Bimanual Mobile Manipulation Using the Cooperative Dual Task-Space Framework and Vector Fields Inequalities

Juan José Quiroz-Omaña and Bruno Vilhena Adorno

Abstract—**This work proposes a strategy for bimanual manipulation using the cooperative dual task-space framework (CDTS) and constrained kinematic control based on quadratic programming. We use vector fields inequalities (VFI) to prevent undesired end-effector orientations and violation of joints limits. Experiments on a real two-arm mobile manipulator show that the approach allows performing cooperative tasks while respecting all constraints.**

I. Introduction

Multi-arm robotic have several advantages, such as the ability to handle large or heavy objects [1], but the integration of two or more robotic systems is challenging for both modeling and control and, therefore, requires suitable strategies.

Chiacchio et at. [2] propose the cooperative task space for bimanual manipulation directly defining the absolute and relative positions and orientations to represent the cooperative task. Adorno [3] generalizes the cooperative space using dual quaternions and proposes the cooperative dual task-space framework (CDTS). This strategy is free of representational singularities and allows the full description of the manipulation task in terms of the relative and absolute poses by using respectively, the relative pose $\underline{\boldsymbol{x}}_r$ and the absolute pose $\underline{\boldsymbol{x}}_a$, as shown in Fig. 1. This approach has been used in bimanual manipulation and human-robot interaction [4]. Figueredo et al. [5] exploits the kinematic redundancy in the CDTS framework by relaxing task specifications. The authors propose a hysteresis-based switching strategy to ensure stability and convergence to the desired region of interest.

We also explore the kinematic redundancy in the CDTS framework by relaxing task specifications using mathematical programming, which allows dealing with inequality constraints directly in the optimization formulation. We use vector fields inequalities (VFI) [6] and conic constraints [7] to prevent undesired orientations in the manipulated object and violation of joint limits while performing cooperative manipulations.

This work was supported by the Brazilian agencies CAPES, CNPq (424011/2016-6 and 303901/2018-7), FAPEMIG, and by the INCT (National Institute of Science and Technology) under the grant CNPq 465755/2014-3.

J.J. Quiroz Omaña is with the Graduate Program in Electrical Engineering - Federal University of Minas Gerais (UFMG) - Av. Antônio Carlos 6627, 31270-901, Belo Horizonte-MG, Brazil. Email: juanjqo@ufmg.br. B.V. Adorno is with the Department of Electrical Engineering - Federal University of Minas Gerais (UFMG) - Av. Antônio Carlos 6627, 31270-901, Belo Horizonte-MG, Brazil. Email: adorno@ufmg.br.

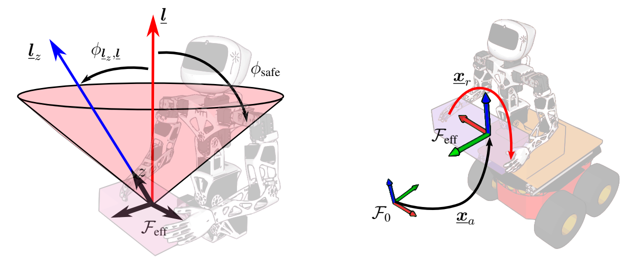

Figure 1. On the *left,* two Plücker lines with a conic constraint that limit the the angle between them. On the *right,* the cooperative dual task-space representation: the absolute variable $\underline{\boldsymbol{x}}_a$ and the relative variable $\underline{\boldsymbol{x}}_r$.

II. Task Space Control

Given a desired task $\boldsymbol{x}_d \in \mathbb{R}^m$, where $\dot{\boldsymbol{x}}_d = \boldsymbol{0}$, $\forall t$, and the task error $\tilde{\boldsymbol{x}} \triangleq \boldsymbol{x} - \boldsymbol{x}_d$, the generation of the control signal $\boldsymbol{u}$ can be written as an optimization problem that minimizes the joints velocities, $\dot{\boldsymbol{q}} \in \mathbb{R}^n$, in the l_2-norm sense, as follows

$$\begin{aligned} \boldsymbol{u} \in \underset{\dot{\boldsymbol{q}}}{\operatorname{argmin}} \quad & \left\| \boldsymbol{J}\dot{\boldsymbol{q}} + \eta\tilde{\boldsymbol{x}} \right\|_2^2 + \lambda^2 \left\| \dot{\boldsymbol{q}} \right\|_2^2 \\ \text{subject to} \quad & \boldsymbol{W}\dot{\boldsymbol{q}} \leq \boldsymbol{w}, \end{aligned} \tag{1}$$

