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Control of redundant robot arms with null-space compliance and singularity-free orientation representation

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HIGHLIGHTS

- Robot pose is controlled while addressing a compliant behaviour within the null space.
- Singularity-free representations for the orientation part are employed.
- A dynamic controller is designed without the need of any exteroceptive sensors.
- Theoretical proofs and experiments are presented to validate the approach.

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ABSTRACT

This paper tackles the problem of controlling the position and orientation, expressed in a singularity-free representation form, of the end-effector of a redundant robot, while addressing an active compliant behaviour within the null-space. The manuscript extends the work in Sadeghian et al. (2014) by explicitly addressing the orientation part. In order to successfully accomplish the task, a dynamic controller is designed without need of any exteroceptive sensors information. A rigorous stability analysis is provided to confirm the developed theory. Experiments are finally carried out to bolster the performance of the proposed approach.

1. Introduction

The new generation of robots should have the intrinsic ability to share the operational environment with humans. Often physical interaction occurs, and this may happen at any part of the manipulator body. The contact can be both intentional (i.e., required for collaborative tasks) or unintentional (i.e., unexpected collisions). To guarantee a safe robot reaction to physical interaction, suitable control strategies must be adopted, which may require the measurement or the estimate of the exchanged forces and moments, as well as the effective robot inertia, the relative velocity and the distance between the robot and the human [1].

One solution could be to cover the whole manipulator body with a sensitive skin [2] to obtain a direct measure of the exchanged force and moment as well as of the contact point. Nevertheless, this solution seems to be rather far to be applied at the moment. In case it is not possible to cover the arm with sensors, an alternative solution is to estimate the exchanged forces and moments on the basis of the available measures of joints position and/or torque, by using suitable observers [3] or neural interpolators [4]. This approach is adopted in [5] for collision detection and safe reaction.

For safety reasons, in order to keep limited the exchanged forces and moments, the manipulator is often requested to be compliant in response to physical interaction. From a mechanical point of view, such compliance can be passively achieved by using elastic decouplings between the actuators and the commanded links through fixed or variable joint stiffness [6]. On the other hand, active compliance relies on the control action, and impedance control is the widest adopted approach to actively control the robot compliance [7–10]. If the external interaction is likely to occur only on some parts of the manipulator (i.e., the end-effector), a force/torque sensor helps in fully control the desired interaction with the environment via software. In case of redundant robots, a compliant behaviour can be imposed so as not to interfere with the main task [9,11], an thus the so called null-space compliance or impedance is obtained. This is particularly useful in those situations where it is desirable to have the control of the interaction within the joint space. In such cases, the external forces affecting the main task must be suitably measured and/or estimated to allow an impedance behaviour as a secondary task without

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compromising the main one. Null-space impedance can be also achieved in multi-priority framework at acceleration level [11], or employing both a task error-based disturbance observer and a momentum-based observer [12]. A particular feature of the algorithm developed in [12] is that it allows to fully compensate the error in the task space caused by the physical interaction. Of course, this is possible only if the robot possesses a sufficient number of redundant degrees of freedom. In some applications, it is advisable to select a minimal number of task variables to be kept unaffected in the case of physical interaction. Moreover, the task variables are usually a subset of those representing the end-effector position and orientation. For example, if a robot waiter is carrying a trail with some food, when somebody pushes the arm, it is important to avoid the change of orientation of the trail, or, at least, any roll and pitch motions. Other approaches with redundant robots do not instead explicitly require the use of an active or passive compliance, but the manipulator's posture is optimized to minimize the impact/external wrench while carrying out the main task [13].

This work further develops what presented in [12], where the algorithm is presented with reference to generic task variables. In this paper, instead, the task variables are explicitly the position and orientation of the end effector. The orientation is considered in a non-minimal singularity free representation, *e.g.*, axis-angle, unit quaternion. Notice that using one of these two orientation representations, the theoretical framework within [12] fails since the closed-loop equations related to the angular part are not in a linear form. As in [12], the pursued goal is to control the robot manipulator in the Cartesian space while achieving an active compliant behaviour in the null-space. A dynamic term filtering both the effects of velocity and external forces is added to the controller to solve the task. A rigorous stability analysis is also provided. Notice that neither joint torque sensors nor force/torque sensors at the end-effector are required to accomplish the sought job.

The outline of the manuscript is as follows. Section 2 presents the mathematical background necessary to introduce the proposed control in Section 3. The stability proof of the closed-loop system is carried out in Section 4. Experiments confirming the provided theory are provided in Section 5. Section 6 finally concludes the manuscript.

