Trajectory Tracking and Control of Multiple Robot Arms on a Free-Floating Spacecraft for Debris Removal

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***Abstract*—In this work, we propose the idea of using dedicated small spacecrafts carrying multiple robot arms for space debris removal. Future space missions are expected to have computers with high computational capabilities. Hence, a model predictive control architecture is used to generate the control commands. The small spacecraft in consideration carries two identical 3-DoF robot arms attached diagonally opposite to each other. Thus the workspace covered by the robot arm increases. We show trajectory tracking simulation results of the proposed free-floating spacecraft to demonstrate the concept.**

***Index Terms*—Trajectory tracking, Model predictive control, Spacecraft manipulator, Debris removal**

I. Introduction

NASA estimates that there are around half a million pieces of space junk currently floating around in the Lower Earth Orbit (LEO) [7]. These debris not only possess a huge threat to the existing functional satellites but also for any future missions. Quantitatively, on an average calculated during 2004–12, 72 objects were placed into LEO per year and this rose to 125 post 2012. It is estimated that the space environment can be stabilised when on the order of 5–10 objects are removed from LEO per year.

Space environment poses some unique challenges such as latency in communication, extreme safety requirements and reduced processing powers due to which the level of autonomy in decision making is far less than its counterparts on earth. To enable fully autonomous decision making, future space missions are expected to operate under autonomy level E4 according to the European Co-operation for Space Standardization (ECSS) [5]. This would enable future robots to have more computational resources for carrying out complex optimizations which until now are very limited and also to perform various activities (like space exploration, servicing and repair.) without any or minimal human intervention.

The main contribution of this work is the idea of using spacecrafts dedicated for debris removal equipped with multiple robot arms. Also, perform trajectory tracking and control of two 3-DoF arms attached to the spacecraft using a model predictive control algorithm. These spacecrafts are assumed free floating (with no active attitude disturbance control system) and hence any motion of the robot arm would induce a movement on the spacecraft. We present the simulations of trajectory tracking and control of two robotic arms attached to the spacecraft using a model predictive control algorithm. Robotic arms on spacecraft are preferred over other debris removal methods because it can be easily extended to other orbital applications like on-orbit servicing and assembly, and autonomous rendezvous and docking.

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II. Formulation

A. Kinematic and Dynamics of free-floating spacecrafts

Prior works [6, 9, 10] on the kinematic and dynamic equations of free-floating spacecrafts are available in the literature. We provide the main equations here for completeness.

$$\begin{aligned} v_{eef} &= (J_m - J_s I_s^{-1} I_m)\dot{\phi}_m \\ &= J^* \dot{\phi}_m \end{aligned} \tag{1}$$

where v_{eef}, J_m, J_s, I_s, I_m and $\dot{\phi}_m$ are respectively the end-effector velocity, manipulator Jacobian, spacecraft Jacobian, 3 × 3 satellite inertia matrix, 3 × nDoF manipulator inertia matrix and the manipulator joint velocities. Here nDoF corresponds to the number of actuated joints. This formulation assumes that the momentum is conserved and is zero at the beginning. The dynamic formulation can be expressed as

$$M(\phi)\ddot{\phi} + C(\phi, \dot{\phi}) = \tau \tag{2}$$

where τ is the control torque to be applied at the manipulator joints, $M(\phi)$ and $C(\phi, \dot{\phi})$ are respectively the mass and Coriolis and centripetal matrices.

B. Feedback Linearization

Substituting the joint torques, τ with a fictitious input, $\alpha\tau' + \beta$ and substituting $\alpha = M(\phi)$ and $\beta = C(\phi, \dot{\phi})$ [2] without loss of generality, we could linearize the eq. (2) and can write each individual joint variables in state space form as

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tau'$$
$$\dot{x} = A'x + B'\tau' \tag{3}$$

where x_1 and x_2 corresponds to the angular displacement and velocity of the actuated joints.

