Toward Crane–Robot Cooperative Manipulation in Curtain Wall Installation: A State-of-the-Art Analysis and Methodological Perspective

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Abstract -

The need to handle heavy loads safely and precisely in complex and unstructured environments is driving the increasing use of robotic systems in construction and field robotics. Curtain wall panel installation is one representative task that can benefit from such systems, requiring the accurate placement of large and heavy façade elements. Hybrid crane–robot systems are a promising solution in this context, as they combine the load-bearing capability of cranes with the precision and flexibility of robotic manipulators. This paper provides a focused analysis of the current state and the state of the art in robotized curtain wall applications, highlighting existing approaches in crane–robot cooperation and compliant manipulation. Based on this analysis, a methodological perspective is proposed to guide the development of compliant and adaptive robotic assistance for fine positioning tasks. Preliminary studies are used to illustrate key trade-offs between compliance, accuracy, and load sharing. The contribution of this work is to clarify open challenges and outline research directions toward cooperative crane–robot systems for safe and precise façade installation.

Keywords -

Robotics; Construction; AI; Control Systems; Façade

1 Introduction

The installation of large curtain wall modules is a critical and safety-sensitive operation in modern construction [1, 2]. These modules are heavy and bulky components that must be positioned with high accuracy to meet architectural and structural tolerances. In current practice, this task is largely performed manually: a crane transports the panel close to its target location, while several workers—typically positioned at the panel corners—physically guide and fine-position it during the final alignment and installation phase. These operations are carried out at height and in close proximity to suspended loads, exposing workers to significant safety risks. In addition, manual installation is physically demanding and often leads to variability in accuracy and efficiency. Because of these limitations, there is growing interest in exploring robotized systems for façade panel installation [3]. Within this context, this research is conducted as part of the AMALTEA project, an EU-funded initiative aimed at reshaping the curtain-wall façade value chain through robotics, AI, and digital tools to improve sustainability, safety, and process reliability while enabling human-in-the-loop collaboration. Motivated by these goals, a hybrid system is considered in which a spider crane is combined with robotic manipulators mounted on a mobile platform, as shown in Figure 1.

Figure 1. **System Overview**: crane-robot system concept for automated curtain wall panel installation. (Adapted from the AMALTEA project proposal and refined by the authors).

The setup illustrated in the figure represents an initial conceptual configuration; the current system extends this concept by incorporating two robotic manipulators, as detailed in Section 3.1. In this configuration, the crane supports the weight of the panel and performs coarse positioning, while the robotic system assists in fine positioning and alignment, following concepts explored in previous robotic curtain-wall installation systems. Within this shared-control framework, the central technical challenge lies in enabling the robotic manipulators to precisely fine-position the panel while remaining compliant to crane-induced motion. The robots must regulate interaction forces to ensure safety, while simultaneously adapting to external disturbances and object motions that are not under their direct control [4, 5]. This dual requirement—accurate manipulation combined with compliant behavior under externally imposed motion—defines the core difficulty of robotic assistance in crane-supported façade installation and motivates the need for adaptive impedance and compliance strategies [6, 7]. Accordingly, this paper aims to provide a structured analysis of the problem space and to outline a methodological framework for addressing crane–robot cooperative manipulation in façade installation scenarios.

