Multi-Priority Control in Redundant Robotic systems; an Application to Physical Human-Robot Interaction

Hamid Sadeghian
h.sadeghian@me.iut.ac.ir
March 2013
Department of Mechanical Engineering
Isfahan University of Technology, Isfahan 84156-83111, Iran

Mehdi Keshmiri*, mehdik@cc.iut.ac.ir (Supervisor)
Mohammad J. Sadigh†, jafars@cc.iut.ac.ir (Advisor)
Luigi Villani‡, luigi.villani@unina.it (Advisor)
Bruno Siciliano§, bruno.siciliano@unina.it (Advisor)
Department Graduate Program Coordinator

Abstract
This research presents a dynamic level control algorithm to meet simultaneously multiple desired tasks based on their allocated priorities for redundant robotic systems. It is shown that this algorithm can be treated as a general framework to achieve control over the whole body of the robot. The control law is an extension of the well-known acceleration based control to redundant robots, and considers also possible interactions with the environment at any point of the robot body. The stability of this algorithm is proven and some of the previously developed methods are formulated using this approach. To control the interaction on the robot body, null space impedance control is developed within the multi-priority framework. Furthermore, the problem of task space control, while guaranteeing a compliant behavior for the redundant degrees of freedom, is considered. This issue may arise in the case where the robot experiences an interaction on its body, especially in the presence of humans. The proposed approach guarantees accurate task execution and compliance of the robot body during intentional or accidental interaction, simultaneously. The asymptotic stability of the task space error is ensured by using suitable observers for estimating and compensating the generalized forces acting on the task variables, without using joint torque measurements. Two different controller-observer algorithms are designed based on the task space error and the generalized momentum of the robot. The performance of the proposed algorithms is evaluated by numerical simulations as well as experiments on a 7R KUKA lightweight robot arm.

Keywords: Redundant robots, Multi-priority control, Null space impedance control, Physical human-robot interaction

I. INTRODUCTION

Robots are termed kinematically redundant when they possess more degrees of freedom than those necessary to achieve a desired task. Redundant degrees of freedom can be conveniently used to perform some additional tasks besides the main task. These additional tasks can be a performance objective or for example a given Cartesian position of a point on the body of robot.
In order to solve the conflict between tasks in the case where several tasks are going to be satisfied simultaneously, the so-called task priority strategy was developed. This formulation uses first-order differential kinematics equation and solves redundancy in the Least-Squares (LS) sense, based on the assigned priority by resorting to pseudo-inverse solution.

New applications where robots are employed near humans are growing rapidly. Unlike the industrial robots, which are stiff to guarantee high precision, the robots used in anthropic environments must be designed with high degree of compliance. This is especially true for the applications requiring physical Human-Robot Interaction (pHRI), not only because of unexpected impacts of robots with humans, but also for the execution of collaborative tasks requiring intentional exchange of forces. Safe human-robot coexistence can be guaranteed combining different strategies. The safest approach is to avoid any unwanted collision. This, however, can be achieved using exteroceptive sensors such as cameras that are ineffective in the case of fast interaction. Hence, appropriate collision detection and reaction strategies must be adopted. Suitable observers can be used to estimate the collision forces from joint positions or torques. In any cases, robot compliance must be increased in order to reduce the interaction forces. Compliance can be introduced passively by using elastic decoupling between the actuator and the driven link with fixed or variable joint stiffness, or actively by relying on fast control loops. Impedance control represents an effective approach for controlling actively the robot's compliance during the interaction. The problem of impedance control has been extensively studied in the literature. The compliant behavior usually is given to the task variables to control the interaction of the end effector. However, the impedance behavior can be also imposed to the joint variables to enhance safety.

This thesis contributes to multi-priority control at the acceleration level for redundant robotic systems and establishes a general framework to achieve dynamic control over the whole body of the robot. It is shown that by proper choice of the additional tasks, besides preserving the stability of the internal motion, it is possible to derive some of the previous results in the literature within this framework. Specifically, the Hsu's controller and Khatib’s hierarchical control algorithm are reformulated. To cope with algorithmic singularities a possible solution is also presented.

