Practicalities of Symmetric vs. One-Side-Dominant Absolute Task Control in Bimanual Robots

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Abstract. Control of bimanual robot tasks can be implemented in different manners. When considering such tasks, it is not uncommon to exploit their combined kinematic structure and separate the control in absolute and relative motion. The reference point for the absolute motion can be set at a desired point, however, despite similarities in the derivation of the kinematic control and the behavior itself, the selection of the absolute pose reference point can result in different behavior and different interface for bimanual collaborative tasks. In this paper we explore practical differences when applying bimanual symmetric and one-side-dominant control and the effects it has on the interface with a person operating such setups.

Keywords: bimanual robot · dual-arm robot · symmetric control · absolute and relative task

1 Introduction and Related Work

Symmetric control of a dual-arm or bimanual robot system considers both arms, i.e., robots, as a single system. Such control architecture can be used to fully characterize the operational space and allow specification of the task in relative and absolute coordinates, resulting in geometrically meaningful motion variables defined at both the position and the orientation levels [1]. This type of control can be used, for example, in a human-robot cooperation scheme, as shown, e.g., in [2]. The essence is in separately defining the gains for absolute and relative motion, which define the behavior when an operator physically interacts with the robots. The literature lists other physical human-robot interaction schemes, for example, in [3–5].

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However, there are different options in implementing symmetric control of bimanual tasks, as the absolute pose of the bimanual robot can be defined practically arbitrarily. For example, the absolute pose of the robot can be defined as a point between the two arms of the dual-arm system, making it a shared quantity between them [6]. The other option is that the absolute pose of the system is defined as a variable that depends only on one, dominant arm [7]. In such a case, the other arm only adjusts its motion to maintain a relative pose. While both these instances have been described in the literature, see, e.g. [8–10], in this paper we explore the practical implications of symmetric vs. one-side-dominant bimanual task control, specifically for physical human-robot interaction. Our implementation with two KUKA iiwa robots is shown in Fig. 1.

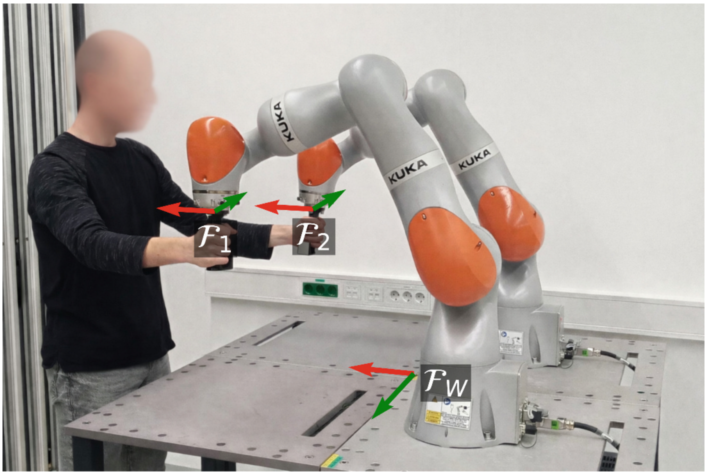


Fig. 1. Experimental setup consisting of two KUKA LBR iiwa 14 manipulators during a physical human-robot interaction task.

As stated in [11], defining the gains of absolute and relative robot behavior has considerable effect on the behavior of the system when operated through physical interaction. Besides defining the gains, the behavior of the system also relies on the determination of the absolute task pose, and it can significantly influence the reactions of the operator, specifically if the behavior is not intuitive.

In the following sections, we first define the kinematic and dynamic framework for bimanual systems, establishing the mathematical basis for both symmetric and one-side-dominant formulations. Next, we detail the Cartesian impedance control architecture used to implement these tasks on our experimental setup. This is followed by the experimental evaluation comparing the two formulations, specifically analyzing the temporal position response and the resulting torque-error relationship during physical interaction. Finally, we discuss the practical implications of these results regarding actuator loading, control stiffness, and task-specific suitability in human-robot collaboration.

2 Problem Formulation

All experiments were conducted on a physical bimanual robotic system composed of two KUKA LBR iiwa 14 manipulators. The manipulators are rigidly mounted in a common workspace, and all links are assumed rigid. Coordination between the manipulators is achieved solely through external control.