2 State of the Art

2.1 Robotic Systems for Curtain Wall Installation

Over the past decades, several research efforts have investigated robotic systems to support or partially automate façade panel handling and installation, driven by the need to improve safety, productivity, and placement accuracy in construction environments. Already in the mid-1990s, Oda [8] presented an automated exterior curtain wall installation system, demonstrating that the interest in robotizing this process is not recent but has existed for nearly three decades. This early work highlighted the technical feasibility of mechanized and robotic assistance for façade installation, while also revealing limitations in adaptability to real site conditions. Extensive developments in construction robotics were carried out in Japan during the 1980s and 1990s, supported by coordinated government and industry initiatives aimed at fully automated building construction. Major contractors such as Shimizu, Obayashi, and Takenaka developed large-scale systems including SMART, ABCS, and T-Up, which explored integrated approaches combining prefabrication, automated material handling, and robotic assembly [9, 10, 11]. These works highlight the importance of considering façade design in conjunction with robotic manipulation. In particular, conventional fastening and alignment strategies—originally developed for manual assembly—pose challenges for robotic systems, motivating the need for robot-oriented design solutions. In the context of the AMALTEA project, this aspect is addressed in a dedicated work package focusing on the design of façade panels tailored for robotic installation. The integration of such design-for-robotics principles with the manipulation strategies proposed in this work represents an important direction for future research. A particularly relevant contribution is presented by Bock et al. [12], who introduce a hybrid system in which a crane provides load support and coarse positioning, while dual manipulators guide and align the panel. The system is modeled through a decomposition-based dynamic formulation with elastic–dissipative interaction forces, enabling force-based control and load distribution. This approach demonstrates strong potential for crane–robot cooperation. Nevertheless, it requires further research toward adaptive and robust cooperative manipulation strategies. Yu et al. [1] investigated curtain wall installation through on-site experiments using a system that combines an excavator for coarse positioning with a 3-DOF gripper for fine alignment, highlighting both feasibility and practical limitations in positioning accuracy and coordination. Similarly, the Automation System for Curtain Wall Installation II (ASCI II) proposed by Choi et al. [2] introduced impedance-based human–robot cooperative control for constrained positioning tasks. More recently, Heuer et al. [13] proposed a modular platform for semi-automated façade assembly with human–robot collaboration, while Iturralde et al. [14] present a cable-driven parallel robot with a large workspace and dedicated end-effector, requiring specialized infrastructure. While differing in scale, technological maturity, and system architecture, these approaches collectively illustrate a sustained and long-standing research interest in robotized curtain wall installation and highlight both the potential and the persistent limitations of current system designs when deployed in real construction settings.

2.2 Vision-Based Perception for Façade Installation

Alongside robotic manipulation systems, visual perception has emerged as a key enabling technology for automated curtain wall installation, as accurate detection and localization of façade frames and panels are essential for precise positioning. Recent work addresses this challenge using deep-learning-based semantic segmentation. Wu et al. [15] propose a dual-flow aggregation network for curtain wall frame segmentation, targeting robot pose estimation during installation tasks. Complementary work introduces context-based architectures to improve segmentation robustness. Other work focuses on deployability in real construction scenarios. Hassen et al. [16] present a lightweight segmentation model for real-time perception, while Wu et al. [17] enhance robustness under challenging conditions using edge information. Overall, these works highlight significant progress in vision-based curtain wall detection, but largely treat perception in isolation rather than as part of an integrated robotic system.

2.3 Robot–Crane Collaborative Manipulation of Heavy Elements

Beyond perception, a central challenge in façade installation lies in the coordination of multiple manipulation systems under heavy payload constraints. In robot–crane collaborative systems, one of the main objectives is to ensure that robotic manipulators are never overloaded by the weight or dynamics of the payload. Recent work explores robot–crane coordination strategies [18, 19], focusing on regulating interaction forces and ensuring safe operation. Ambrosino et al. [18] adopt a trajectory-based explicit reference governor to enforce safety and feasibility constraints, while Rosales et al. [19] introduce shared control schemes for cooperative manipulation. These approaches generally assume automated crane systems and are validated mainly in laboratory setups with simplified models. In addition, these approaches typically assume automated crane operation, whereas in real construction environments cranes are commonly human-operated and remain difficult to automate due to safety, certification, and operational constraints.

2.4 Dual-Arm and Robot-Centric Manipulation of Heavy Planar Objects

A closely related line of work considers dual-arm manipulation of heavy planar elements with the support of external lifting devices that are not explicitly integrated into the control loop. Hayakawa et al. [4] propose a dual-arm robotic system for manipulating heavy plates while a vacuum lifter supports most of the payload. Their framework coordinates the two arms through kinematic and force constraints, enabling synchronized motion and load distribution. However, the robot remains the primary driver of object motion. Hu and Cao [5] develop an adaptive impedance controller for dual-arm manipulation, adjusting stiffness and damping based on interaction forces, but validate it only in simulation. Other works address compliance and cooperation [20, 21, 22], but remain within robot-centric paradigms and do not consider crane-supported manipulation.

