Automatica 53 (2015) 416–423

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Brief paper

Prioritized multi-task compliance control of redundant manipulators☆

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ARTICLE INFO

Article history:
Received 6 November 2013
Received in revised form
19 December 2014
Accepted 25 December 2014
Available online 12 February 2015

Keywords:
Hierarchical control
Redundant manipulators
Robotics
Stability analysis
Impedance control

ABSTRACT

We propose a new approach for dynamic control of redundant manipulators to deal with multiple prioritized tasks at the same time by utilizing null space projection techniques. The compliance control law is based on a new representation of the dynamics wherein specific null space velocity coordinates are introduced. These allow to efficiently exploit the kinematic redundancy according to the task hierarchy and lead to a dynamics formulation with block-diagonal inertia matrix. The compensation of velocity-dependent coupling terms between the tasks by an additional passive feedback action facilitates a stability analysis for the complete hierarchy based on semi-definite Lyapunov functions. No external forces have to be measured. Finally, the performance of the control approach is evaluated in experiments on a torque-controlled robot.

1. Introduction

Manipulators with more degrees of freedom (DOF) than necessary for a specific task have several advantages compared to their non-redundant counterparts. Kinematic redundancy usually leads to a larger dexterous workspace and it provides the capability to incorporate additional, simultaneous subtasks. These properties are essential for robots operating in dynamic and unstructured environments, e.g. households or crowded places. Several ways exist to control a robot in its task space (Li & Cheah, 2013; Moosavian & Papadopoulos, 2007), but the Operational Space Formulation (OSF) by Khatib (1987) is probably the most well-known concept. Decoupled linear dynamics on the main task level, which is similar to feedback linearization in nonlinear control theory, allows to separately handle different simultaneous tasks. A dynamically consistent priority-based hierarchy among these tasks can be set up by utilizing null space projection techniques (Dietrich, Wimböck, Albu-Schäffer, & Hirzinger, 2012b; Khatib, Sentis, Park, & Warren, 2004; Nakamura, Hanafusa, & Yoshikawa, 1987; Sentis & Khatib, 2005; Siciliano & Slotine, 1991). However, a stability proof for the complete robot using the OSF is not known (Nakanishi, Cory, Mistry, Peters, & Schaal, 2008). Early works on redundancy resolution involved the augmentation of additional task coordinates (Baillieul, 1985) which lead, however, to new algorithmic singularities and inertial couplings. A dynamic decoupling between the primary task and the null space subtasks can be achieved via shaping of the reflected inertia. The extended task space approach was generalized to compliant motion control by Peng and Adachi in Peng and Adachi (1993).

If external forces are considered, then it is necessary to incorporate them in the controller to obtain a decoupled behavior w.r.t. these forces, such as in the OSF. While forces exerted on the end-effector can often be measured by a six-axis force–torque-sensor, external forces acting in the null space are more problematic and require observers or additional instrumentation. It is well known that impedance control can be implemented without measurement of external forces, if the desired impedance is characterized by a desired compliance in terms of stiffness and damping (Albu-Schäffer, Ott, Frese, & Hirzinger, 2003). In this case the desired inertia corresponds to the natural inertia of the robot. In Natale, Siciliano, and Villani (1999), a spatial Cartesian impedance controller was extended by an additional null space control action so that asymptotic convergence of the null space velocity error term could be shown. In the context of impedance control, the minimization of a quadratic norm of a lower-priority impedance error has been treated in Platt, Abdallah, and Wampler (2010). Recently we have developed passivity-based

☆ This work was partially funded by the projects EuRoC (grant agreement no. CP-IP 608849) and SAPHARI (grant agreement no. ICT-287513). The material in this paper was partially presented at the 2008 IEEE International Conference on Robotics and Automation, May 19–23, 2008, Pasadena, California, USA and at the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, November 3–7, 2013, Tokyo, Japan. This paper was recommended for publication in revised form by Associate Editor Antonio Loria under the direction of Editor Andrew R. Teel.