C. Model Predictive Control

For our MPC [1] formulation, we use a prediction horizon of 5 seconds. The formulation can be shown as in eq. (4)

$$J = x^T P x + \int_{t_0}^{T-1} x^T Q x + u^T R u \; dt \tag{4}$$

subject to the constraints

$$\dot{x} = Ax + B\tau$$
$$x(0) = x_0$$

where $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$. Here Q ($\geqslant 0$) and R (> 0) are respectively the time varying state and control cost matrices (usually diagonal matrices), P is the stabilizing matrix obtained by the solution of algebraic Ricatti equation at every time instant, t_0, T are the initial and final time respectively, A and B are obtained by diagonally stacking up A' and B' equal to the number of joints and u is the control input. Interested readers may refer to [4] for a detailed explanation. Since we are dealing with a free-floating spacecraft, it is important to note that only the robotic arms are actuated. The motion of the spacecraft is due to the reaction forces induced on it from the arms. Thus the P matrix only acts as a stabilizer to the arm motion

III. Simulations

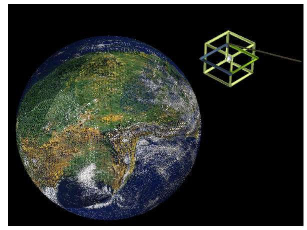
We show simulations done in Mayavi [8] of two identical robot arms which are attached diametrically opposite to each other on the spacecraft as shown in Fig 1. The Denavit-Hartenberg [3] values and the dynamic parameters of the robot arm used in the simulations are as shown in table I and table II.

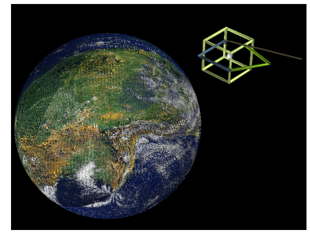
TABLE I
DH parameters of the robot arm

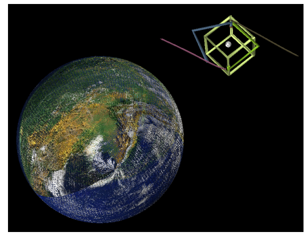
Joint	α (rad)	a (m)	d (m)	θ (rad)
1	$-\pi/2$	0.0	0.5	θ_1
2	$\pi/2$	0.0	0.0	θ_2
3	0	1.0	0.0	θ_3
flange	0	1.0	0.0	θ_3

TABLE II
Dynamic Parameters

	Satellite Link 0	Link 1	Link 2	Link 3
Mass (kg)	200.0	20.0	50.0	50.0
l (m)	2.10	0.25	2.5	2.5
I_x	1400.0	0.1	0.25	0.25
I_y	1400.0	0.10	26.0	26.0
I_z	2040.0	0.10	26.0	26.0


(a) Home position


(b) Start of motion of arm 1


(c) Arm 1 comes back and arm 2 starts motion

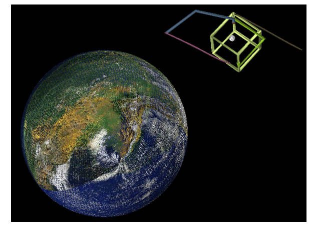
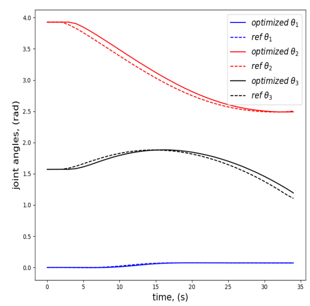
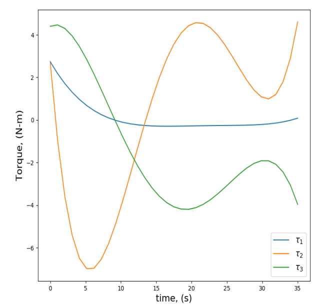

(d) Arm 2 reached goal

Fig. 1. Two arm trajectory tracking to reach debris



(a) Joint Angles



(b) Control inputs

Fig. 2. Tracking performance of the controller for arm 1

IV. Results

Fig 2 gives the tracking performance of the model predictive controller for arm 1. The average error in tracking the reference trajectory for joint 1, joint 2 and joint 3 are respectively 0.03%, 0.18% and 0.2% respectively. The simulation video is available at https://youtu.be/xeEQBiDpLLg

V. Conclusions and Future work

From simulations, we have demonstrated the possibility of having multiple robot arms on the same spacecraft. Further, it is shown that a model predictive tracking controller could be developed to track a trajectory. The slight error in tracking could be attributed to the hand tuning of control gain matrices, Q and R.

For future work, it would be interesting to see how more than two arms could be used and simultaneous actuations of the arms with minimal attitudinal changes to the spacecraft.

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