2.5 Adaptive Compliance Control: Toward Learning-Based Approaches

Adaptive compliance enables robots to regulate interaction behavior by adjusting stiffness and damping in response to task demands and external disturbances. This capability is essential in contact-rich and safety-critical manipulation, where robots must balance motion accuracy and compliant interaction. Two principal paradigms are commonly employed: impedance control, which regulates the dynamic relation between motion and forces, and admittance control, which maps measured forces to motion and is widely used in shared-control scenarios. Shared admittance control is widely used in human–robot co-manipulation. Cacace et al. [23] propose a shared admittance framework based on operator intention estimation. Learning-based approaches extend this by enabling online adaptation of impedance parameters. Racca et al. [7] and Gao et al. [24] demonstrate adaptation in contact-rich tasks, while Sidhik et al. [25] address changing-contact scenarios through hybrid modeling. Recent work further explores learning-based impedance and policy-based approaches [6, 26, 27]. However, most existing methods assume robot-centric object motion. In façade installation, manipulation is object-driven: the crane governs global motion, while the robot must remain compliant during transport and increase stiffness for fine alignment. This requirement is not explicitly addressed in existing frameworks, motivating the approach proposed in this work.

2.6 Comparative Analysis of Existing Systems

Table 1 provides a structured comparison of representative robotic systems for façade installation and heavy object manipulation. The comparison considers system architecture, manipulation assumptions, and validation level. The table highlights a consistent trend across prior work: most approaches adopt a robot-driven paradigm, where the robot is treated as the primary source of object motion, while external lifting devices are either simplified or only partially integrated into the control loop. Even in cooperative or shared-control settings, crane behavior is typically modeled under controlled, reduced, or simplified conditions. In contrast, real construction scenarios are inherently object-driven, with the global motion dictated by a human-operated crane that introduces uncertainty and limited controllability. This mismatch between existing assumptions and practical conditions represents a key gap in the current state of the art. The comparison in Table 1 is intended to explicitly expose this gap and to support the main contribution of this paper: a structured analysis that identifies open challenges and motivates the development of adaptive, compliant, and object-driven manipulation strategies. In addition, preliminary results are provided to support key methodological choices of the proposed approach, including the adoption of a dual-manipulator configuration and the use of compliant control strategies.

3 Methodology

3.1 Overview of the Novel Proposed Robotic Approach

The proposed approach considers a hybrid manipulation system composed of two robotic manipulators mounted on an Autonomous Ground Vehicle (AGV) and a spider crane responsible for supporting the majority of the panel weight,

Table 1. Comparison of representative robotic systems for façade installation and heavy object manipulation.

Work	System Type	Manipulation & Control Assumptions	Validation
Oda [8]	Dedicated installation machine	Robot-driven	Controlled setup
Yamazaki et al. [9]; Taylor et al. [10]	Integrated automated construction systems	Robot-driven; system-level automation; prefabrication and process co-design for automated assembly	On-site deployment
Bock et al. [12]	Mobile dual-arm manipulator + crane	Object-driven (hybrid); elastic–dissipative interaction; crane as trajectory source	Simulation
Yu et al. [1]	Excavator + 3-DOF manipulator	Hybrid; operator-assisted fine positioning	On-site test
Choi et al. [2]	Mobile manipulator for human–robot cooperation	Robot-driven cooperative positioning; impedance + position control	On-site test
Iturralde et al. [14]	Cable-driven parallel robot + modular end-effector	Robot-driven; task-specific end-effector	Controlled-environment on-site test
Hayakawa et al. [4]	Dual-arm robot + vacuum lifter	Hybrid; velocity-based impedance control to follow lifter motion	Laboratory experiment
Hu and Cao [5]	Dual-arm robot	Robot-driven; adaptive variable impedance; force/position control	Simulation
Ambrosino et al. [18]	Lightweight robotic arm + lifting mechanism	Shared handling; ERG-based constrained control	Laboratory experiment
Rosales et al. [19]	Robot + crane (robot acting as crane)	Shared control; dual admittance control for robot and crane	Laboratory experiment
Proposed approach	**Mobile dual-arm robot + human-operated spider crane**	**Object-driven; adaptive impedance/admittance; human-operated crane**	**On-site test foreseen**