As a result of task prioritization, the so-called null space impedance control is introduced to handle the physical interaction between robot and the environment (human). The approach is motivated by the need of having control over the interaction of the robot body with the environment in the joint space in spite of the task space control. It is shown that, in order to ensure impedance behavior as the secondary task without affecting the main task, the external forces acting on the main task variables must be suitably compensated by the controller. This is possible, e.g., if the external torques are measured or estimated. In the case that this estimations are not available, any interaction on the robot body affects the main task. An example of application scenario is depicted in Fig. 1, where a robot working on a table experiences a contact with a human. This contact may produce errors on the main task of the robot. The goal is to minimize the error of the main task and at the same time, to ensure safe interaction through active compliance in the null space of the main task. To this purpose, two control approaches which do not require direct joint torque measurements are proposed. The first scheme is based on a disturbance observer which estimates the external forces acting on the task variables on the
basis of the task space error. The second scheme relies on the momentum-based observer. In both cases, the overall stability of the systems are shown through rigorous analysis.

Almost all of the proposed methods are verified numerically and experimentally on a 7DOF KUKA LWR4 robot.

II. RESULTS AND DISCUSSION

A. Multi-priority Control at Acceleration Level; A General Framework

The goal of dynamic multi-priority control is to derive a control torque which will cause the system to track the desired main task exactly, while, at the same time, system redundancy is exploited to realize a number of sub-tasks according to some desired priorities.

The dynamic model of a robot manipulator can be written in compact form as

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) + \tau_{\text{ext}} = \tau, \]  

with known notation. In this formulation, \( \tau_{\text{ext}} \) is the external torque resulting from any interaction on the manipulator. For given task space command accelerations \( \ddot{x}_c, \ddot{x}_s \), the corresponding solution for the joint space command acceleration \( \ddot{q}_c \), is given by

\[ \ddot{q}_c = J_c^T(\ddot{x}_c - J_c \dot{q}) + J_c^T [\dddot{x}_c - J_c \ddot{q} - J_c J_c^T (\dddot{x}_c - J_c \dddot{q})] + N_c \eta, \]  

where

\[ J_c = J_2 N_1, \]
\[ N_2 = \prod_{j=1}^{L} (I - J_j^T J_j). \]

The basic issue in this formulation is the differential order at which resolution takes place. The general solution for \( L \) tasks also can be extended [1], [2].

Once the command acceleration \( \ddot{q}_c \) is obtained, well-known concept of inverse dynamics can be used to find the driving torques

\[ \tau = M(q)\ddot{q}_c + C(q, \dot{q})\dot{q} + g(q) + \tau_{\text{ext}}, \]
In this equation, \( \tau_{\text{ext}} \) is the vector of measured or estimated external torques acting on the robot. Under the assumption of perfect torque measurement, we have, \( \tau_{\text{ext}} \approx \tau_{\text{car}} \).

Equation (2) and (4) can be treated as a general framework to control the whole behavior of the redundant robotic system by multiple priorities and even multi-point control. A nice property of (2) is that, if desired, it can be easily used for any kind of force motion control by a proper choice of the operational command acceleration. This kind of formulation can explain the previously proposed acceleration level resolution techniques in the framework of task prioritization by a proper choice of sub-tasks.

The closed-loop behavior of the system in the main task space is obtained as

\[
J_i J_i^T [\dot{x}_i - \dot{x}_i^c] = 0,
\]

which, under the full rank assumption for \( J_i \), gives \( \dot{x}_i = \dot{x}_i^c \). The closed-loop equation for \( i \)-th subtask is obtained as

\[
J_i J_i^T [\dot{x}_i - \dot{x}_i^c] = 0,
\]

which ensures the minimization of \( ||\dot{x}_i - \dot{x}_i^c|| \) subject to all higher priority tasks. Thus, if \( i \)-th task is independent from all higher priority tasks and thus \( J_i \) is full rank, this sub-task is correctly executed. In other case, when \( J_i \) is not full rank, the \( i \)-th task is not performed completely and just the above norm minimization is performed with respect to all higher priority tasks.

