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Online optimization scheme with dual-mode controller for redundancy-resolution with torque constraints

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ABSTRACT

In this paper, an online optimization scheme is proposed for the real time path-tracking control of the redundant robot manipulator. In the proposed scheme, the inequality constraints are extended to the torque level to avoid the torque saturation. Besides, a dual-mode optimal controller is used to yield a feasible input during each control period, to resolve the solution space decreasing problem. Then the scheme is formulated as a Quadratic Program (QP), the computationally efficient Knitro-Based solver is applied to remedy the inescapable redundancy-resolution problem. Furthermore, the comparisons based on the different path tracking simulations between the proposed method and the velocity-level schemes demonstrate that the former is safer and more applicable. The experiment on a physical robot system further verifies the physical realizability of the proposed method.

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1. Introduction

The robot manipulator is redundant which means that it has more degrees of freedom (DOF) than required to achieve a prescribed task. The redundant DOF is normally used as the flexibility to avoiding obstacles or singularities, minimizing joint torques [1–3]. Path tracking planning is an appealing topic in the robotics field. The pseudo-inverse based method, including gradient projected method [4], extended Jacobian method [5,6], augmented Jacobian method [7,8] and weighted least norm method [9], can be used to solve this problem conveniently. These methods are generally used to implement some subtasks (secondary task), such as the singularity avoidance [10,11], torque optimization [12], and some multi-subtasks resolution [13,14]. However, some physical limits of the redundant manipulator may be neglected in these methods, such as joint-velocity limits, joint-acceleration limits, which may lead to a saturation and considerable path tracking errors, or even cause possible physical damage [15].

According to the literature published in the robotic field, online optimization method proposed a new perspective for resolving kinematics-redundancy problem during the recent decades [15,16]. Relatively, the online methods could be used to conquer the defects of the pseudo inverse based methods. In the online scheme, the equality and inequality constraints in the joint-velocity level [17,18] or in the acceleration-level [19,20] could be considered effectively. These schemes are generally configured as a quadratic program (QP) [20,21]. The constraints may reflect the control strategy in our engineering application and the QP is converted to a nonlinear optimal problem, which is solved approximately by many solvers, such as numerical methods [22] and some types of neural networks based method [23], such as Zhang neural network (ZNN) solver and gradient neural network (GNN) solver [24].

As a brief summarization, the current online method mostly solved the redundancy-resolution problem on the velocity or acceleration level. The scheme for resolving kinematics in the velocity level probably introduces the discontinuity phenomenon during a continuous path tracking task [19]. This problem could be solved using the scheme in the acceleration-level, but the influence of gravity or the load of the end-effector is not taken into consideration effectively [20,21]. On the other hand, the constraints of these schemes are established based on the kinematics model of the redundant robot. Nevertheless, they may not suitable for some path tracking task. For example, the dual-arm of the humanoid robot executes a path tracking task when the gravity of the arm and the load of the end-effector are considered. In this situation, the capacity or the driving ability of the joint actuator is the main limits for the task. It may lead the torque saturation for the control work if the capacity of the actuator is neglected. Fortunately, the physical quantity of the torque can be used to characterize this limit based on the robot dynamics.

Considering the engineering application of the humanoid arm, the constraints model must be extended to the torque level.

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Because the constraints in torque level synthetically consider the constraints in the joint velocity and acceleration level, which are stricter than that on the velocity or acceleration level. Obviously, the stricter constraints may decrease the solution space, which may cause some path tracking tasks unable to be finished. For another, the torque is computed based on the dynamics model; this may lead a heavy computation load when it is implemented in the engineering application, the current solvers based kinematics level may not suitable to this on dynamics level.

For extending the constraints to the torque level and solving its caused problem, a dual-mode controller is integrated to solve the redundancy-resolution problem in a limited space, and a Knitro instrument is applied in our work for resolving the redundancy-resolution in dynamics level firstly. Finally, the simulated and the experimental work are also presented in this paper to verify its efficiency.