2. Background

The equations of motion of a n joints robot arm can be written in the joint space according to the following compact matrix form [7]

$$\boldsymbol{B}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} - \boldsymbol{\tau}_{ext}, \tag{1}$$

where $\boldsymbol{q} \in \mathbb{R}^n$, $\dot{\boldsymbol{q}} \in \mathbb{R}^n$ and $\ddot{\boldsymbol{q}} \in \mathbb{R}^n$ are the position, velocity and acceleration joint vectors, respectively; $\boldsymbol{B}(\boldsymbol{q}) \in \mathbb{R}^{n\times n}$ is the inertia matrix in the joint space; $\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \in \mathbb{R}^{n\times n}$ is the matrix collecting Coriolis and centrifugal effects; $\boldsymbol{g}(\boldsymbol{q}) \in \mathbb{R}^n$ is the gravity vector term; $\boldsymbol{\tau} \in \mathbb{R}^n$ is the control torques vector; $\boldsymbol{\tau}_{ext} \in \mathbb{R}^n$ is the vector representing the external torques acting on the joints.

Notice that $\boldsymbol{\tau}_{ext}$ is a disturbance representing both joints torque due to the physical interaction with the environment and unmodelled effects. In this paper, it is assumed that the manipulator is equipped neither with torque sensors in the joints, nor with force/torque sensors. Therefore, it is not possible to measure $\boldsymbol{\tau}_{ext}$.

Considering a redundant manipulator ($n > 6$, in general), a joint space impedance control can be achieved in the null-space of the Cartesian task, or using a multi-priority redundancy resolution scheme [14]. Let Σ_i and Σ_e be the inertial and end-effector reference frames, respectively. Denote with $\boldsymbol{p}_e \in \mathbb{R}^3$ and $\boldsymbol{R}_e \in SO(3)$ the position and the orientation, respectively, of Σ_e in Σ_i. Consider the vector $\boldsymbol{\upsilon} = \begin{bmatrix}\dot{\boldsymbol{p}}_e^{\mathrm{T}} & \boldsymbol{\omega}_e^{\mathrm{T}}\end{bmatrix}^{\mathrm{T}} \in \mathbb{R}^6$, where $\boldsymbol{\omega}_e \in \mathbb{R}^3$ is the angular velocity of Σ_e with respect to Σ_i. The following relation between the joints velocity and the end-effector velocity holds

$$\boldsymbol{\upsilon} = \boldsymbol{J}(\boldsymbol{q})\dot{\boldsymbol{q}}, \tag{2}$$

where $\boldsymbol{J}(\boldsymbol{q}) \in \mathbb{R}^{6\times n}$ is the so-called geometric Jacobian of the robot arm [7]. A general inverse solution to (2) is given by $\dot{\boldsymbol{q}} = \boldsymbol{J}(\boldsymbol{q})^{\dagger}\boldsymbol{\upsilon} + \boldsymbol{N}(\boldsymbol{q})\dot{\boldsymbol{q}}_N$, where $\boldsymbol{J}(\boldsymbol{q})^{\dagger} \in \mathbb{R}^{n\times 6}$ is any generalized inverse of $\boldsymbol{J}(\boldsymbol{q})$, and $\boldsymbol{N} \in \mathbb{R}^{n\times n}$ is the matrix projecting the vector $\dot{\boldsymbol{q}}_N \in \mathbb{R}^n$ to the null-space of $\boldsymbol{J}(\boldsymbol{q})$. The vector $\dot{\boldsymbol{q}}_N$ represents internal redundancy motions of the manipulator joints that do not affect the end-effector velocity $\boldsymbol{\upsilon}$. It is assumed that the robot does not pass close to singular joint configurations, i.e. $\boldsymbol{J}(\boldsymbol{q})$ is full rank.

In order to better characterize the internal motions of a redundant manipulator, one solution is to use the so-called *joint space decomposition method* [9]. In this case the Cartesian coordinates are augmented by adding $r = n - 6$ auxiliary variables $\boldsymbol{\lambda} \in \mathbb{R}^r$ to the end-effector velocity $\boldsymbol{\upsilon}$. These auxiliary variables are defined as

$$\dot{\boldsymbol{q}} = \boldsymbol{N}\dot{\boldsymbol{q}}_N = \boldsymbol{Z}(\boldsymbol{q})\boldsymbol{\lambda}, \tag{3}$$