Note that, if the rank of the overall augmented Jacobian is lower than the number of joints coordinate \( n \), then the residual null space velocity must be controlled to avoid unstable behavior. Without loss of generality, let us assume that only one task (the main task) is assigned, and the null space of \( J_i \) is non empty. To ensure the stability of the null space velocity, let us choose \( \xi \) in (7) which ensures the minimization of \( ||\dot{x}_i - \dot{x}_i^c|| \) subject to all higher priority tasks. Thus, if \( i \)-th task is independent from all higher priority tasks and thus \( J_i \) is full rank, this sub-task is correctly executed. In other case, when \( J_i \) is not full rank, the \( i \)-th task is not performed completely and just the above norm minimization is performed with respect to all higher priority tasks.

\[
\dot{q}_e = J_i^T (\dot{x}_i - \dot{J}_i \dot{q}) + N_i [\dot{x}_i^c - \dot{N}_i \dot{q}].
\]

By the above command acceleration, the closed-loop equation for the sub-task from (22) is given by

\[
N_i [\dot{e}_y + K e_y] = 0,
\]

where \( e_y = N_i (\xi - \dot{q}) \) is the null space velocity error. The above equation does not guarantee that \( e_y \) goes to zero, since \( N_i \) is not full-rank. The stability of this closed-loop is shown in [2].

In conclusion, the internal stability is guaranteed in the same multi-priority framework, by a simple choice for the lowest priority task. In the above equations, one can choose \( \xi = 0 \), and thus as long as manipulator avoids singularity, null space velocity will go to zero.

It is worth to observe that the null space command acceleration \( \phi_{\text{ns}} = N_i [\dot{x}_i^c - \dot{N}_i \dot{q}] \) in (7) which guarantees internal stability, coincides with the null space stabilizing control introduced by Hsu et al. In that paper, the following control acceleration was proposed

\[
\dot{q}_e = J_i^T (\dot{x}_i - \dot{J}_i \dot{q}) + N_i [\ddot{\xi} + KN_i (\xi - \dot{q})] - (J_i^T J_i + \dot{J}_i^T J_i) J_i (\xi - \dot{q}).
\]

This equivalence is shown in [2]. Here, by (7) and (8) we give a reasonable intuition behind (9) with a more appealing and simple form.

At the end of this section it is worth to mention that, since the acceleration level formulation is
based on LS, it suffers from high norm solution near algorithmic singularity where projected Jacobians lose rank. A possible solution to treat algorithmic singularity within multi-priority framework in acceleration level has been presented in this research [2].

B. Priority Oriented Adaptive Control

In order to address dynamic uncertainties during multi-priority control, an adaptive control algorithm is presented. This formulation is developed based on velocity level and ensures convergence of the task space error as well as all prioritized subtasks error in the presence of uncertainty in parameters. For more details the reader is referred to [3].

C. Null Space Impedance Control

For a redundant manipulator, it is possible to have some kind of joint impedance and task space impedance simultaneously. Namely, a joint space impedance can be achieved in the null space of the main task as a result of a multi-priority redundancy resolution scheme [2]. Using this approach it is possible to control the interaction both on the end effector and on the robot body. For the null space impedance control, the command joint acceleration \( \dot{\ddot{q}}_c \) is introduced as

\[
\dot{\ddot{q}}_c = \mathbf{J}^T (\dddot{x}_c - \mathbf{J} \dot{\dddot{q}}) + N [\dddot{q}_d + M_d^{-1} (B_d \dddot{q} + K_d \ddot{q} - \tau_{\text{null}})].
\]

Here \( \dddot{x}_c \) is the \((m \times 1)\) command acceleration in the task space with dimension \( m < n \), \( \dddot{q} = \dot{q}_d - q \) where \( q_d(t) \) is the desired configuration in the joint space, \( M_d, B_d \) and \( K_d \) are the impedance matrices and \( \tau_{\text{null}} \) is the vector of the measured external torques acting on the robot.

