Control Strategies for the Task Definition of Constrained Bimanual Manipulation

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Seyonne Leslie-Dalley, Keir Groves, Bruno Vilhena Adorno

***Abstract*—This work describes two use-cases to present strategies for the definition of constrained bimanual manipulation tasks. We use the cooperative dual task-space (CDTS) framework, vector field inequalities (VFIs) and geometric primitives such as Plücker lines and planes to implement collision avoidance with the environment and preserve the integrity of the task. Simulations of the use-cases were carried out and showed that all implemented constraints were upheld through the execution of the bimanual manipulation task.**

I. Introduction

Cooperative control of two or more manipulators allows for the completion of a broader range of tasks that would have otherwise been infeasible for a single manipulator [1]. Although a suitable control strategy is required to fulfill the cooperative task, it is also essential that a collision avoidance technique is implemented to ensure the safety of the manipulators and preserve the manipulated object [2].

Marinho *et al.* [3] developed a novel method for implementation of explicit constraints directly in closed-loop control laws using Vector Field Inequalities (VFIs), preventing robots from entering restricted regions or alternatively being enclosed in a safe region. Their framework used dual quaternion algebra due to the advantages it has over other representations, such as being compact, free from representational singularities, and able to represent several geometric primitives straightforwardly [4]. Quiroz-Omaña and Adorno [5] coupled the methods in [3] with the Cooperative Dual Task Space (CDTS) framework proposed in [6] to prevent the violation of joint limits and undesired end-effector orientations whilst completing bimanual manipulation tasks on a two-arm mobile manipulator.

Similar to [5], we also use the CDTS framework and VFIs. However, instead this work presents two use-cases of parallel coordinated bimanual manipulation tasks [7]. The use-cases present how these methods can be applied to two fixed-base manipulators so that they can complete a cooperative manipulation task while explicitly accounting for constraints related to obstacles as well as end-effector poses.

II. Control Strategy

The closed-loop kinematic controller implements a linearly-constrained quadratic optimization problem where hard constaints such as obstacle avoidance and joint limits are enforced as differential inequalities in the control input. Considering a desired task variable $\boldsymbol{x}_d \in \mathbb{R}^m$ and the task error $\tilde{\boldsymbol{x}} \triangleq \boldsymbol{x} - \boldsymbol{x}_d$, the control input $\boldsymbol{u}$ is obtained from

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

where $\boldsymbol{J} \in \mathbb{R}^{m \times n}$ is the relevant task Jacobian, $\eta \in (0, \infty)$ is the proportional gain that determines the convergence rate, and $\lambda \in (0, \infty)$ is the damping factor used to penalise high joint velocities. In addition, the matrix $\boldsymbol{W} \triangleq \boldsymbol{W} \in \mathbb{R}^{p \times n}$ and the vector $\boldsymbol{w} \triangleq \boldsymbol{w} \in \mathbb{R}^p$ impose p linear constraints on the control input necessary to complete the task.

III. Manipulation Tasks

The following section describes two bimanual manipulation tasks. Each task defined uses primitives from the CDTS framework [6] for task relaxation, thus releasing degrees of freedom (DOFs) to enforce constraints. The constraints are defined using VFIs and geometric primitives such as planes and cones determined by Plücker lines.

A. Carrying and Balancing Objects

The goal is to move an object whilst maintaining a certain orientation, which is useful when moving a tray with a cup while minimising spillages. The desired movement can be defined in respect to a translation of the held object with a bounded orientation, whilst the relative pose of the end-effectors is kept constant to hold the object. This task can be split into two main sub-tasks:

1) Maintaining contact with the object.
2) Maintaining the cup orientation below a threshold to prevent spillage.

Firstly, to ensure the relative pose $\boldsymbol{x_r}$ is constantly kept within a threshold, the following inequality is defined,

$$2\left(\boldsymbol{x}_r - \boldsymbol{x}_{r_d}\right)^T \boldsymbol{J}_r \dot{\boldsymbol{q}} \leq -\eta\left(\|\boldsymbol{x}_r - \boldsymbol{x}_{r_d}\|_2^2 - d_{\max}\right),$$

where $\boldsymbol{x}_r$ and $\boldsymbol{x}_{r_d}$ denote the current relative pose and the desired relative pose, $\boldsymbol{J}_r$ denotes the Jacobian of the relative pose and $d_{\max}$ is the maximum allowed deviation from the desired relative pose. This is then implemented as an inequality constraint in the controller (1). Secondly, the cup orientation is constrained by defining two Plücker lines—one always vertical passing through the center of the held object and the other dynamic—and constraining the angle between them by using a conic constraint [8], as shown in Fig. 1a.