The remainder of the paper is organized as follows. Section 2 presents the formulation of the two online optimization schemes (resolution in velocity level and resolution in the acceleration level). Section 3 formulates the robot modeling method and robot control constraints. The dual-mode controller is presented in Section 4, which is followed by the simulation and experiment results in Section 5. The conclusion and future work are given finally.

In this paper, a dual-mode online optimization scheme with torque constraints is proposed for the first time. The contribution of this paper is three-fold.

Firstly, the inequality constraints model is designed in the torque level for the redundancy-resolution, which synthetically considered the constraints in the joint velocity and acceleration level. It may formulate the predesigned physical limits more comprehensive and applicable.

Secondly, a dual-mode optimal controller is developed and incorporated to resolve the end effector tracking problem when the robot moved under a limited solution space.

Thirdly, corresponding to the computation based on the dynamic model, the efficient solver based on Knitro instrument is also first applied for redundancy-resolution in this paper.

2. Preliminary formulation

The relationship between the orientation/position vector $\mathbf{r}(\mathbf{t}) \in \Re^m$ of the end-effector in the Cartesian space and the joint angle vector $\boldsymbol{\theta}(\mathbf{t}) \in \Re^n$ in joint space could be depicted through a time varying equation:

$$\mathbf{r}(\mathbf{t}) = f\left(\boldsymbol{\theta}(\mathbf{t})\right) \tag{1}$$

Due to the nonlinearity and redundancy of the mapping $f(\cdot)$, such a problem if often solved at the velocity or acceleration level. Differentiating (1) with respect to time t yields the relationship between the Cartesian velocity $\dot{\mathbf{r}}(\mathbf{t})$ and the joint velocity $\dot{\boldsymbol{\theta}}(\mathbf{t})$

$$\dot{\mathbf{r}}(\mathbf{t}) = \mathbf{J}\left(\boldsymbol{\theta}(\mathbf{t})\right)\dot{\boldsymbol{\theta}}(\mathbf{t}) \tag{2}$$

where $\mathbf{J}(\boldsymbol{\theta}(\mathbf{t})) = \partial f(\boldsymbol{\theta}(\mathbf{t}))/\partial\boldsymbol{\theta}(\mathbf{t}) \in \Re^{m\times n}$ is the Jacobian matrix. Differentiating the (2) could further yield the relationship between the end-effector acceleration $\ddot{\mathbf{r}}(\mathbf{t})$ and the joint-acceleration $\ddot{\boldsymbol{\theta}}(\mathbf{t})$;

$$\ddot{\mathbf{r}}(\mathbf{t}) = \mathbf{J}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \dot{\mathbf{J}}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} \tag{3}$$

where the $\dot{\mathbf{J}}(\boldsymbol{\theta})$ is the time derivative of the Jacobian matrix , the Eqs. (1)–(3) depict the kinematics of the robot manipulator, and the solution for this method is infinite, because the robot manipulator is redundant degree of freedom, namely, the Jacobian matrix is not a square matrix.

The pseudo inverse-based method to the (2) and (3) can be formulated as two parts, namely, least-norm particular solution and homogeneous solution, like as Eqs. (4) and (5)

$$\dot{\boldsymbol{\theta}} = \mathbf{P}\dot{\mathbf{r}} + \left(\mathbf{I}-\mathbf{P}\mathbf{J}\right)\boldsymbol{\Phi} \tag{4}$$

$$\ddot{\boldsymbol{\theta}} = \mathbf{P}\ddot{\mathbf{r}}_{\mathbf{a}} + \left(\mathbf{I}-\mathbf{P}\mathbf{J}\right)\boldsymbol{\Phi} \tag{5}$$

where the $\mathbf{P} = \mathbf{J}^{\mathbf{T}}(\mathbf{J}\mathbf{J}^{\mathbf{T}})^{-1} \in \Re^{n\times m}$ denotes the pseudo inverse matrix of the $\mathbf{J}(\boldsymbol{\theta})$, $\ddot{\mathbf{r}}_{\mathbf{a}} = \ddot{\mathbf{r}}-\dot{\mathbf{J}}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} \in \Re^m$, and $\boldsymbol{\Phi}$ is an arbitrary vector selected as gradients of some performance indices.