Applying this command to the system, and by the assumption of perfect torque measurement, \( \tau_{\text{null}} \cong \tau_{\text{ext}} \), produces the task space and null space closed-loop dynamics as follows

\[
\dddot{x} = \dddot{x}_c,
\]

\[
N [\dddot{q} + M_d^{-1} (B_d \dddot{q} + K_d \ddot{q}) - M_d \tau_{\text{ext}}] = 0.
\]

By a proper choice of the null space impedance matrices, it is possible to achieve a desired compliant behavior for the robot body.

Equations (11) and (12) have been obtained in the case that the external torques acting on the manipulator can be directly measured or estimated. When the external torque information is not available, the following closed-loop equations are obtained in place of (11) and (12) as

\[
\dddot{x} = \dddot{x}_c - \mathbf{J} M^{-1} \tau_{\text{ext}},
\]

\[
N [\dddot{q} + M_d^{-1} (B_d \dddot{q} + K_d \ddot{q}) - M_d \tau_{\text{ext}}] = 0.
\]

Note that, by using the dynamically consistent generalized inverse, \( \mathbf{J}^\# = \mathbf{M}^+ \mathbf{J}^T (\mathbf{J} \mathbf{M}^+ \mathbf{J}^T)^{-1} \) in the command acceleration and choosing \( M_d = \mathbf{M} \), the following equation for the null space can be derived,

\[
N^\# [\dddot{q} + B_d \dddot{q} + K_d \ddot{q} - \tau_{\text{ext}}] = 0.
\]

Therefore, a desired compliance can be still achieved in the null space [4].

Equation (15) represents the impedance behavior projected in the null space, with dimension \( n - m \), through \( n \) equations that, therefore, are not all independent. On the other hand, the stability analysis based on these equations is quite difficult. This problem can be overcome by
considering a \((n \times r)\) matrix \(Z(q)\), with \(r = n - m\), such that \(JZ = 0\), and introducing a \((r \times 1)\) velocity vector \(v = (v_1, \ldots, v_r)^T\), such that

\[
\hat{q}_n = N\hat{q} = Zv.
\]

A convenient choice of \(v\) based on (16) is given by left inertia-weighted generalized inverse \(v = Z^\dagger \hat{q} = (Z^T MZ)^{-1} Z^T M\hat{q}\). By choosing \(v\) as second priority task in (2), the command acceleration is obtained as,

\[
\hat{q}_c = J^T(\bar{x}_c - J^T \hat{q}) + Z(\dot{\bar{x}}_c - \dot{Z}^T \hat{q}).
\]

By substituting the above command acceleration in the control law (4) in absence of external torque estimation and applying to the system with dynamic (1), and also by the defining command

\[
\dot{v}_c = \dot{v}_d + A_d^T(B_d \hat{v} + Z^T K_d \hat{q}),
\]

with \(K_d\) and \(B_d\) symmetric and positive definite matrices, \(\hat{v} = v_d - v\) and \(A_d = Z^T M\), the corresponding null space closed-loop is obtained as

\[
A_d \ddot{v} + B_d \dot{v} + Z^T K_d \hat{q} = Z^T \tau_{ext}.
\]

This gives null space impedance behavior in the minimal representation form.

D. Task Space Control during Physical Interaction

In view of the task space dynamics (13), it is clear that any interaction on the body of the manipulator may deviate from the desired task, depending on the choice of the command acceleration [4]. In this thesis, four propositions based on two different approaches are proposed.