where $\boldsymbol{J} \in \mathbb{R}^{m \times n}$ is the task Jacobian, $\eta \in (0, \infty)$ is a gain, $\lambda \in [0, \infty)$ is a damping factor, and $\boldsymbol{W} \in \mathbb{R}^{l \times n}$ and $\boldsymbol{w} \in \mathbb{R}^l$ are used to impose linear constraints in the control inputs as the vector fields inequalities. Since we use the ℓ_2-norm (i.e., the commonly used Euclidean norm), the control signal is obtained from a local optimization problem. Furthermore, when there are no constraints, the control input generated by the optimization problem (1) is equivalent to the kinematic controller based on the damped least-square inverse (also called singularity-robust inverse) [8].

III. Task Space Specifications

In the CDTS framework, the task specification of the cooperative variables $\underline{\boldsymbol{x}}_r$ and $\underline{\boldsymbol{x}}_a$ requires 12 robot degrees of freedom (DOF). This can be very restrictive in some scenarios depending on the available number of robot DOF or the application. In those cases, it is advantageous to define target regions instead of one specific position and/or orientation, in order to relax the task and, therefore, release some DOF, which can be used to perform additional tasks. For instance, if the goal is to put a tray on a table using both robot arms, we can use the relative pose $\underline{\boldsymbol{x}}_r$ to define the geometric relationship between both end-effectors, thus ensuring the tray integrity, and the absolute pose $\underline{\boldsymbol{x}}_a$ to move it around the workspace. Instead of controlling the absolute pose that requires 6 DOF,

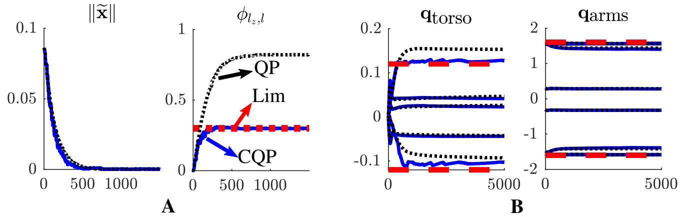

Figure 2. ***A***. On the *left*, norm of the task error. On the *right*, the angle $\phi_{\underline{l}_z,\underline{l}}$ between the plate centerline and a vertical line. ***B***. The joints positions of the torso and both arms. The dashed red line denotes the joints limits. The horizontal axis corresponds to iterations.

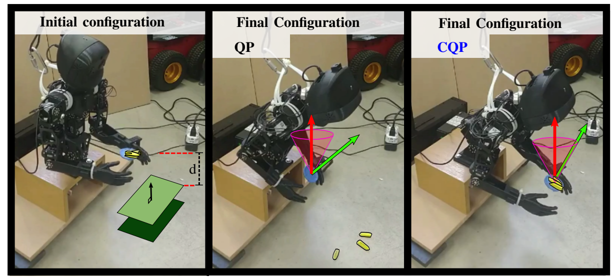

Figure 3. On the *left*, the robot grasps a (virtual) snack plate. The infinite green plane denotes the desired region. On the *middle,* the final robot configuration using the unconstrained controller. The red cone denotes the maximum allowed plate orientation. On the *right,* the final robot configuration in the constrained case.

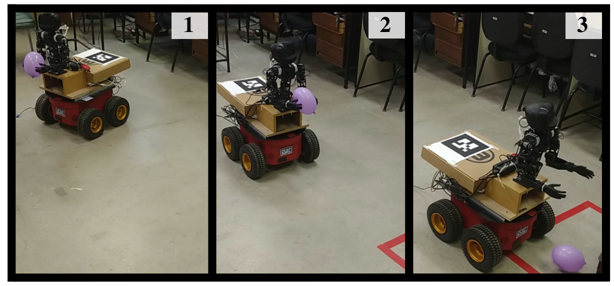

Figure 4. Snapshots of the second experiment. The mobile two-arm manipulator grasps the ball and takes it to the desired point.

we can control only the absolute distance d_a, which requires one DOF, while ensuring that the plate is not too tilted to prevent dropping its contents by using a conic constraint [7], which requires one more DOF (if the constraint is activated) as shown in Fig. 1. In this way, instead of performing a 12-DOF task, we relax it to a 8-DOF task, namely 6 DOF required by the relative variable plus up to 2 DOF required by the absolute variable.