which remains human-operated. The decision to retain a human-operated crane is driven by practical considerations: fully autonomous crane systems are rarely commercially available, difficult to certify, and challenging to deploy in unstructured construction environments due to safety, regulatory, and perception constraints [18, 19]. The curtain wall panel is connected to the manipulators through vacuum gripping devices, enabling non-invasive attachment while allowing force regulation and compliant interaction. This system architecture reflects typical construction practices, in which cranes provide coarse positioning of heavy elements, while fine alignment is performed locally. A dual-manipulator configuration is adopted due to the large mass and dimensions of the curtain wall panels addressed in this study. Distributing interaction forces across two arms reduces peak joint loads, improves stability against external disturbances, and provides redundancy during manipulation. In addition to the manipulation subsystem, the envisioned system layout includes a distributed perception setup composed of two fixed cameras per building floor (upper and lower viewpoints) and one camera mounted on the wrist of each manipulator. Each manipulator is further equipped with a vacuum gripper integrated with sensing capabilities. This multi-view configuration is intended to support robust panel pose estimation, alignment monitoring, and safety supervision during installation. The overall system architecture, including the AGV, dual manipulators, crane interface, grippers, and camera placement, is illustrated in the schematic of Figure 2.

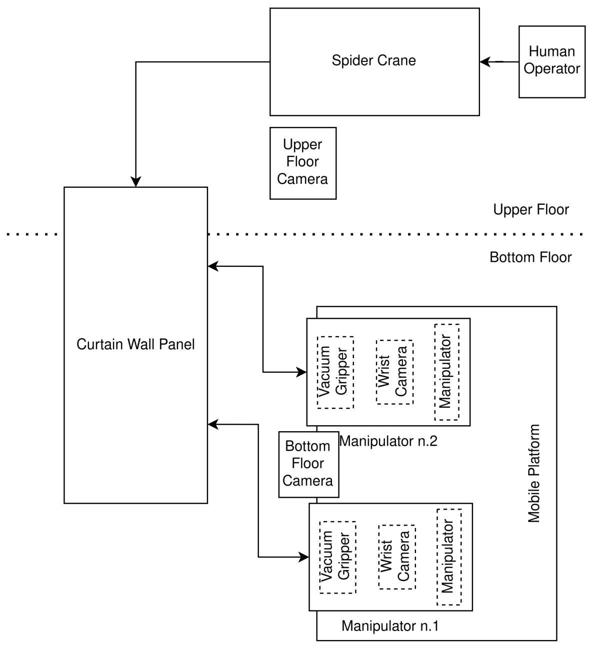

Figure 2. Schematic of the proposed system architecture (self-developed by the authors).

It is important to note that this configuration represents the proposed and envisioned system layout, which guides the research activities presented in this work, rather than a fully implemented or deployed platform. Furthermore, additional sensing modalities such as total stations and LiDAR scanners are currently being evaluated for inclusion in the system to further enhance positioning precision, global accuracy, and environmental awareness. These sensors are expected to complement the camera-based perception pipeline, particularly in large-scale or partially occluded construction scenarios. It should be noted that this configuration is part of the envisioned system and is currently under development, and is not fully implemented within the scope of this work. To support the feasibility of the proposed dual-manipulator design, a simulation framework was developed that integrates the NVIDIA Isaac Sim environment with ROS2, enabling realistic dynamic simulation and joint-level effort analysis during panel motion. Figure 3 illustrates the system layout as modeled in Isaac Sim, showing the dual-arm manipulators mounted on the AGV. Pendulum-like trajectories of the suspended panel were used to emulate crane-induced motion, fixing the crane and moving the panel only with the robot. The simulated panel has a mass of 300 kg and dimensions of 3 m × 1.5 m, representative of industrial curtain wall modules, while robot motion is generated using MoveIt-based planning.

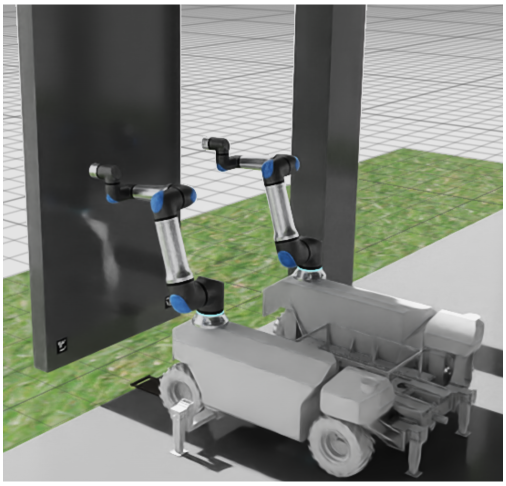

Figure 3. Simplified simulation model of the dual-arm manipulators on an AGV in NVIDIA Isaac Sim, adopted for preliminary design evaluation.