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http://dx.doi.org/10.1016/j.automatica.2015.01.015
0005-1098/

whole-body compliance control concepts utilizing joint torque sensing (Dietrich, Wimböck, Albu-Schäffer, & Hirzinger, 2012a; Dietrich et al., 2012b). Several works treated the problem of prioritized multi-task control at the kinematic level. Chiaverini (1997) proposed a singularity-robust inverse kinematics for a simple hierarchy of two tasks. Antonelli (2009) provided a stability proof for prioritized closed-loop inverse kinematics. However, only the kinematic case was covered in that work. Another issue in the context of hierarchy-based control is the occurrence of discontinuities in the control law due to a change in the rank of the Jacobian matrices or in the inequality constraints. Mansard et al. have dealt with these issues in Mansard, Khatib, and Kheddar (2009). In Ott, Kugi, and Nakamura (2008), we have presented a stability analysis for a null space compliance controller with a simple hierarchy of two priority levels. A primary Cartesian task is inertially decoupled from a null space task by proper choice of coordinates, and asymptotic stability is shown utilizing semi-definite Lyapunov functions. The dynamics formulation is based on Park (1999), where the primary task coordinates are augmented by appropriate dynamically consistent null space velocities. As a result, the inertia matrix of the error dynamics becomes block-diagonal which corresponds to a decoupling of the kinetic energies related to the priority levels. A similar dynamics formulation was also utilized by Oh (Oh, Chung, & Youm, 1998) for the implementation of an impedance controller. The stability analysis, however, was limited to null space damping. The non-integrability of the null space velocities represents a major obstacle for such a stability analysis (Ott et al., 2008).

Recently Nakanishi et al. compared eight established OSF controllers from a theoretical and empirical perspective (Nakanishi et al., 2008). Although exponential stability can be shown for the main task the authors state that "*null space dynamics so far resist insightful general analytical investigations* (…) *If stability could be proven for this family of operational space controllers, operational space control would be lifted to a more solid foundation*". Control approaches for the tracking problem of redundant manipulators have been proposed lately, which also enable a stability analysis of the null space error. The subtask convergence is handled by a kinematic approach and the resulting joint velocity is utilized within a task space controller (Sadeghian, Keshmiri, Villani, & Siciliano, 2012; Zergeroglu, Dawson, Walker, & Setlur, 2004). An extended OSF approach with stable null space posture control was presented in Sentis, Petersen, and Philippsen (2013). In all these works the tracking problem in the absence of external forces was considered.

Here, we extend the work initiated in Dietrich, Ott, and Albu-Schäffer (2013) and Ott et al. (2008). In Ott et al. (2008), null space compliance control was proposed, which utilizes a decoupling control action to separate a high priority task from one null space task. In Dietrich et al. (2013), we considered a hierarchy of multiple prioritized tasks. Here we condense these works, reduce them to the essential, compare them to the state of the art, and discuss the stability properties. Experiments on a torque-controlled robot validate the results. Our first contribution is the derivation of a dynamics formulation which features a hierarchical decoupling between the tasks. Based on this formulation, we implement a compliance controller for all priority levels, which does *not require feedback of external forces* and inertia shaping. Our second contribution is the stability analysis of the closed-loop system via semi-definite Lyapunov functions. This analysis is based on passivity theory and is made possible thanks to the specific dynamics representation. To the best of our knowledge, it is the first stability proof for a complex hierarchy with an arbitrary number of priority levels.

The article is organized as follows: after the problem formulation in Section 2, the hierarchical dynamics is derived in Section 3. Section 4 addresses the control design. Section 5 contains the stability analysis and the discussion to compare the approach to the state of the art. Section 6 shows experiments on a torque-controlled robot.

2. Problem formulation

2.1. Multi-task compliance control

The dynamic equations of a robot with n DOF can be written as

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} + \boldsymbol{\tau}^{\text{ext}}. \quad (1)$$

The symmetric, positive definite inertia matrix is given by $\boldsymbol{M}(\boldsymbol{q}) \in \mathbb{R}^{n\times n}$ and depends on the joint configuration $\boldsymbol{q} \in \mathbb{R}^n$. Coriolis and centrifugal effects are represented by $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} \in \mathbb{R}^n$, gravitational effects are taken into account by $\boldsymbol{g}(\boldsymbol{q}) \in \mathbb{R}^n$. The generalized forces $\boldsymbol{\tau} \in \mathbb{R}^n$ are considered as the control inputs, $\boldsymbol{\tau}^{\text{ext}} \in \mathbb{R}^n$ denotes the external forces. The term $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ complies with the property $\dot{\boldsymbol{M}}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})^T$, which is equivalent to the skew symmetry of $\dot{\boldsymbol{M}}(\boldsymbol{q},\dot{\boldsymbol{q}}) - 2\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$.