2.1 System Description

Let robot $i \in \{1, 2\}$ have joint coordinates $\mathbf{q}_i \in \mathbb{R}^{n_i}$, with n denoting the number of joints. The pose of each end-effector with respect to a fixed inertial frame $\mathcal{F}_W$ is denoted by

$$\mathbf{T}_i = \begin{bmatrix} \mathbf{R}_i & \vec{p}_i \\ \mathbf{0} & 1 \end{bmatrix} \in \mathrm{SE}(3), \tag{1}$$

where $\vec{p}_i \in \mathbb{R}^3$ is the position and $\mathbf{R}_i \in \mathrm{SO}(3)$ is the orientation[i]. The corresponding spatial twist is

$$\vec{\xi}_i = \begin{bmatrix} \vec{v}_i \\ \vec{\omega}_i \end{bmatrix} = \mathbf{J}_i(\mathbf{q}_i)\,\dot{\vec{q}}_i, \tag{2}$$

where $\mathbf{J}_i \in \mathbb{R}^{6\times n_i}$ is the geometric Jacobian of robot i. For convenience, the joint coordinates and Jacobians of the bimanual system in relative and absolute task space are stacked as

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_1 \\ \mathbf{q}_2 \end{bmatrix}, \quad \mathbf{J} = \begin{bmatrix} \mathbf{J}_{\mathrm{rel}} \\ \mathbf{J}_{\mathrm{abs}} \end{bmatrix} \tag{3}$$

where the relative Jacobian is defined as $\mathbf{J}_{\mathrm{rel}} = \begin{bmatrix} -\mathbf{J}_1 & \mathbf{J}_2 \end{bmatrix}$. The absolute Jacobian $\mathbf{J}_{\mathrm{abs}}$ can be defined differently depending on the task definition; two possible definitions are given in Eqs. 7 and 9.

2.2 Absolute and Relative Task Decomposition

Bimanual manipulation tasks are commonly decomposed into:

1. **Relative task:** controls the pose of one end-effector with respect to the other, and captures internal constraints such as grasp geometry or object rigidity.
2. **Absolute task:** governs the global motion of the bimanual system in the workspace.

The relative pose is expressed in terms of relative position and relative orientation as:

$$\vec{p}_{\mathrm{rel}} = \vec{p}_2 - \vec{p}_1, \quad \mathbf{R}_{\mathrm{rel}} = \mathbf{R}_1^\top \mathbf{R}_2 \tag{4}$$

[i] The subscript ^{w} is omitted for clarity; all vectors/matrices are expressed in the world frame unless otherwise specified.

The corresponding relative task error is

$$\vec{e}_{\mathrm{rel}} = \begin{bmatrix} \mathbf{R}_1 \vec{p}^{\,1}_{\mathrm{rel,d}} - \vec{p}_{\mathrm{rel}} \\ \mathrm{Log}\big(\mathbf{R}_{\mathrm{rel,d}} \mathbf{R}_{\mathrm{rel}}^{\top}\big) \end{bmatrix}, \quad (5)$$

where the subscript $_d$ denotes a desired quantity, and the superscript ^{1} indicates the vector is expressed in robot 1's end-effector frame and mapped to the world frame via $\mathbf{R}_1$. Relative task error $\vec{e}_{\mathrm{rel}}$ is expressed in the global frame. The relative task is identical for all formulations considered in this work.

2.3 Symmetric Absolute Task Formulation

In symmetric bimanual control, the absolute task is defined as a shared quantity representing the global motion of the dual-arm system like used in [1,2]. The translational component is[ii]

$$\vec{p}^{\,\mathrm{sym}}_{\mathrm{abs}} = \frac{1}{2}(\vec{p}_1 + \vec{p}_2), \quad (6)$$

and the rotational component is obtained via an appropriate averaging operation on $SO(3)$. The absolute task error is defined same for both formulations as $\vec{e}_{\mathrm{abs}} = \vec{p}_{\mathrm{abs},d} - \vec{p}_{\mathrm{abs}}$, representing the deviation of the bimanual system from its desired global trajectory. The absolute twist and Jacobian at the velocity level are

$$\vec{\xi}^{\,\mathrm{sym}}_{\mathrm{abs}} = \frac{1}{2}\begin{bmatrix}\mathbf{I}_6 \; \mathbf{I}_6\end{bmatrix}\begin{bmatrix}\vec{\xi}_1 \\ \vec{\xi}_2\end{bmatrix}, \quad \mathbf{J}^{\mathrm{sym}}_{\mathrm{abs}} = \frac{1}{2}\begin{bmatrix}\mathbf{J}_1 \; \mathbf{J}_2\end{bmatrix}. \quad (7)$$

2.4 One-Side-Dominant Absolute Task Formulation

In the one-side-dominant formulation (superscript ^{r1}), the absolute task is defined exclusively by a single dominant manipulator, while coordination is enforced through the relative task. This breaks symmetry in task execution and concentrates absolute motion control on one arm [12].

