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A parametric analysis of a controlled deployable space manipulator for capturing a non-cooperative flexible satellite

A. Stolfi[a], P. Gasbarri[a,*], M. Sabatini[b]

[a] Department of Mechanical and Aerospace Engineering, Sapienza Università di Roma, Rome, Italy
[b] Department of Astronautics, Electrical and Energetics Engineering, Sapienza Università di Roma, Rome, Italy

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ABSTRACT

In the near future robotic systems will be playing an increasingly important role in space applications such as repairing, refueling, re-orbiting spacecraft and cleaning up the increasing amount of space debris. Space Manipulator Systems (SMSs) are robotic systems made of a bus (which has its own actuators such as thrusters and reaction wheels) equipped with one or more deployable arms. The present paper focuses on the issue of maintaining a stable first contact between the arms terminal parts (i.e. the end-effectors) and a non-cooperative target satellite, before the actual grasp is performed. The selected approach is a modified version of the Impedance Control algorithm in which the end-effector is controlled in order to make it behave like a mass-spring-damper system regardless of the reaction motion of the base, so to absorb the impact energy. The effects of non-modeled dynamics in control determination such as the structural flexibility of the manipulator and the target satellite are considered as well, and their impact on control effectiveness is analyzed. The performance of the proposed control architecture and a parametric analysis are studied by means of a co-simulation involving the MSC Adams multibody code (for describing the dynamics of the space robot and target) together with Simulink (for the determination of the control actions). The results show that the first contact phase of the grasping operation of a large satellite requires careful tuning of the control gains and a proper selection of the end-effector dimensions; otherwise, the large geometric and inertia characteristics of the target could lead to a failure with serious consequences. Both successful and underperforming cases are presented and commented in the paper.

1. Introduction

The increasing number of launched satellites per year calls for solutions to keep free operational space for telecommunication systems in geo-synchronized orbit, as well as to avoid the endangering of space systems in LEO (Low-Earth Orbit) [1]. One example for such dangerous situations is the uncontrolled and accidental de-orbiting of a huge satellite like ENVISAT. Many challenges will have to be faced in future on-orbit servicing missions such as the capture of un-functional satellites, spent spacecraft or last stages of rockets [2,3] by means, for example, of Space Manipulator Systems (SMSs). SMSs are robotic systems made of a bus (which has its own actuators such as thrusters and reaction wheels) equipped with one or more deployable arms. Some of the above cited challenges are related to accurate position and attitude control in autonomous tracking and rendezvous operations between the chaser and target satellites. This is mainly due to the uncertain kinematic state and inertia and structural characteristics of the non-cooperative target. Another issue is related to the control during the contact phase between the robotic arms mounted on the chaser and the target. In fact, the relative motion between two objects must be carefully controlled to avoid unexpected collisions and/or damages on the robotic systems during the contact phase. One interesting approach usually employed to control contact phenomena is the so-called Impedance Control [4] which imposes that the mechanical impedance of the manipulator end-effector is regulated. It is worth noting that Impedance Control applied to fixed-base robotic arms has experienced a remarkable development in terrestrial applications whereas its possible use on free-flying aero/space systems still requires extensive analyses.

In a recent work [5] an impedance control for aerial robotic manipulators has been proposed and its effectiveness analyzed where the control is composed by three modules: an impedance filter, an inverse kinematic module and a motion controller. The technological developments in light-weight robotic arms allowed the adoption of multi-degree of freedom (DoF) manipulators mounted on remote-piloted air platforms as shown in Ref. [6] where a free-flying platform with a three-arm manipulator, with two DoF for each arm, was proposed. Such

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[*] Corresponding author.
E-mail addresses: angelo.stolfi@uniroma1.it (A. Stolfi), paolo.gasbarri@uniroma1.it (P. Gasbarri), marco.sabatini@uniroma1.it (M. Sabatini).

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aerial systems demonstrated they can be used also for *hard* operations in external environment as shown in Ref. [7] where the authors presented experiments on a quadrotor equipped with two 2-DoF arms turning a valve. Of course, such operations require sophisticated control laws able to manage both external contact forces and external disturbances as shown in Refs. [8] and [9] where different controllers based on the impedance control scheme were applied to unmanned air vehicles hosting robotic arms.

Indeed, the effectiveness of the use of aerial manipulators was also proven via experimental campaigns performed on a multirotor vehicle with a 6-DoF manipulator, available at the Centro Avanzado de Tecnologías Aeroespaciales in Sevilla. Such experimental setup has been designed and developed within the EU-funded ARCAS (Aerial Robotics Cooperative Assembly System) project [10], aimed at developing a cooperative free-flying robotic system for assembly and structure construction.

Analogously to aerial systems, the design of manipulators for space applications has to consider their free-floating nature. Consequently, in a SMS the motion of its robotic arms affects the attitude and position of the base platform and vice versa. This characteristic is denoted as "dynamic coupling" between the manipulator arms and the base platform and makes the dynamics modeling and motion planning of a space robot much more complicated than those of fixed-base manipulators [11].

The missions involving the use of SMSs are usually divided into different phases: a) Orbital approach; b) Rendezvous; c) Robotic arms deployment; d) Pre-grasping; e) Grasping and operations. In this work we will focus on phase d) having the task of maintaining a stable contact between the manipulator terminal parts (i.e. the end-effectors) and a target spacecraft after their first contact by using the Impedance Control approach.

