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Reaction torque control of redundant space robotic systems for orbital maintenance and simulated microgravity tests

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ABSTRACT

This paper presents the theoretical formulation and the experimental validation of a novel solution for the inverse kinematics of redundant space robotic systems aimed at locally minimizing the torque transferred to the spacecraft due to the robotic arm movement. The differential kinematics is formulated at the acceleration level and an additional constraint is imposed in order to locally minimize the torque transferred to the spacecraft center of mass. This problem can be expressed as a constrained linear least squares problem and a closed-form solution is obtained. An extension of this method is presented in order to take into account the physical limits of the manipulator, by limiting the joint accelerations under acceptable values. In this case the problem can be expressed as a constrained linear least squares problem with both equality and inequality constraints. The proposed solution has been experimentally tested using a 3D free-flying robot previously tested in an ESA Parabolic Flight Campaign. In this test campaign the 3D robot has been converted in a 2D robot taking advantage of its modular structure, and it has been suspended by means of air-bearings on a granite plane. In this way it is possible to perform simulated microgravity tests without time constraints. The base of the robot is fixed on ground by means of a custom design dynamometer, which measures the torque transferred to ground to be minimized. The experimental results validated the proposed solutions and confirmed their good performance.

1. Introduction

Space robotics has an important role in current space missions. Free-flying robots, namely robotic arms fixed to a free-flying base controlled by means of thrusters or other position and attitude control devices, could be used for extra-vehicular activities (EVA), intra-vehicular activities (IVA), and space servicing missions [1–3]. In these scenarios the robot joints should perform trajectories designed to minimize the dynamic disturbances induced on the spacecraft in order to reduce the consumption of the attitude control system (ACS), which is necessary to maintain the desired attitude and avoid communication problems.

The use of a redundant manipulator allows the fulfillment of this task: the joint trajectories can be selected in order to locally minimize the spacecraft angular velocity, exploiting the momentum and angular momentum conservation laws, according to a *kinematic approach* [4–11]. On the other hand, other authors proposed a *dynamic approach*, which is also used in this paper, whose aim is to reduce the reaction forces and torques transferred to the base spacecraft by exploiting the manipulator redundancy. A local optimization approach for reaction minimization was first proposed by De Silva [12], and then presented in more detail by Quinn et al. [13], who derived a method based on a Rayleigh–Ritz

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Nomenclature

D	diameter of the circular end-effector trajectory
d	components of the reaction torque to be controlled
e_{exp}	torque error due to not modeled effects and to the uncertainty on the dynamic parameters used in the flexible joints simulator
e_{flex}	torque error due to joint flexibility
e_{tot}	total torque error between the rigid joints simulator torque and the experimental torque
$\boldsymbol{I}$	identity matrix
$\boldsymbol{I_s}$	spacecraft inertia tensor
$\boldsymbol{J}$	manipulator Jacobian matrix
k	components of the end-effector pose to be tracked
$\boldsymbol{M}_T$, $\boldsymbol{n}_T$	mass matrix and centrifugal and Coriolis term in the dynamics of the spacecraft reaction torque
n	degrees of freedom of the manipulator
$\boldsymbol{q}$	joint variables of the manipulator
$\overline{\ddot{\boldsymbol{q}}}_l, \overline{\ddot{\boldsymbol{q}}}_u$	lower and upper joint acceleration limits
r	degree of redundancy of the manipulator
$\boldsymbol{T}_{ACS}$	torque about the spacecraft center of mass generated by the attitude control system
$\boldsymbol{T}_B$	reaction torque about the spacecraft center of mass
T_{exp}	experimental torque
T_{flex}	flexible joints simulator torque
T_{∞}	rigid joints simulator torque
$\boldsymbol{x}$	actual end-effector pose
$\boldsymbol{x}_d$	desired end-effector pose
$\boldsymbol{Z}$	projection matrix on the null space of the manipulator Jacobian
ζ_0	arbitrary vector in the joint acceleration space
λ	weighting factor
$\boldsymbol{\omega}_s$	spacecraft angular velocity

technique using a partitioning scheme of the Jacobian matrix and polynomial shape functions in order to determine the joint trajectories. Nenchev and Yoshida [14,15] introduced the reaction null-space (RNS) concept in order to study the existence of zero reaction paths in the manipulator workspace. Krenn and Shäfer et al. [16,17] proposed a Lagrangian constrained optimization method for redundancy resolution, in which second and fourth order polynomials are used in order to approximate the motion of the base. Recently, Cocuzza and Pretto [18] proposed an optimization method based on a weighted pseudoinversion of the Jacobian matrix.

In this paper inverse kinematics (IK) redundancy resolution schemes based on a *constrained least squares* approach are introduced, aimed at locally minimizing the reaction torque disturbance transferred to the spacecraft by redundant manipulators. The proposed solutions have been implemented in a Matlab simulator in order to evaluate their performance for a three degrees of freedom (DOF) planar manipulator, and then experimentally tested for validation.

The main contributions of the present work are: (1) the introduction of a constrained least squares IK solution for the local minimization of the torque transferred to the spacecraft, (2) the extension of this solution by introducing joint acceleration constraints in order to take into account the physical limits of the manipulator joints, and (3) the experimental validation of the presented solutions, with an insight on the effect of joint flexibility on their performance.

The 3D free-flying robot used in this study was previously tested in the microgravity environment of ESA Parabolic Flights [19–22], in which the IK solution proposed by Caccavale and Siciliano [6] was implemented. The 3D robot has then been converted in a 2D robot thanks to its modularity in order to perform planar tests [20,23], in which the microgravity environment can be simulated without time constraints (see [24] for other possible test-beds). Air-bearings are used to sustain the links weight, and a dynamometer is used to measure the reaction torque.

The paper is organized as follows: Section 2 presents the motivation and the advantages of the proposed solutions, Section 3 describes the formulation of the problem and reports state of the art concepts adapted for the purposes of this work, Section 4 introduces the original IK solutions, Section 5 describes the experimental set-up, Section 6 presents the simulation and experimental tests, and Section 7 concludes the paper.

2. Motivation and advantages of the proposed solutions

In the operating scenario of a space manipulator during a target approach manoeuvre, the *free-floating mode*, i.e. manipulation with the ACS and the propulsion system turned off, should be used in the final target approach phase both because it leads to more accurate end-effector (EE) positioning [1] and for safety reasons. On the other hand, in the target coarse approach manoeuvre, a low disturbance motion should be used together with the ACS turned on in order to reduce the time for the manoeuvre and for the recovery of the desired attitude with respect to a conventional spline manipulation [1]. In this way the risk of approaching the manipulator workspace boundary is also reduced. Another possibility is to use the *coordinated control* of the manipulator and base attitude by means of angular momentum feed-forward compensation [25,26].

In this context two possible operating scenarios in which the use of a *dynamic approach* is more advantageous than a classical *kinematic approach* are foreseen:

(1) in any manipulation manoeuvre carried out with the ACS turned on, for example in the target coarse approach phase [1], if a *dynamic approach* is used the dynamic disturbances to be compensated with the ACS are directly minimized, leading to a reduced ACS energy consumption;
(2) when multiple manipulators are mounted on the same base spacecraft, their dynamic disturbances can