Depending on which arm is selected as dominant, the system can also be described as a coupled asymmetrical left- or right-dominant configuration [8]. The *follower* manipulator primarily adjusts its motion to maintain the desired relative pose between the end-effectors. While the dominant arm also participates in defining the relative task through its motion, the follower actively compensates to enforce the relative constraint, breaking the symmetry of task execution. Without loss of generality, robot 1 is chosen as the leading manipulator :

$$\mathbf{T}^{\mathrm{r1}}_{\mathrm{abs}} = \mathbf{T}_1. \quad (8)$$

[ii] The superscript ^{sym} indicates the symmetric variation of the absolute task; it does not signify the frame of the vector/matrix.

At the velocity level:

$$\vec{\xi}^{\mathrm{r1}}_{\mathrm{abs}} = \vec{\xi}_1, \quad \mathbf{J}^{\mathrm{r1}}_{\mathrm{abs}} = \begin{bmatrix} \mathbf{J}_1 & \mathbf{0} \end{bmatrix}. \tag{9}$$

The follower's contribution is implicit through the relative task, which ensures that the end-effectors maintain the prescribed relative pose while the leader drives the absolute motion.

3 Analysis and Comparison

To evaluate the practical implications of task formulation, we implement a unified control structure. This allows us to isolate the effects of the absolute task definition from other control parameters, such as gain selection or hardware-specific dynamics. The specific implementation details are provided below.

3.1 Control Architecture

Both absolute task formulations - symmetric and one-side-dominant are implemented within the same Cartesian impedance control framework. The control loop runs at a fixed frequency of 500 Hz.

For each formulation, the Cartesian control law computes a desired task-space wrench based on pose and velocity errors:

$$\vec{F} = \mathbf{K}\,\vec{e} + \mathbf{D}\,\dot{\vec{e}}, \tag{10}$$

where $\mathbf{K}$ and $\mathbf{D}$ are diagonal stiffness and damping matrices, task-space error and its derivative are denoted as $\vec{e} = [\vec{e}^{\top}_{\mathrm{abs}}, \vec{e}^{\top}_{\mathrm{rel}}]^{\top}$ and $\dot{\vec{e}} \in \mathbb{R}^6$, comprising absolute and relative components. Identical gain values are used across all experiments and formulations to ensure a fair comparison.

The resulting Cartesian wrench is mapped to joint torques via the Jacobian transpose:

$$\vec{\tau} = \mathbf{J}^{\top}\vec{F}. \tag{11}$$

No null-space objectives or secondary tasks are employed, allowing the effects of the absolute task formulation to be observed directly.

3.2 Absolute Task Tracking Without Relative Constraint

In this scenario, the relative task is disabled to isolate the absolute task's performance. Both the symmetric and one-side-dominant formulations begin from the same nominal configuration and utilize identical impedance control parameters. Rather than following a reference trajectory, the system is perturbed by physically displacing one robot through external interaction. By inducing a comparable magnitude of absolute pose error in both variants, we can examine the system's response to identical deviations without the influence of a predefined motion. Consequently, any observed variations in joint torque distribution arise solely from the underlying mapping of the absolute task to the manipulators.

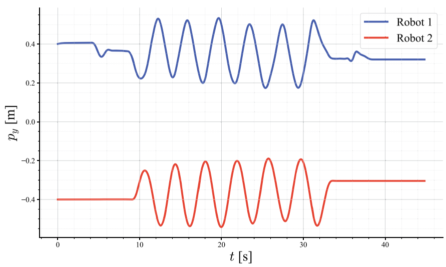
4 Experimental Evaluation

Physical interaction experiments were conducted to compare the formulations, focusing on temporal response and torque-error relationships.

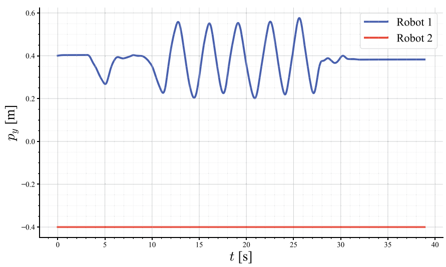
4.1 Temporal Position Response

Figure 2 illustrates the Y-axis position of both end-effectors over time. In the *Symmetric formulation* (Fig. 2a), an external displacement applied to the system results in a synchronized response from both manipulators. Because the absolute position is defined as the mean $\vec{p}_{\text{abs}}^{\text{sym}} = \frac{1}{2}(\vec{p}_1 + \vec{p}_2)$, the control law distributes the restorative wrench across both arms. This results in the movement visible between 10 s and 30 s, where Robot 2 tries to minimize the collective absolute error caused by the perturbation on Robot 1.

In contrast, the *One-side-dominant formulation* (Fig. 2b) shows Robot 1 acting as the sole carrier of the absolute task. While Robot 1 undergoes significant displacement to track the absolute reference, Robot 2 remains stationary at its initial position of −0.4 m. This confirms that under the one-side-dominant definition $\mathbf{J}_{\text{abs}}^{\text{r1}} = \begin{bmatrix}\mathbf{J}_1 & \mathbf{0}\end{bmatrix}$, the joint torques for Robot 2 are decoupled from the absolute task error.



