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Multiple-arm space free-flying robots for manipulating objects with force tracking restrictions

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Abstract

Multiple Impedance Control (MIC) is an algorithm that enforces designated impedance at various levels, i.e. on the manipulated object, all cooperating manipulators, and the moving platform of a robotic system. In this paper, a force tracking strategy inspired by a human control system is added to the MIC algorithm and the general formulation is revised to fulfill a desired force tracking strategy for object manipulation tasks. The stability analysis of the MIC algorithm based on the Liapunov Direct Method, besides error analysis, shows that a good tracking of cooperative manipulators and the manipulated object is guaranteed. Next, using MAPLE and MATLAB tools, a system of three manipulators mounted on a space free-flying robot is simulated. The task is moving an object based on given trajectories which come across an obstacle, to examine the performance of the developed control law. The results show that, even in the presence of both external disturbances and an impact due to collision with the obstacle, the response of the MIC algorithm is smooth. Moreover, based on the embedded force tracking strategy, the contact force is confined to follow a desired trajectory. Also, it is shown that decreasing the values of the controller mass matrix elements results in reducing both the object position and force tracking error.

Keywords: Mobile robots; Impedance control; Robotic manipulators; Modeling; Simulation

1. Introduction

The deployment of space structures and satellite launches is widely increasing, and extending the life of such systems will require various inspections, assembly, repair and maintenance capabilities in space. So far, astronauts using a Shuttle-Arm are meeting these requirements. However, the cost of human life support facilities, the limited time available for the maneuver, and the high risks involved due to different hazards, are some serious restrictions. Therefore, it is expected that robotic devices will play a more important role in future missions [2,6,19]. To increase the mobility of in-orbit robotic systems, Space Free-Flying Robots (SFFRs) in which manipulators are mounted on a thruster-equipped spacecraft, have been proposed, Fig. 1. Unlike fixed-based robots, the base body of an SFFR is allowed to respond freely to dynamic reaction forces due to the arms motion. Hence in order to control such a system during a chase and capture maneuver, or an object manipulation task, it is essential to consider the dynamic coupling between the arms and the base, while different control strategies may be adapted [21,22,25,29]. Also it should be noted that the joint forces/torques are limited due to actuator weight constraints in space [24].

Hybrid position/force control admits interaction with the environment, and has been the basic strategy of several proposed dynamic implementations [8,23]. However, due to the fact that separate force and position subspaces must be maintained, and control mode switching must be made at many points during most tasks, hybrid control does not provide an attractive interface. Unexpected situations make these switching decisions even more difficult, i.e. the set of normal constraints may not be easily recognized. Tackling the shortcomings of the hybrid position/force control, a new approach has been proposed in [30]. Dealing with a multi-arm cooperative system, a feedforward procedure for determining the nominal motion, whereby the system's desired motion belongs to a set of nominal motions, has been proposed

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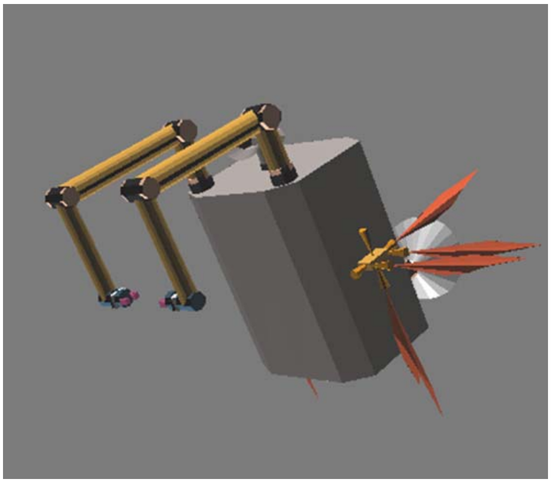

Fig. 1. A simulated SFFR with multiple manipulators.

in [31]. The procedure originates from the solution of the elastic structure cooperative motion taking into account all specific properties of the cooperative manipulation.

