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A non-linear model predictive controller with obstacle avoidance for a space robot

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Abstract

This study investigates the use of the non-linear model predictive control (NMPC) strategy for a kinematically redundant space robot to approach an un-cooperative target in complex space environment. Collision avoidance, traditionally treated as a high level planning problem, can be effectively translated into control constraints as part of the NMPC. The objective of this paper is to evaluate the performance of the predictive controller in a constrained workspace and to investigate the feasibility of imposing additional constraints into the NMPC. In this paper, we reformulated the issue of the space robot motion control by using NMPC with predefined objectives under input, output and obstacle constraints over a receding horizon. An on-line quadratic programming (QP) procedure is employed to obtain the constrained optimal control decisions in real-time. This study has been implemented for a 7 degree-of-freedom (DOF) kinematically redundant manipulator mounted on a 6 DOF free-floating spacecraft via simulation studies. Real-time trajectory tracking and collision avoidance particularly demonstrate the effectiveness and potential of the proposed NMPC strategy for the space robot.

Keywords: Non-linear model predictive control; Obstacle avoidance; Space robot

1. Introduction

The existence of the space debris limits the future space activities and increases the risk of the operative satellites. How to remove these impeditive factors received fairly significant attentions. The application of space robots to perform such task is attractive as a result of their versatility, flexibility and expandability. Over the past few decades, series of researches have been conducted in the field of space robots. Examples include "Robot Technology Experiment (ROTEX)" (Hirzinger et al., 1994), "Engineering Test Satellite VII (ETS-VII)" (Oda et al., 1996) and "Orbital Express (OE)" (Ogilvie et al., 2008). In light of the space robots currently planned by world wide space agencies, an increase in the number and capacity of the robots applied in space missions will be a foregone conclusion in the coming future (Rekleitis et al., 2007).

In order to perform manipulation near space debris, how to control the motion of a robotic manipulator in its workspace with satisfactory performance has been a prime concern over the past few decades. One of the most widely used method for the space robots is the resolved motion acceleration control (RMAC) as developed in Umetani and Yoshida (1989) and Papadopoulos and Moosavian (1995). It employs a mathematical model of the space robot for dynamics compensation. Another widespread control technique is adaptive control as introduced in Xu et al.

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(1992) and Abiko and Hirzinger (2009). However, above control strategies own such deficiencies: inability to solve system input and output boundaries, lack of optimization, and incapability to deal with additional constraints. Originated from the chemical processing industries, model predictive control (MPC) (Qin and Badgwell, 2003) has gradually expanded its application to the other field, such as in Lin and Liu (2012), McCourt and de Silva (2006) and Jasour and Farrokhi (2009). However, the practical application of MPC in the field of space robotics is still rare. Another inevitable issue during space manipulator's motion is collision avoidance. Conventionally, it is treated as a high level planning problem which is independent from the design of the control strategy. Numerous solutions, like global planning methods (Galicki, 1992; Stilman, 2010), harmonic potential functions (Kim and Khosla, 1992), Jacobian null-space (Glass et al., 1995), position control (Seraji and Bon, 1999), Jacobian transpose method (Lee and Buss, 2007) and constrained local optimization (Zhang and Wang, 2004; Kanoun et al., 2011) have been developed to solve such issue during path planning. Considering the application background of space debris removal, the shortages of the traditional control methods and the demands of real-time collision avoidance motivate us to seek new methods for space robots to meet the specific space missions.

In this paper, we propose a general control framework with non-linear model predictive control (NMPC) applied to a kinematically redundant space manipulator considering collision avoidance and joint physical limits. The reason for choosing a kinematically redundant manipulator is the redundancy resolution can be employed for additional objectives, such as minimize base disturbance, avoid collision, or maximize the manipulability, and so forth. The fundamental idea of this paper is to separate the realization of the predefined task, depicted by the minimization of cost function, from the constraints of input, output and anti-collision. Inspired by the velocity damper method (Kanehiro et al., 2009), anti-collision constraints can be initially translated into uniform inequality conditions, then integrated into a quadratic programming (QP) procedure to obtain an optimal resolution over the receding horizon. The method proposed in this paper shows it is a bridge connecting the upper path planning level and lower actuator's control level, moreover, it handles the multi-variable optimal control problems with constraints in a comprehensive and systematic way.

The rest of the paper is organized as follows. Section 2 presents the general dynamics model of a space robot. Through feedback linearization, a linearised model is derived from the highly non-linear space robot model. Section 3 illustrates the collision detection and the conversion of the anti-collision issue as the linear inequality constraints. Section 4 gives the NMPC design in detail regarding to the linearised model mentioned in Section 2. An overview of the NMPC, optimization index, inequality constraints handling and QP procedure are included in this section. The simulation results are presented in Section 5. Our discussions, conclusions and future works are listed in the last section.