Proposition 1: Let us denote with \(\bar{\tau}\) the estimated external torque and with \(\hat{\tau} = \tau_{ext} - \bar{\tau}\) the estimation error. Under the assumption of constant (or slowly time-varying) unknown external torque, for selected constant positive definite matrix \(\Gamma_f\), the control law (4) in the absence of torque estimation, with the joint space command acceleration (17), the null space command acceleration (18) and the task space command acceleration (20) and the task space command acceleration

\[
\ddot{x}_c = \dot{x}_d + P \ddot{x} + A_d^T((\mu_s + K)\dot{x} + J^T \hat{\tau}),
\]

with the disturbance observer

\[
\dot{\hat{\tau}} = -\Gamma_f^{-T} J^T \dot{x},
\]

guarantees that \(\ddot{x}\) and \(\dot{\hat{\tau}}\) go to zero asymptotically while a compliant behavior is imposed in the null space of the main task. Moreover, \(\hat{\tau}\) remains bounded and the closed-loop system is stable.

The controller-observer law in the task space of Proposition 1 can be modified according to Proposition 2 where the command acceleration is based on the PD+ controller written in the task space.

Proposition 2: The command acceleration and disturbance observer in Proposition 1 can be replaced by

\[
\ddot{x}_c = \dot{x}_d + A_d^T((\mu_s + D)\ddot{x} + K\ddot{x} + J^T \hat{\tau}),
\]

and disturbance observer

\[
\dot{\hat{\tau}} = -\Gamma_f^{-T} J^T (\dot{x} + \gamma f(\ddot{x})),
\]
where $\gamma$ is a properly chosen constant positive gain. The stability of whole system, the convergence of $\ddot{x}$ and $\dot{x}$ to zero, and the compliant behavior in the null space of the main task are preserved.

Proposition 3: In the presence of constant (or slowly time-varying) unknown external torque, for positive definite matrices $K_i$ and $K_p$, the control law given by (4), (17), (18) and the task space command acceleration

$$\ddot{x}_c = \ddot{x}_d + K_i \ddot{x} + K_p \dot{x} - A_k J^T \tau,$$

(25)

which leads to the closed-loop equation

$$A_i \ddot{x} + (\mu_c + D) \dot{x} + K \dot{x} = J^T \tau,$$

(28)

This preserves the robot natural dynamics.

Remark: In above propositions, the non-minimal form command acceleration

$$\ddot{q}_c = J^T (\ddot{q} - J \dot{q}) + N_c [\ddot{q}_d + M^{-1} (B \ddot{q} + K \ddot{q})],$$

(29)

can be used instead of (17), which leads to the null space closed-loop behavior (15). Despite this choice seems more intuitive, the stability proof is not easy, since the parameterization of the null space position and velocity errors in (22) is non minimal.

The above propositions were empirically evaluated on KUKA LWR4 robot arm by various experiments [5]. (See Fig. 2 and Fig.3 for example)

E. Global Impedance Control

The global impedance control of dual-arm 7-DOF cooperative manipulators is considered in this section. Global compliant behavior for the whole system is achieved using impedance at three levels. A centralized impedance control strategy is provided to confer a compliant behavior to the object, while an active decentralized impedance control with force tracking is enforced to the end-effectors to control the internal forces on the object. A compliant behavior for the body
of the dual-arm system is obtained by means of null space impedance control. The developed control scheme is verified in a simulation environment composed of two cooperating 7-DOF KUKA lightweight arms carrying a common object [6].

III. CONCLUSION

Acceleration level multi-priority control algorithm has been presented in this thesis. It has been shown how this formulation can be treated as a general framework to achieve control over the whole body of a robot. The generality of the algorithm has been shown by formulating
several control algorithms within a same framework. The internal stability and possible solution to cope with algorithmic singularity during multi-priority control has been demonstrated. Null space impedance control has been proposed as a result of task prioritization. In order to alter task space tracking error during any interaction, two nonlinear controller-observer approaches have been presented. The controllers utilize redundancy of the system to ensure safe and dependable physical interaction without using torque sensors. The experimental results obtained from a torque controlled KUKA LWR4 robot have confirmed the theoretical findings.

SELECTED REFERENCES