In the Impedance Control (IC) approach the end-effector is controlled to make it behave like a mass-spring-damper system regardless of the reaction motion of the base so to absorb the impact energy [12]. It is well known that traditional IC is a simple but effective method that can also be employed for contact force tracking. Using this method, the location of the environment relative to the robot and the stiffness of the environment must be known a priori and usually the desired force is constant as shown in Ref. [13]. An interesting control applied to a space free flying robotic system is the so called Multiple Impedance Control (MIC). MIC is a model-based algorithm that enforces a designated impedance on several cooperating arms, the manipulated object and the moving base. Indeed, the MIC law was proposed to control both path tracking and inner forces tuning to manipulate an object with two cooperative arms [14]. Nevertheless, MIC requires a detailed knowledge of the inertial and mechanical properties of all the elements that constitute the robotic system and the object to be manipulated.

Unfortunately, when dealing with space applications where a chaser satellite must operate on an uncooperative target, the presence of uncertainties on the dynamics of the space robot and target spacecraft could jeopardize the mission. Recently, a study on the pre-contact phase between the end-effector and a tumbling object has been performed by taking uncertainties into account [15]. The goal was to develop a control strategy capable of minimizing the impact on the attitude of the servicing satellite. This was achieved by synchronizing the motion of the end-effector with that of the target satellite such that the physical interception from the capturing operation will have zero or minimal attitude impact on the servicing satellite. Generally speaking, the presence of a residual relative motion between the two spacecrafts after rendezvous requires a sophisticated control in order to avoid undesired detachment of the target during capture. In Ref. [16] a Hybrid Impedance/Position Control was applied to a one-arm manipulator for the detumbling of a non-cooperative satellite. In the above cited works both the spacecraft are modeled as rigid systems. Indeed, flexible appendages such as solar arrays and antennas are mounted on the spacecraft and their dynamic behavior could affect the performance of the robotic manipulator control system [11]. On account of that, contact dynamics between a target and a robotic arm needs deep investigation when the control law must be defined. Since the dynamics is affected by uncertainties, the controller must be robust enough to overcome this problem.

In a previous study [17] the authors investigated the application of the IC approach to a two-arm space manipulator used to capture a non-cooperative target. Both chaser and target satellites were considered rigid. The combination of IC together with Proportional-Derivative (PD) Control (referred to as Impedance + PD Control) was developed. This work is intended as a follow-up. The un-modeled effects of the flexibility have been addressed. Indeed, structural flexibility features have been introduced on both the SMS and the target satellite. Furthermore, a reduction to a one-arm configuration is here considered to investigate the feasibility of reducing the manipulator overall design complexity while achieving the same mission objectives. In fact, de-tumbling a large uncooperative satellite with only one arm could lead to a more difficult task with respect to the dual-arm case since the angular motion of the target could potentially not be controlled with one single point of contact. At this scope, the end-effector configuration has been modified to compensate for the lack of one of the two arms by adding a rotational degree of freedom to the end-effector itself, analyzing the influence of its geometrical properties on the control effectiveness.

The performance of the proposed control architecture will be evaluated by means of a co-simulation involving the MSC Adams multibody code - here used to describe the fully non-linear and flexible dynamics of both the SMS and the target satellite - together with Matlab/Simulink for the determination of the control actions, which will be based on a multibody model of the dynamic system.

The paper is organized as follows: in Section 2 the essential kinematics and dynamics equations of the space manipulator are recalled. In Section 3 an insight of the Impedance + PD Control concept is presented for a single-arm space manipulator. In Section 4 the results obtained from numerical simulations by considering the elasticity of the space manipulator and the target satellite are commented and compared, also by taking different end-effector dimensions into account. To conclude, in Section 5 the final remarks will be presented.

2. Space manipulator mathematical modeling

The dynamics equations of a space manipulator, constituted by a base platform and a chain of links connected with each other through revolute joints, can be derived through classical multibody formulations the details of which are not reported here for the sake of brevity; they can be found for instance in Refs. [18,19]. In this work the procedure to obtain the governing equations for the SMS is based on Kane's formulation [20,21]. Furthermore, the governing equations used to define the control actions calculated in Simulink that will be applied to the SMS (Impedance + PD Control) are derived under the hypothesis that the solar panels attached to the chaser (i.e. the SMS) are rigid. This hypothesis will be removed in the MSC Adams environment where the dynamics of the "real" spacecraft systems will be described through a fully flexible multibody approach. Analytical details of the present formulation are not reported here for the sake of brevity; they can be found in Ref. [17]. It suffices here to say that:

1) It has been assumed an inertial reference frame which has its origin at the position of the SMS base center of mass at $t = 0$;
2) Starting from the Newtonian state vector $\boldsymbol{X}$ and by defining the minimum set of the Lagrangian variables $\boldsymbol{Q}$ (here defined as the vector containing the base position and attitude variables, the arm joint angles, the distance of the center of the end-effector contact plate from the endpoint of the arm last link and the contact plate joint angle (see Fig. 2), it is possible to define the Jacobian matrix $\mathbf{J}$ which relates the time derivatives of the former to those of the latter: $\dot{\boldsymbol{X}} = \mathbf{J}\dot{\boldsymbol{Q}}$;