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Optimum Trajectory Generation for Redundant/Hyper-Redundant Manipulators

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Abstract: This paper presents an optimization technique to develop minimum energy consumption trajectories for redundant/hyper-redundant manipulators with pre-defined kinematic and dynamic constraints. The optimization technique presents and combines two novel methods for trajectory optimization. In the first method, the system's kinematic and dynamics constraints are handled in a sequential manner within the cost function to avoid running the inverse dynamics when the constraints are not satisfied. Thus, the complexity and computational effort of the optimization algorithm is significantly reduced. For the second method, a novel virtual link concept is introduced to replace all the redundant links to eliminate physical impossible configurations before running the inverse dynamic model for the trajectory optimization. The method is verified on a three-degree-of-freedom redundant manipulator.

Keywords: Optimum trajectory planning, energy minimization, constraint handling, cost function, redundant manipulators, hyper-redundant manipulator, virtual link.

1. INTRODUCTION

Although the non-redundant commercial robot's performance and capability provide significant advantages for industrial implementations, however, in today's modern industrial world consist of multi-task industrial issues. The requirements of industrial applications are vastly complex, difficult and these applications demand better performance and flexibility such as drilling, cutting, medical robotics, maintenance of nuclear reactors etc. In order to meet these demands, robotic manipulators may have more degrees-of-freedom than essential due to execute intended complicated jobs like human arms. The extra degrees-of-freedom can be named redundant, and redundancy mainly aims at increasing the robotic manipulator's dexterity.

Research on redundant robotic manipulator is still active and redundancy can also be utilised to handle other cost criteria effectively. For example, redundancy has been used to achieve collision avoidance in working space Patel et al. (2005) and Ping et al. (2009), preventing singularities where the manipulator lose some degrees-of-freedom Duarte et al. (1999) and Huo et al. (2008), avoiding limits of joints Assal et al. (2006) and Mare et al. (2010), minimizing some cost function such as reducing jerk Sullivan et al. (1998) and Yang et al. (2008), reducing deviation of the end-effectors Ata et al. (2006) and Singla et al. (2010), reducing time Ma et al. (2000) over a intended task. Redundancy can also be exploited for fault tolerance during the intended task Yan et al. (1998),Rodney et al. (2008),Roberts et al. (2009) and Soylu et al. (2010). In addition to these, energy consumption can be reduced by utilising redundancy Halevi et al. (2011) in trajectory optimization. For example, a cost function was formulated by the input electrical energy/power and trajectory deviation for a redundant manipulator Hirakawa et al. (1997).

In a fully actuated system, inverse kinematic solution of non-redundant robotic manipulators generally offers minimal numerical computational complexity and the number of control inputs is equal to the degrees of freedom of the system. However, in the redundant case, inverse kinematic solutions and control of the redundant link become more and more complicated and trajectory optimization problem also become increasingly difficult with each added redundant degree-of-freedom Dasgupta et al. (2009). Because, utilised trajectory optimization algorithm can be numerically and computationally extremely complex and challenging issue due to the large number of optimization parameters and various constraints which need to be handled effectively during the optimization process of the computationally intensive inverse dynamic model. Moreover, the success of any optimization procedure, the trajectory optimization algorithm should be easily used on various types of non-redundant, redundant and hyper-redundant manipulators and the various types of constraint equations should be handled effectively during the trajectory optimization procedure. To determine the optimum solution

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successfully for trajectory optimization in redundant case, computationally efficient optimization procedures are preferred for a given task.

This paper presents a novel constraint handling method and an efficient control algorithm for trajectory optimization to prevent computational complexity of the redundant and hyper-redundant manipulators. One of the main contributions of this paper is to provide constraint handling procedure is computationally efficient as kinematic and dynamic constraints are included in the cost function to prevent running inverse dynamic model when all constraints are not satisfied. Thus, the complexity and computational effort of the optimization algorithm is significantly reduced. And second contribution of this paper, all the redundant links are acting as a single link. Hence, it makes controlling these links easier and control complexity of the redundant/hyper-redundant manipulators is reduced. This control algorithm prevents inverse dynamic failure even if the manipulator is within the workspace during the optimization process. The effectiveness of the proposed methods is initially demonstrated using computer simulations and then same intended trajectories are implemented experimentally by utilising the Katana 450 6M industrial robotic manipulator based on links 2, 3 and 4.

The organization of the rest of the paper can be summarized as follows. The system description and dynamics has been presented in Section 2. The procedure of optimum trajectory planning has been introduced in Section 3. The proposed methods have been shown in Section 4. The experimental implementation and results have been illustrated in Section 5.