2. Modelling of a space robot

Before discussing the dynamics of a space robot in detail, some symbols and variables used in the following sections are listed in Table 1. A space robotic system is composed of a spacecraft and an n DOF manipulator, in total $n+1$ bodies as shown in Fig. 1. Many investigations have been conducted in the field of the space robot dynamics. Refer to Wang and Walter (2013), the dynamics equations of a space robot using Lagrangian mechanism can be expressed as follows

$$\begin{bmatrix} \mathbf{H}_b & \mathbf{H}_{bm} \\ \mathbf{H}_{bm}^{\mathrm{T}} & \mathbf{H}_m \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_b \\ \ddot{\boldsymbol{\theta}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}_b \\ \boldsymbol{c}_m \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}_b \\ \boldsymbol{\tau} \end{bmatrix} + \begin{bmatrix} \mathbf{J}_b^{\mathrm{T}} \\ \mathbf{J}_e^{\mathrm{T}} \end{bmatrix} \boldsymbol{f}_e \tag{1}$$

where $\ddot{\boldsymbol{x}}_b = (\ddot{\boldsymbol{r}}_b, \dot{\boldsymbol{\omega}}_b) \in \mathbb{R}^6$ is the vector of linear and angular accelerations of the base expressed in the inertial frame, $\ddot{\boldsymbol{\theta}} \in \mathbb{R}^n$ represents joint accelerations of the manipulator. If no external force and moment vectors applied to the end-effector, i.e. $\boldsymbol{f}_e = \boldsymbol{0}$ and no active actuators are applied to the base, i.e. $\boldsymbol{f}_b = \boldsymbol{0}$, then this is called a free-floating space robot. According to the angular momentum conservation law, the total momentum $\boldsymbol{L}_0 \in \mathbb{R}^6$ around the system center of mass is conserved in the free-floating mode, which can be expressed by

$$\boldsymbol{L}_0 = \mathbf{H}_b \dot{\boldsymbol{x}}_b + \mathbf{H}_{bm} \dot{\boldsymbol{\theta}} \tag{2}$$

Suppose the initial momentum $\boldsymbol{L}_0 = \boldsymbol{0}$, since $\mathbf{H}_b$ is always invertible, by substituting the motion of the base $\dot{\boldsymbol{x}}_b = -\mathbf{H}_b^{-1}\mathbf{H}_{bm}\dot{\boldsymbol{\theta}}$ into the kinematic mapping of the end-effector, $\dot{\boldsymbol{x}}_e = \mathbf{J}_b \dot{\boldsymbol{x}}_b + \mathbf{J}_e \dot{\boldsymbol{\theta}}$, the motion of the end-effector is given as follows

$$\dot{\boldsymbol{x}}_e = \begin{bmatrix} \dot{\boldsymbol{r}}_e \\ \boldsymbol{\omega}_e \end{bmatrix} = \mathbf{J}_g \dot{\boldsymbol{\theta}} = \left(\mathbf{J}_e - \mathbf{J}_b \mathbf{H}_b^{-1} \mathbf{H}_{bm} \right) \dot{\boldsymbol{\theta}} \tag{3}$$

Table 1
Kinematic and dynamic symbols used in the paper.

Symbols	Representation
J_i, C_i	Joint i and mass center of link i
$\boldsymbol{a}_i, \boldsymbol{b}_i \in \mathbb{R}^3$	Position vectors from J_i to C_i and from C_i to J_{i+1}
$\boldsymbol{r}_{C_i} \in \mathbb{R}^3$	Position vector of mass center of link i
$\boldsymbol{r}_b, \boldsymbol{r}_e \in \mathbb{R}^3$	Position vectors of base and end-effector
$\boldsymbol{\omega}_b, \boldsymbol{\omega}_e \in \mathbb{R}^3$	Angular velocities of base and end-effector
$\mathbf{I}_i \in \mathbb{R}^{3\times 3}, m_i \in \mathbb{R}$	Inertia matrix and mass of link i
$\mathbf{H}_b \in \mathbb{R}^{6\times 6}$	Inertia matrix of the base
$\mathbf{H}_{bm} \in \mathbb{R}^{6\times n}$	Coupling inertia matrix between base and manipulator
$\mathbf{H}_m \in \mathbb{R}^{n\times n}$	Inertia matrix of the manipulator
$\boldsymbol{c}_b \in \mathbb{R}^6, \boldsymbol{c}_m \in \mathbb{R}^n$	Vectors of velocity dependent non-linear terms
$\boldsymbol{f}_b, \boldsymbol{f}_e \in \mathbb{R}^6$	Vectors of force and moment exert on base and end-effector
$\boldsymbol{\tau} \in \mathbb{R}^n$	Torque exert on manipulator joints