All authors are with the Manchester Centre of Robotics and AI at the University of Manchester. E-mails: seyonne.leslie-dalley@postgrad.manchester.ac.uk, keir.groves@.manchester.ac.uk, and bruno.adorno@.manchester.ac.uk.

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B. Carrying and Transporting Large/Heavy Objects

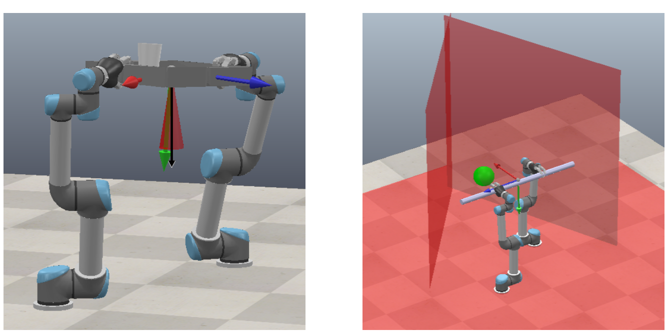
To transport an object to a desired region while avoiding collisions with the environment, the task variable can be defined similar to III-A. Alternatively, it can be defined by minimising the distance between the object and a defined region. Similar to III-A, a relative pose error inequality is also defined to maintain contact with the object.

Assuming walls and the floor are modelled using planes, then VFIs can be used for collision avoidance by describing the distance functions between planes and the collidable entities (e.g., cylinders, spheres, cuboids) associated with the transported object and their corresponding distance Jacobians [3].

IV. Simulations and Discussions

We performed simulations of manipulation tasks described in Sections III-A and III-B. The tasks were simulated using CoppeliaSim[1] for visualisation and DQ Robotics [9] to model and control the manipulators and define the geometric primitives used in the constraints. The setup for the simulations are shown in Fig. 1, where two UR5 manipulators with six DOFs were used to complete the bimanual manipulation tasks. For the task of balancing an object, the maximum angle the tray is allowed to tilt is $\phi_{\max} = 0.05\,\mathrm{rad}$, and the maximum deviation from the relative pose is $d_{\max} = 0.03$ to prevent deforming the tray. For the task of moving an object shown in Fig. 1b, the safe distance from the walls represented by red planes are given by $d_{\text{wall}} = 0.05\,\mathrm{m}$ and the maximum deviation from the relative pose is given by $d_{\max} = 0.03$.

Fig. 2 shows that the conic constraint and the relative pose error constraint were respected during the execution of the carrying-and-balancing an object task. Additionally, Fig. 3 shows that for the transportation task both the relative distance and the plane constraints were upheld, as expected.



(a) Balancing an object. (b) Transportation of an object.

Fig. 1. In *(a)*, the angle between the black vertical Plücker line and the one collinear with the green arrow must be smaller than the half-angle of the red cone to prevent spillage. In *(b)*, the green sphere defines the desired region for the centre of the object, and the red planes define walls and the floor in the environment.

V. Conclusion

This work described two use-cases to present strategies for defining bimanual manipulation tasks using VFIs. Simulations of the use-cases have shown that constraints are enforced throughout the task execution. Future works will focus on developing the CDTS framework to include the extension proposed by [7] to represent both coordinated and uncoordinated bimanual manipulation tasks and further implement constraints within the extended framework.

[1] https://www.coppeliarobotics.com/coppeliaSim

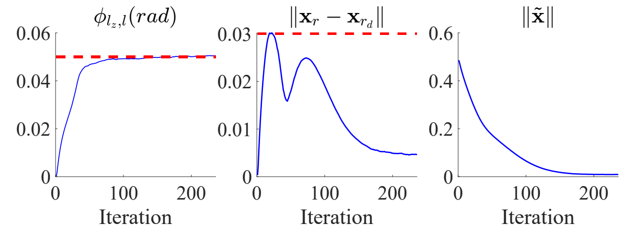


Fig. 2. From left to right: the tilting angle with respect to a vertical line; norm of the relative pose error; norm of the task error. Dashed lines represent the constraints.

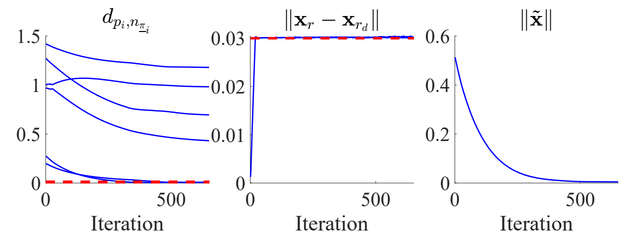


Fig. 3. From left to right: the distance from either end of the object to the two walls and the floor; norm of the relative pose error; norm of the task error. Dashed lines represent the constraints.

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