3.2 Shared Crane–Robot Manipulation Strategy

The primary objective of the proposed methodology is to enable shared motion between the crane and the robotic manipulators while preventing overload conditions on both systems. The crane is responsible for supporting the static load of the panel and performing coarse positioning, whereas the robotic manipulators assist in fine positioning, alignment, and disturbance rejection. In this configuration, the manipulators must comply with crane-induced motion, which is not directly controlled by the robot, while still being capable of generating corrective actions to achieve accurate placement. The first step toward this objective consists of establishing a reliable connection between the robotic system and the panel. This includes integrating a multi-camera vision system to provide real-time six-degree-of-freedom pose estimation of the panel. The estimated panel pose is supplied to the robotic control framework and used as the primary reference for object-level control. By reasoning about the motion of the panel rather than solely the end-effector trajectories, the manipulators can better accommodate externally induced motion while maintaining alignment objectives.

3.3 Compliant Control Integration

Building on the perception pipeline, compliant control strategies are considered to ensure safe and stable robot–panel interaction under external disturbances. In this work, a Cartesian impedance controller from the CRISP framework [28] is adopted and evaluated as a baseline, due to its stability and experimentally validated performance on a UR5 manipulator. The controller is applied in the simulation framework to assess its suitability for panel-referenced tracking under crane-induced motion. Future work will focus on the integration of this controller with UR30 robots, accounting for higher payload, inertia, and torque constraints, the integration and evaluation of an admittance control scheme, and the experimental assessment of the controllers' performance in a fully integrated robot–crane setup.

3.4 Toward Adaptive Compliance and Learning-Based Control

While fixed compliance parameters provide basic safety, façade installation requires stiffness to vary with task phase and interaction context. High compliance is needed during crane-driven motion, whereas increased stiffness is required for accurate alignment and insertion. Adaptive stiffness control is therefore a central focus of the proposed methodology. Learning-based models will be explored to adjust impedance and admittance parameters based on panel motion, interaction forces, and task context. The goal is to enable the robot to distinguish between crane-induced forces and fine-positioning interactions, and to modulate compliance accordingly. This direction will guide subsequent data collection, model development, and experimental validation.

4 Preliminary Results

4.1 Torque Comparison

Following the system setup and simulation framework described in Section 3.1, joint torques were evaluated for single- and dual-manipulator configurations during crane-supported panel motion. The comparison focuses on the *wrist 1* joint, which is particularly sensitive to payload-induced loads. As anticipated from the load-sharing principle discussed earlier, the single-manipulator configuration exhibits higher peak torques and larger temporal variations. When two manipulators are employed, *wrist 1* torques are consistently reduced and exhibit smoother profiles, confirming a more balanced distribution of dynamic loads and improved resistance to crane-induced disturbances, as shown in Figure 4. These results validate the choice of a dual-arm architecture for heavy panel manipulation.

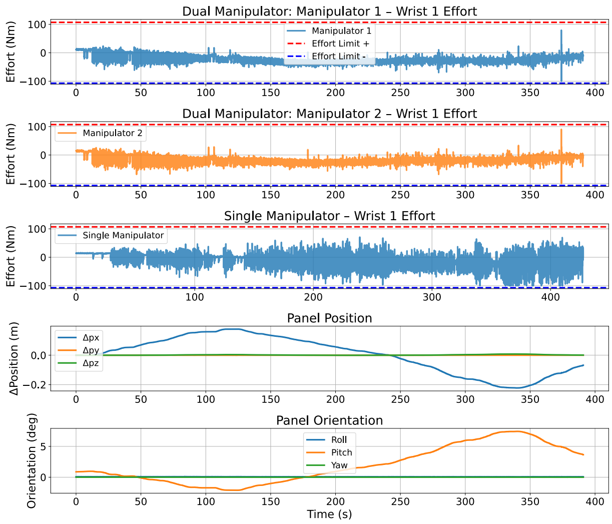

Figure 4. **NVIDIA Isaac Sim simulation results**: comparison of *wrist 1* joint effort limits for dual and single manipulator configurations alongside panel position and orientation metrics over time.

