constraint equations, we can compute the base's reaction torques which can be further used as a feed forward part of the controller to better stabilize the manipulator's attitude. The overall guidance and control system structure is presented in fig. 2.

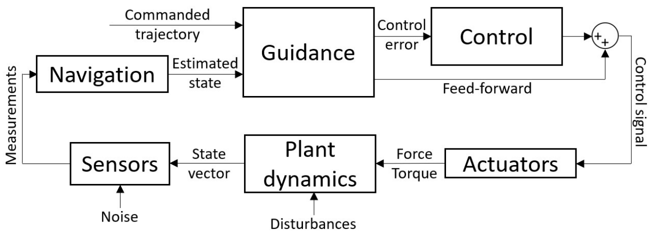

Fig. 2. The overall guidance and control system structure

3. Concluding Remarks

Applying DEM to inverse kinematics as well as to dynamics to calculate the feed-forward controller part allowed to handle efficiently guidance and control designs for free-flying manipulator.

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