(a) Symmetric formulation



(b) One-side-dominant formulation

Fig. 2. End-effector Y-axis positions for symmetric and one-side-dominant formulations.

4.2 Torque-Error Relationship

The relationship between absolute tracking error and the resulting restorative torque is illustrated in Fig. 3. This analysis focuses on the first joint (Joint 1), as it performs the primary work during displacements along the Y-axis; a similar response is also observable in Joints 3 and 5, albeit to a lesser degree. While both formulations exhibit a linear trend consistent with the impedance control law $\vec{F} = \mathbf{K}\vec{e} + \mathbf{D}\dot{\vec{e}}$, the resulting gradients differ significantly between the two versions.

The symmetric formulation, shown in blue, displays a notably lower slope. This reduced torque demand per joint is a direct consequence of the 1/2 factor in the symmetric Jacobian $\mathbf{J}_{\text{abs}}^{\text{sym}}$, which effectively distributes the restorative load across the bimanual chain. In contrast, the one-side-dominant formulation, shown in red, exhibits a significantly steeper gradient. Because Robot 1 is solely responsible for the absolute task in this configuration, it must generate the entire restorative wrench internally, leading to higher instantaneous torques for any given magnitude of absolute error.

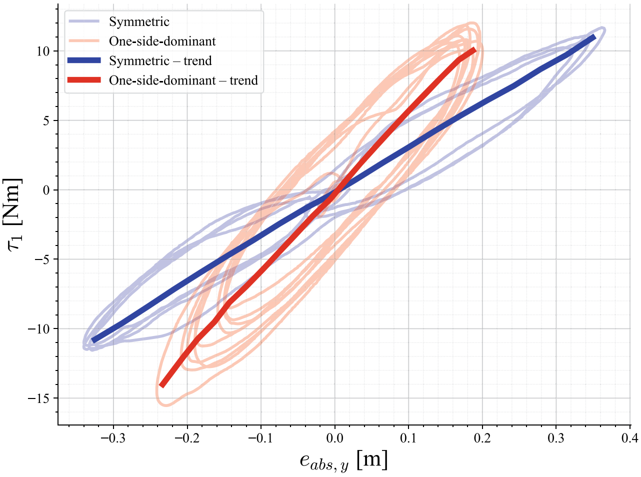


Fig. 3. Impedance control torque in Joint 1 based on absolute task formulation.

5 Discussion

The choice of absolute task formulation is far more than a kinematic detail; it fundamentally dictates the mechanical impedance perceived by both the robot actuators and the human operator. Our results demonstrate that the symmetric formulation naturally facilitates load sharing across the entire bimanual chain. By distributing the absolute error through the transposed Jacobian $\frac{1}{2}[\mathbf{J}_1\ \mathbf{J}_2]^\top$, the control effort is spread across all 14°C of freedom. This characteristic is particularly critical when manipulating heavy payloads, as it prevents torque saturation in a single arm by leveraging the combined capacity of both manipulators. Conversely, the one-side-dominant approach places the entire dynamic burden on the leader, effectively limiting the system's payload to the overhead of a single robot.

Beyond load distribution, the formulation significantly impacts the interaction's physical feel. The steeper gradients in Fig. 3 demonstrate that the one-side-dominant configuration yields a much stiffer response to global tracking errors. In this mode, the leader behaves as a high-impedance source that remains robust to trajectory deviations but feels less compliant to an operator during physical collaboration. The symmetric version, however, halves the apparent stiffness of the individual manipulators relative to the absolute task, creating a more forgiving and ergonomic interface.

While the decoupling observed in Fig. 2b makes the one-side-dominant architecture ideal for tasks where a secondary tool must stay isolated from the primary arm's global motion, it lacks the mutual adjustment required for complex cooperative work. For high-precision assembly, the symmetric formulation's ability to let both agents contribute to object stability makes it the superior choice for maintaining the integrity of a shared workspace.

6 Conclusion and Future Work

This study compared symmetric and one-side-dominant absolute task formulations in bimanual control. Experimental results on KUKA LBR iiwa manipulators show that the symmetric formulation facilitates load sharing and lower reflected stiffness, while the one-side-dominant version provides a stiffer, decoupled response by concentrating the task on a single leader arm. These results indicate that absolute task formulation should be treated as a first-order design choice in bimanual humanrobot interaction, rather than a purely kinematic convenience. Future work will investigate adaptive gain scheduling to mitigate high joint torques in dominant-arm configurations and conduct human-in-the-loop studies to evaluate the ergonomic impact and intuitiveness of these control schemes in collaborative assembly tasks.

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