IV. Experimental Results

We performed two experiments using ROS, Python and DQ Robotics [9], which was used for both robot modeling and the description of the geometric primitives. We set the control loop rate to 50Hz due to low-level drivers limitations. We implemented two controllers: the Quadratic-Program (QP), which does not take into account constraints, and the Constrained Quadratic-Program (CQP), which does. Both controllers are based on (1) and we use quadprog[1] to solve them.

In the first experiment, whose setup is shown in Fig. 3, we used the upper body of the Poppy humanoid robot,[2] which is composed of a 5-DOF torso and two 4-DOF arms. The goal is to manipulate a (virtual) snack plate using both robot hands and minimize the distance to a green plane that is at a distance $d = 0.08m$ from the initial location. This task requires 6 DOF to control $\underline{\boldsymbol{x}}_r$ and one DOF to minimize the absolute distance d_a, that is, the distance between the origin of the absolute frame, given by $\underline{\boldsymbol{x}}_a$, and the plane. We enforced a conic constraint to keep the plate tilting $\phi_{\underline{l}_z,\underline{l}}$ below a threshold, denoted as $\phi_{\text{safe}} = 0.3\,\text{rad}$, which requires, when activated, one more DOF.

Figure 2*A* shows that, in both cases, the task is fulfilled with the same convergence rate. Nevertheless, the angle constraint is respected only in the constrained case, as expected.

We performed a second experiment, whose setup is shown in Fig. 4, using the upper body of the Poppy humanoid robot serially coupled to a mobile platform. The goal is to put a ball on a desired point using both robot hands. As in the previous experiment, the task requires 6 DOF to control $\underline{\boldsymbol{x}}_r$ and one DOF to minimize the absolute distance d_a. We enforce 13 conic constraints, one for each joint [7], in order to avoid violating joint limits.

Figure 2*B* shows that only in the constrained case the controller respected all joint limit constraints.

[1]https://pypi.org/project/quadprog/

[2]https://www.poppy-project.org/en/robots/poppy-humanoid

V. Conclusions

This work implemented whole-body control strategies based on the cooperative dual task-space framework and vector fields inequalities. This allows for cooperative manipulations and task relaxation. We evaluated the proposed method on a real platform and the results showed that the robot always prevents undesired orientations and respects the joint limit constraints while performing cooperative tasks. Future works will be focused on the implementation on a full humanoid with balance tasks and cooperative tasks with more robots.

References

[1] F. Caccavale and M. Uchiyama, "Cooperative Manipulators," in *Springer Handbook of Robotics*. Springer, 2008, ch. 29, pp. 701–718.

[2] P. Chiacchio, S. Chiaverini, and B. Siciliano, "Direct and Inverse Kinematics for Coordinated Motion Tasks of a Two-Manipulator System," *J. Dyn. Syst. Meas. Contr.*, vol. 118, no. 4, pp. 691–697, dec 1996.

[3] B. V. Adorno, "Two-arm Manipulation: From Manipulators to Enhanced Human-Robot Collaboration," PhD thesis, Université Montpellier 2, 2011.

[4] B. V. Adorno, a. P. L. Bó, and P. Fraisse, "Kinematic modeling and control for human-robot cooperation considering different interaction roles," *Robotica*, vol. 33, no. 2, pp. 314–331, feb 2015.

[5] L. Figueredo, B. Adorno, J. Ishihara, and G. Borges, "Switching Strategy for Flexible Task Execution using the Cooperative Dual Task-Space Framework," in *IEEE/RSJ IROS*. Chicago: IEEE, 2014, pp. 1703–1709.

[6] M. M. Marinho, B. V. Adorno, K. Harada, and M. Mitsuishi, "Active Constraints Using Vector Field Inequalities for Surgical Robots," in *IEEE ICRA*. IEEE, may 2018, pp. 5364–5371.

[7] J. J. Quiroz-Omana and B. V. Adorno, "Whole-Body Control With (Self) Collision Avoidance Using Vector Field Inequalities," *IEEE Rob. Autom. Lett.*, vol. 4, no. 4, pp. 4048–4053, oct 2019.

[8] Y. Nakamura and H. Hanafusa, "Inverse Kinematic Solutions With Singularity Robustness for Robot Manipulator Control," *J. Dyn. Syst. Meas. Contr.*, vol. 108, no. 3, p. 163, 1986.

[9] B. V. Adorno and M. M. Marinho, "DQ Robotics: a Library for Robot Modeling and Control Using Dual Quaternion Algebra," oct 2019. [Online]. Available: http://arxiv.org/abs/1910.11612