To better introduce our dual-mode optimal controller, the following redundancy-resolution schemes (with one at the velocity level and the other at the acceleration level) are presented, investigated, and formulated finally as solvable QPs, which could be applied in real-time motion control of the robot manipulators.

2.1. Velocity-level redundancy-resolution scheme

The normally used minimum-velocity-norm criterion [25,26] has been widely adopted by most researchers in the velocity-level redundancy-resolution scheme, including an optimal objective and an equality constraint, as shown in the following:

$$\text{Minimize} \quad \frac{1}{2}\|\dot{\boldsymbol{\theta}}\|_2^2 \tag{6}$$

$$\text{Subject to} \quad \mathbf{J}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} = \dot{\mathbf{r}} \tag{7}$$

where $\|\cdot\|_2$ denotes the two-norm of a vector and (7) relates to the end-effector's primary task in task space. The $\|\dot{\boldsymbol{\theta}}\|_2^2/2 = \dot{\boldsymbol{\theta}}^{\mathbf{T}}\dot{\boldsymbol{\theta}}/2$, and superscript “T” denotes the transposes of a vector. Generally, the scheme (6), (7) can be expressed as a time-varying QP problem that is subject to an equality constraint, as shown in the following:

$$\text{Minimize} \quad \frac{1}{2}\mathbf{x}^{\mathbf{T}}\mathbf{W}\mathbf{x} + \mathbf{q}^{\mathbf{T}}\mathbf{x} \tag{8}$$

$$\text{Subject to} \quad \mathbf{C}\mathbf{x} = \mathbf{d} \tag{9}$$

where $\mathbf{x} = \dot{\boldsymbol{\theta}} \in \Re^n$, $\mathbf{W} = \mathbf{I} \in \Re^{n\times n}$ denote the identity matrix, $\mathbf{C} = \mathbf{J} \in \Re^{m\times n}$, $\mathbf{d} = \dot{\mathbf{r}} \in \Re^m$, and $\mathbf{q} = 0 \in R^m$.

2.2. Acceleration level redundancy-resolution scheme

Similarity, the redundancy resolution in the acceleration level can be depicted in the following:

$$\text{Minimize} \quad \left(\ddot{\boldsymbol{\theta}} + \mathbf{p}\right)^{\mathbf{T}}\left(\ddot{\boldsymbol{\theta}} + \mathbf{p}\right)/2 \tag{10}$$

$$\text{Subject to} \quad \mathbf{J}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} = \mathbf{r}_{\mathbf{a}} \tag{11}$$

Where$\mathbf{p} = \lambda\dot{\boldsymbol{\theta}}$, and the parameter $\lambda > 0$should be large enough. Thus, the scheme (10) and (11) also could be concluded as a QP formulation shown in the following,

$$\text{Minimize} \quad \frac{1}{2}\mathbf{x}^{\mathbf{T}}\mathbf{W}\mathbf{x} + \mathbf{q}^{\mathbf{T}}\mathbf{x} \tag{12}$$

$$\text{Subject to} \quad \mathbf{C}\mathbf{x} = \mathbf{d} \tag{13}$$

Eqs. (12) and (13) are similar to the (8) and (9), nevertheless, in the acceleration scheme, $\mathbf{x} = \ddot{\boldsymbol{\theta}} \in \Re^n$, $\mathbf{W} = \mathbf{I} \in \Re^{n\times n}$, $\mathbf{C} = \mathbf{J} \in \Re^{m\times n}$, $\mathbf{d} = \ddot{\mathbf{r}}_{\mathbf{a}} \in \Re^m$ and $\mathbf{q} = \lambda\dot{\boldsymbol{\theta}} \in \Re^n$. Scheme (10) and (11) solved the redundancy-resolution problem from the aspect of the acceleration level. This scheme can provide a new prospective to control the manipulator.

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