4.2 Cartesian Impedance Control Evaluation

Building on the Cartesian impedance formulation introduced in Section 3.3, controller behavior was evaluated by varying the Cartesian stiffness gains during panel-referenced end-effector tracking, as summarized in Table 2. The table reports a single translational stiffness k_{pos} and a single rotational stiffness k_{rot}, which are applied uniformly across all Cartesian directions, i.e., $\mathbf{K}_{pos} = k_{pos}\mathbf{I}$ and $\mathbf{K}_{rot} = k_{rot}\mathbf{I}$, and expressed in $[N/m]$ and $[Nm/rad]$, respectively. The damping is kept constant to ensure near-critical behavior. Low stiffness improves compliance but reduces tracking accuracy, whereas higher stiffness increases precision at the cost of compliance, as shown in Figure 5. This trade-off highlights the need for adaptive stiffness modulation to balance accuracy and compliance during façade panel installation.

Table 2. Stiffness parameters used in low and high gain impedance tests.

Parameter	Low Gains	High Gains
k_{pos} $[N/m]$	500.0	1600.0
k_{rot} $[Nm/rad]$	30.0	90.0

5 Conclusion and Future Development

This paper provides a structured analysis of the state of the art in robotic curtain wall installation and highlights key limitations of existing approaches in real construction environments. In particular, it highlights a recurring mismatch between robot-centric manipulation frameworks and installation scenarios in which object motion is dominated by external agents, such as human-operated cranes. Based on this analysis, the paper proposes an object-driven, shared-control perspective for façade installation. Within this perspective, a hybrid system architecture is outlined, combining a human-operated crane for load-bearing with a dual-arm robotic platform for compliant fine positioning. Rather than introducing a finalized control solution, the work outlines the key methodological components required for such systems. Preliminary simulation and control results support the feasibility of the proposed approach and motivate its design choices. The torque comparison highlights the benefits of dual-arm manipulation, while impedance control experiments reveal the trade-off between compliance and accuracy, motivating adaptive stiffness strategies. Future work will focus on integrating the full physical system and validating performance under real crane-supported conditions. In parallel, learning-based approaches will be explored to enable context-aware adaptation of compliance. By framing façade installation as an object-driven cooperative manipulation problem, this work provides a foundation for practical robotic systems in construction.

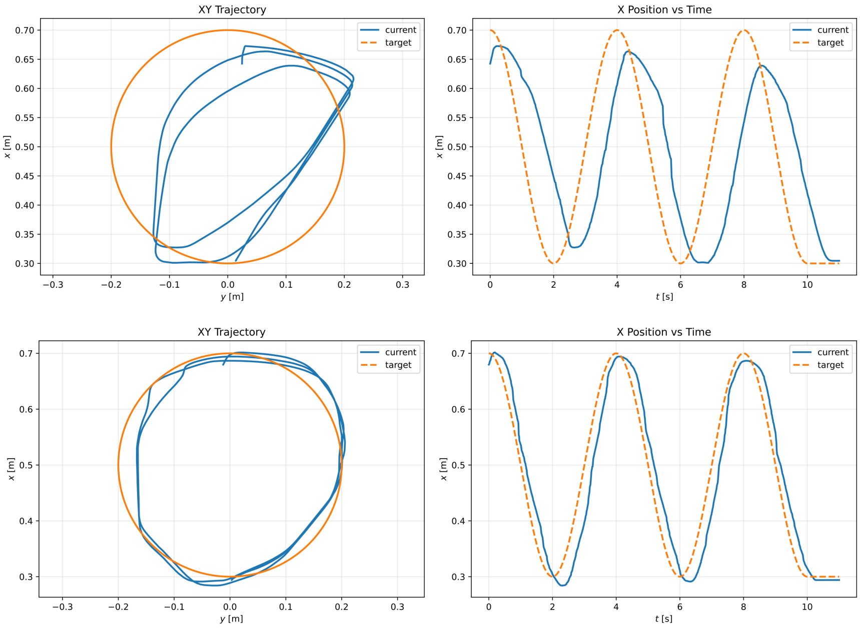

Figure 5. Experimental results obtained with a UR5 manipulator: effect of Cartesian impedance gains on trajectory tracking behavior. **Upper**: robot motion under low stiffness gains. **Bottom**: response with higher gains.

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