We introduce r task coordinate vectors defined via the mappings $\boldsymbol{x}_i = \boldsymbol{f}_i(\boldsymbol{q}) \in \mathbb{R}^{m_i}\ \forall\ 1 \le i \le r$. These tasks with the respective dimensions m_i are arranged in a hierarchical order. The priority levels are defined such that $i = 1$ is top priority and $i_a < i_b$ implies that i_a is located higher in the priority order than i_b. The mappings from joint velocities to task velocities are given by the Jacobian matrices $\boldsymbol{J}_i(\boldsymbol{q}) \in \mathbb{R}^{m_i\times n}\ \forall 1 \le i \le r$:

$$\dot{\boldsymbol{x}}_i = \boldsymbol{J}_i(\boldsymbol{q})\dot{\boldsymbol{q}}, \quad \boldsymbol{J}_i(\boldsymbol{q}) = \frac{\partial \boldsymbol{f}_i(\boldsymbol{q})}{\partial \boldsymbol{q}}. \quad (2)$$

All Jacobian matrices are assumed to be of full row-rank. The primary task is supposed to have the dimension $m_1 < n$ so that a kinematic redundancy of $n - m_1$ DOF remains to accomplish the subtasks in its null space. We aim at a prioritized compliance control and define a task hierarchy which complies with the following conditions:

(1) A task of priority i_b may not disturb any task of priority i_a where $i_a < i_b$. Lower-priority tasks are executed in the null space of *all* higher-priority tasks.
(2) Each control task can be described by a p.d. potential function $V_i(\tilde{\boldsymbol{x}}_i(\boldsymbol{q}))$ w.r.t. $\tilde{\boldsymbol{x}}_i = \boldsymbol{x}_i - \boldsymbol{x}_{i,d}$ with the desired equilibrium $\boldsymbol{x}_{i,d}$. The damping is specified by a p.d. damping matrix $\boldsymbol{D}_i(\boldsymbol{q}) \in \mathbb{R}^{m_i\times m_i}$.
(3) The dimension m_r of the lowest level task may be larger than $n - \sum_{i=1}^{r-1} m_i$ so that the dimension n of the joint space is exceeded by the total dimension of all tasks. A typical example of this would be a joint level compliance on the lowest priority level.

2.2. Relation to the operational space formulation

Some important properties of the OSF (Khatib, 1987) shall be reviewed for which also an extension to multiple prioritized tasks exists (Sentis & Khatib, 2005). We limit our discussion mainly to the issue of inertia shaping related to the main task and refer to Nakanishi et al. (2008) for a more exhaustive analysis of different OSF controllers and their extension to kinematically redundant robots. The main objective is a decoupled dynamics on level one. In case of interaction control, the desired dynamics takes the form

$$\boldsymbol{\Lambda}_d\ddot{\tilde{\boldsymbol{x}}}_1 + \boldsymbol{D}_d\dot{\tilde{\boldsymbol{x}}}_1 + \boldsymbol{K}_d\tilde{\boldsymbol{x}}_1 = \boldsymbol{F}_1^{\text{ext}}, \quad (3)$$

where $\boldsymbol{\Lambda}_d$, $\boldsymbol{D}_d$, and $\boldsymbol{K}_d$ are the desired inertia, damping, and stiffness matrix. The external force $\boldsymbol{F}_1^{\text{ext}}$ in the task space is collocated to $\dot{\boldsymbol{x}}_1$. For position control as discussed in Khatib (1987), one usually chooses $\boldsymbol{\Lambda}_d = \boldsymbol{I}$ and omits the external force on the right hand