2. SYSTEM DESCRIPTION AND DYNAMICS

Fig. 1 shows the six degrees-of-freedom of the Katana 450 robotic manipulators with end-effector tool. It consists of 6 degrees of freedom propelled by 6 DC motors with incremental encoder controlled by independent axis controller hardware. Gears are harmonic drive. The Katana 450 manipulator has an internal control box, which is directly mounted on the robot's foot. The supply voltage is 24VDC and average energy consumption is approximately 50 W. The main board has PPCMPC5200 processor of 400MHz, 32 MB Flash, 64 MB RAM. Operating system is embedded GNU/Linux. Carrying load capacity is approximately 400g. Dynamic modelling of the robot is based on Lagrangian dynamics, which describes the system in terms of its energy. To construct the inverse dynamic model of the system, the DYSIM software is utilized Sahinkaya (2004) and it will operate from within the MatLab/Simulink environment. DYSIM requires the user to specify the mass, inertia and position of centre of mass for each link, as well as identifying the location of ground point. All these required parameters are summarised in Tab 1. The origin of the coordinate system is located at the point where the rotary axis of actuator 2 lier in Fig. 1. The y represents the rotary axis of actuator 2, 3 and 4, respectively. A pictorial example of the definition of Link 2 is connected to the actuator base 2, which is connected to the ground (defined as Base). The maximum reachable point of the manipulator is approximately 0.6024 m from the actuator 2 base point. Link 2, link 3 and link 4 of the Katana manipulator (rotary joints 2, 3 and 4) are considered for the implementation of 3-link redundant manipulator. In this implementation, the base of the manipulator, rotary joints of links 5, and 6 are locked at zero degree relative angles during the redundant implementation. In this case, a system has more control inputs than required in order to control a specified desired motion. That is, the robotic manipulator has three DOFs, but the planar system has two degrees of freedom. In this case, the inverse dynamic equations consists of more unknowns than the number of equations. For the redundant scheme, the manipulator task consists of transporting a load mass of 0.3 kg from an initial point at ($x_i = -0.3095, \quad y_i = 0.4881$) m to a destination at ($x_f = 0.1405, \quad y_f = 0.4381$) m in Cartesian space as shown in Fig. 1. It can be seen from the Fig. 1 that the first link of the manipulator has redundancy, and the rest of the links are non-redundant. The total duration of motion is varied from 4 sec to 10 sec by increments of 2 sec. The DYSIM program selects 11 generalised coordinates

Table 1. Parameters for Katana 450.

Parameters	**Link 2**	**Link 3**	**Link 4**
Mass of Link (kg)	1.022	0.882	0.969
Length of Link (mm)	190	139	273.4
Distance from CoG to end link (mm)	95	35.3	163.4
Inertia of Link ($kg \cdot m^2$)	0.0445	0.0445	0.0114
Friction coef. of Link ($N \cdot ms/rad$)	1.8	1.5	0.39
Mass of gear (kg)	0.233	0.233	0.182
Gear ratio	371	371	100
Limits	**Link 2**	**Link 3**	**Link 4**
Absolute Angle (deg)	132°	245°	224°
Relative Angle (deg)	+102°/-30°	+/-122.5°	+/-112°
Max velocity (deg/s)	72.52	73.53	136.8
Max acceleration (deg/s^3)	2321	2353	4378
Torque ($N \cdot m$)	17	13	9

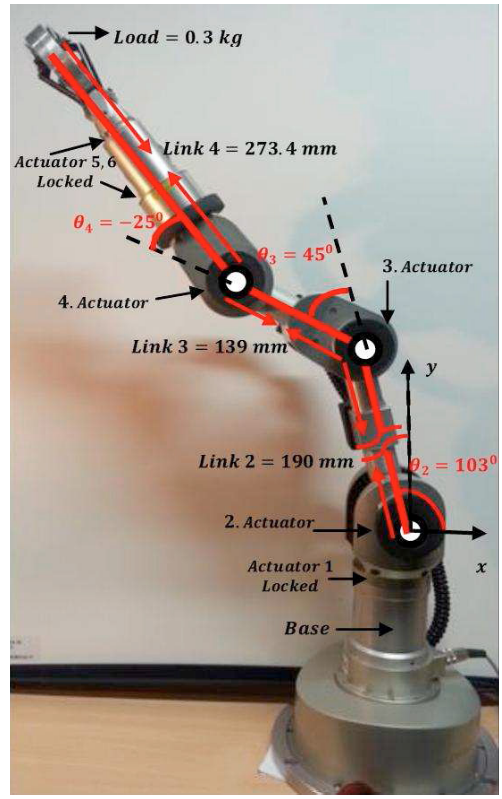

Figure 1. Katana model with one redundancy in link-2.