where $\boldsymbol{Z}(\boldsymbol{q}) \in \mathbb{R}^{n\times r}$ is such that $\boldsymbol{J}(\boldsymbol{q})\boldsymbol{Z}(\boldsymbol{q}) = \boldsymbol{O}_{6\times r}$, where $\boldsymbol{O}_{a\times b} \in \mathbb{R}^{a\times b}$ is a zero matrix of proper dimensions. Therefore $\boldsymbol{Z}(\boldsymbol{q})$ is a matrix spanning the null-space of $\boldsymbol{J}(\boldsymbol{q})$. Having in mind (3), a convenient choice for $\boldsymbol{\lambda}$ is given by the left inertia-weighted generalized inverse of $\boldsymbol{Z}(\boldsymbol{q})$ [15], such that $\boldsymbol{\lambda} = \boldsymbol{Z}(\boldsymbol{q})^{\#}\dot{\boldsymbol{q}}$, with $\boldsymbol{Z}(\boldsymbol{q})^{\#} = \left(\boldsymbol{Z}(\boldsymbol{q})^{\mathrm{T}}\boldsymbol{B}(\boldsymbol{q})\boldsymbol{Z}(\boldsymbol{q})\right)^{-1}\boldsymbol{Z}(\boldsymbol{q})^{\mathrm{T}}\boldsymbol{B}(\boldsymbol{q})$. By this choice, it is possible to extend (2) through the following form

$$\boldsymbol{\xi} = \begin{bmatrix}\boldsymbol{\upsilon}\\ \boldsymbol{\lambda}\end{bmatrix} = \boldsymbol{J}_E(\boldsymbol{q})\dot{\boldsymbol{q}} = \begin{bmatrix}\boldsymbol{J}(\boldsymbol{q})\\ \boldsymbol{Z}(\boldsymbol{q})^{\#}\end{bmatrix}\dot{\boldsymbol{q}}, \tag{4}$$

where

$$\boldsymbol{J}_E(\boldsymbol{q})^{-1} = \begin{bmatrix}\boldsymbol{J}(\boldsymbol{q})^{\#} & \boldsymbol{Z}(\boldsymbol{q})\end{bmatrix}, \tag{5}$$

is non-singular for full rank matrix $\boldsymbol{J}(\boldsymbol{q})$, and $\boldsymbol{J}(\boldsymbol{q})^{\#} = \boldsymbol{B}(\boldsymbol{q})^{-1}\boldsymbol{J}(\boldsymbol{q})^{\mathrm{T}}\left(\boldsymbol{J}(\boldsymbol{q})\boldsymbol{B}(\boldsymbol{q})^{-1}\boldsymbol{J}(\boldsymbol{q})^{\mathrm{T}}\right)^{-1}$ is the so-called dynamically consistent generalized inverse Jacobian [16], which plays a key role in null-space dynamics [9]. Therefore, the following decompositions for the joints velocity and acceleration hold

$$\dot{\boldsymbol{q}} = \boldsymbol{J}(\boldsymbol{q})^{\#}\boldsymbol{\upsilon} + \boldsymbol{Z}(\boldsymbol{q})\boldsymbol{\lambda}, \tag{6}$$

$$\ddot{\boldsymbol{q}} = \boldsymbol{J}_E^{-1}(\boldsymbol{q})\dot{\boldsymbol{\xi}} + \dot{\boldsymbol{J}}_E^{-1}(\boldsymbol{q})\boldsymbol{\xi}. \tag{7}$$

The complete dynamic model in both the task and the null-space can be found in [9]: the related derivation is here avoided.

The control objective is to satisfy a task in the Cartesian space while achieving a compliant behaviour for the manipulator, without affecting the main task. This will be also possible thanks to the aforementioned choice of considering geometric consistent generalized inverse matrices whose metric is induced by the inertia matrix. The following controller is then consider for the dynamic system (1)

$$\boldsymbol{\tau} = \boldsymbol{B}(\boldsymbol{q})\boldsymbol{u}_q + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}), \tag{8}$$

where $\boldsymbol{u}_q \in \mathbb{R}^n$ is a new virtual control input having the dimension of joints acceleration. The closed-loop dynamics assume the following form

$$\ddot{\boldsymbol{q}} = \boldsymbol{u}_q - \boldsymbol{B}(\boldsymbol{q})^{-1}\boldsymbol{\tau}_{ext}. \tag{9}$$

Having in mind (7) and (9), the following command acceleration can be considered [12]

$$\boldsymbol{u}_q = \boldsymbol{J}(\boldsymbol{q})^{\#}\left(\boldsymbol{u}_{\upsilon} - \dot{\boldsymbol{J}}(\boldsymbol{q})\dot{\boldsymbol{q}}\right) + \boldsymbol{Z}(\boldsymbol{q})\left(\boldsymbol{u}_{\lambda} - \dot{\boldsymbol{Z}}(\boldsymbol{q})^{\#}\dot{\boldsymbol{q}}\right), \tag{10}$$

where $\boldsymbol{u}_{\upsilon} \in \mathbb{R}^6$ and $\boldsymbol{u}_{\lambda} \in \mathbb{R}^r$ are new virtual control inputs having the dimension of Cartesian and null-space accelerations,