For a single manipulator in dynamic interaction with its environment, *Impedance Control* has been proposed, which provides compliant behavior of the manipulator [9]. An impedance controller enforces a relationship between external force(s)/torque(s) acting on the environment, and the position, velocity and acceleration error of the end-effector. The implementation of a combined impedance and force control has been proposed to exert a desired force on the environment, and at the same time, generate a desired relationship between this force and the relative location of the point of interaction (contact) with respect to the commanded manipulator location [7]. Adaptive schemes have been presented to make impedance control capable of tracking a desired contact force, which has been described as the main shortcoming of impedance control in an unknown environment [10,27]. Optimizing the regulation of impedance control from the viewpoint of both the transient and steady state responses, relying on the concept of impedance matching to choose optimal parameters, has been also proposed [1]. A Cartesian impedance controller has been presented to overcome the main problems encountered in fine manipulation, i.e. effects of the friction (and unmodeled dynamics) on robot performances and occurrence of singularity conditions [3]. Experimental and simulation investigations into the performance of impedance control implemented on elastic joints have shown the benefits of using this control strategy in compensating any undesirable effects due to system flexibilities [20].

The *Object Impedance Control (OIC)*, an extension of impedance control, has been developed for robotic arms manipulating a common object [26]. The OIC enforces designated impedance not of an individual manipulator endpoint, but of the manipulated object itself. A combination of feedforward and feedback controls is employed to make the object behave like a reference impedance. It has been realized that applying the OIC to the manipulation of a flexible object may lead to instability [11]. Similar strategies have been employed for contact tasks involving multiple manipulators [4,5]. The *Multiple Impedance Control (MIC)* has been developed for several cooperating manipulators [13,15]; it enforces a reference impedance on all cooperative manipulator end-points, as well as the manipulated object. This means that both the manipulator end-effectors and the object are controlled to behave like a designated impedance in reaction to any disturbing external force on the object. Hence, an accordant motion of all participating manipulators and the payload is achieved. Besides, an object's inertia effects are compensated in the impedance law, and at the same time the end-effector(s) tracking errors are controlled. The new MIC algorithm can also be applied to mobile robotic systems, e.g. SFFR, in which manipulators are mounted on a free-flying base [13]. The formulation is adapted to consider the dynamic coupling between the arms and the base while the manipulated object may also include an internal source of angular momentum.

In this paper, after a brief review on the MIC algorithm, a vigorous stability analysis, based on the Liapunov Direct Method is presented which shows that under the MIC law all participating manipulators, the free-flyer base, and the manipulated object exhibit the same designated impedance behavior, as implied by the name "multiple". The MIC is extended then to fulfill a desired force tracking task after impact, which adds to the merits of the original algorithm. Finally, a system of three manipulators mounted on a space free-flyer is simulated, in which a Remote Centre Compliance is attached to the second end-effector. The results show that, even in the presence of both external disturbances and an impact due to collision with an obstacle, the response of the MIC algorithm is smooth. Also, based on the new embedded force tracking strategy, the contact force follows a desired trajectory to fulfill force restrictions.

2. The MIC law for space free-flyers

In this section, a brief introduction to the MIC algorithm is presented. To this end, first the system and object dynamics will be reviewed.

2.1. System dynamics modeling

Assuming that the system consists of rigid elements and applying the general Lagrangian formulation, the equations of motion for a space free-flyer with multiple manipulators, shown in Fig. 1, can be obtained as [14,18]

$$\mathbf{H}(\boldsymbol{\delta}_o, \boldsymbol{\theta})\ddot{\mathbf{q}} + \mathbf{C}(\boldsymbol{\delta}_o, \dot{\boldsymbol{\delta}}_o, \boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) = \mathbf{Q}(\boldsymbol{\delta}_o, \boldsymbol{\theta}) \quad (1)$$

where the vector of generalized coordinates can be chosen as

$$\mathbf{q} = (\mathbf{R}_{C_0}^{\mathrm{T}}, \boldsymbol{\delta}_o^{\mathrm{T}}, \boldsymbol{\theta}^{\mathrm{T}})^{\mathrm{T}} \quad (2)$$

where $\mathbf{R}_{C_0}$ describes the inertial position of the spacecraft center of mass (CM), $\boldsymbol{\delta}_o$ is a set of Euler angles describing the orientation of the spacecraft, and

$$\boldsymbol{\theta} = (\boldsymbol{\theta}^{(1)^{\mathrm{T}}}, \ldots, \boldsymbol{\theta}^{(n)^{\mathrm{T}}})^{\mathrm{T}} \quad (3)$$