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RESEARCH

Adaptive robotic platform for the installation of refurbishment panels

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Abstract
Achieving climate neutrality in the building sector by 2050 requires a comprehensive thermal upgrade of the existing building stock. Currently, heating and cooling account for around 32% of total energy consumption. However, conventional refurbishment methods are highly manual, require complex scaffolding, and involve significant physical effort. Our work presents a novel concept for a scaffold-free installation of ventilated rain-screen panels using a robotic facade platform lifted by a standard construction crane. The system combines an articulated robotic arm with an adaptive trajectory control strategy, enabling precise panel placement in the unstructured environment of construction sites. The developed prototype was tested in indoor and outdoor test scenarios. Results show consistent sub-millimeter placement accuracy. The proposed approach demonstrates how robotics can improve energy-efficient building refurbishment especially with regard to safety, precision, and on-site efficiency.

Keywords Adaptive robotics · Facade-platform · Facade refurbishment · Construction automation

1 Introduction

1.1 Motivation

According to European Commission (2025), the building sector is responsible for about 40 % of the total energy consumption in the EU. In addition, heating, cooling, and hot water account for about 80 % of the energy used in EU households. In order to reduce this energy demand, it is essential to improve the thermal insulation of our building stock. This requires updating the currently insufficient thermal insulation of the existing building stock. Current methods for this upgrade are predominantly manual Deutsches Institut für Wirtschaftsforschung (2025). Moreover, the construction sector is facing a shortage of skilled workers ifo Institut (2025). To improve the low refurbishment rate Deutsches Institut für Wirtschaftsforschung (2025), new methods are needed to increase the current refurbishment rate. According to Chui and Mischke (2019), the integration of automation in the construction sector promises to increase the overall efficiency of construction. Therefore, our work presents a new semi-automated solution for the thermal refurbishment of building envelopes.

There have been attempts to develop automated solutions for construction sites - and specifically for façade work Bock (2015). However, the work Stumm et al. (2018) highlights the limitations in the developments of very specialized single test machines and the need for adaptivity to unstructured environments such as construction sites. Consequently within the design and development process of the presented solution two major design factors were set: 1) Integration with standard machinery and processes 2) High degree of adaptability. Recent research shows that complex adaptive processes can be designed using adaptive robotics, compliant control, and hybrid control systems Devadass et al. (2019).

Façade robotics is still in its infancy stage, with early prototypes demonstrating the potential to address several challenges Kepa Iturralde Lerchundi (2021). However, these systems typically require complex setups to move the robot along the façade. Moreover, none of the systems are designed for the thermal refurbishment of building envelopes (see Section 2). Motivated by this gap, the present work addresses the following research question:

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1. *Can comparable results be achieved with adaptive robotics when combined with a standard construction crane?*
2. *In particular, is it possible to achieve the same accuracy and speed using adaptive robotics?*

1.2 Contribution

As part of the work, a first adaptive crane-guided robotic solution was developed for the installation of the rainscreen ventilated façade system. Instead of complex crane-guided robot platforms, a compact solution was developed that can react to the dynamic forces of a construction site by means of a passive compliance system. The developed platform is able to position itself in coordination with the construction site crane and adapt to the requirements accordingly.

An articulated robot, which is integrated into the adaptive assembly platform, assembles the ventilated rainscreen façade systems with sub-millimeter precision using a new hybrid adaptive control concept. The aim is to show that adaptive control concepts can be used to respond to the complex conditions on the construction site and that this is possible without negative impact on established construction site workflows.

2 Related work

2.1 Adaptive robotics

The use of robotic systems in construction processes requires advanced control concepts that can dynamically adapt to the constantly changing, unstructured conditions found on construction sites Stumm et al. (2016). Today, numerous approaches and prototype developments already address the challenges of adaptive assembly Devadass et al. (2019); Cote et al. (2024); Capunaman et al. (2022); Bieg et al. (2019); Tokac et al. (2023); Sekmen and Challa (2013); Hayes et al. (2024); Chadha et al. (2025); Heuer and Brell-Cokcan (2025). In the following, central concepts and projects are presented which serve as the basis for developing an adaptive robotic façade platform. These include approaches in adaptive path planning, compliance methods–which are particularly important for compensating oscillations in the systems–and hybrid control systems. Together, they enable an integrated solution for automated façade refurbishment.

Unlike fixed trajectories–where a robot moves along a pre-planned path–the term *adaptive robotics* describes the capability to continuously adjust the robot's motion in response to changing conditions in its immediate environment Sekmen and Challa (2013). For example, Capunaman et al. (2022) demonstrate, by integrating vision-based sensor technology into additive concrete printing, how an integrated camera can scan complex substrate layers so that the robot adapts its trajectory accordingly, thereby achieving a uniform printing result. In contrast to conventional, rigid CAD/CAM approaches, this adaptive feedback system enables a dynamic adjustment of tool paths, which results in more precise and efficient manufacturing processes.

In addition to adaptive robotics, physical compliance plays an important role in robot control. Compliance refers to the ability to absorb mechanical forces and respond flexibly to external influences, thus ensuring safe interaction with the environment. A fundamental distinction is made between passive and active compliance Wang et al. (1998). This work Heuer and Brell-Cokcan (2025) developed an end-effector for crane-robot collaboration. By employing the passive compliance of the custom-designed end-effector within a hybrid control concept, the robot is able to achieve fine positioning of heavy components suspended from a crane. In contrast, Devadass et al. (2019) investigated robot-assisted assembly in unstructured environments. In their system, a mobile robot is supported by haptic feedback provided via force-torque sensors (FT sensors) and tactile fiducials, aiming to dynamically adjust the positioning of wood components during manufacturing and assembly. The system is based on the concept of passive compliance, whereby the robot is switched into a *soft mode* that supports human intervention during assembly, thereby compensating for manufacturing inaccuracies.

Hybrid control systems combine the aforementioned concepts by integrating the properties of traditional control methods with adaptive algorithms Garriga-Casanovas et al. (2024). In Chadha et al. (2025), a novel adaptive robotic tamping method was developed to smooth rough surfaces of additive manufactured structures (particularly in the context of Impact Printing). A specially designed end-effector, mounted on a robot, is employed; the prototype utilizes integrated force and displacement sensing to adjust its closed-loop control. This enables the system to adaptively regulate the pressure on a clay wall in accordance with material properties (e.g., the changing green strength), thereby achieving an even and smooth surface.

These approaches underline the value of advanced hybrid control strategies to address the unstructured nature of construction sites. In particular, with respect to the oscillations of crane platforms (as described in Heuer et al. (2024)), both passive and active compliance systems offer a means to compensate for these variations - as demonstrated by this work Heuer and Brell-Cokcan (2025) and Devadass et al. (2019). Furthermore, concepts such as fabrication grammar (see Tokac et al. (2023)) can further support control strategies by increasing the autonomy of the systems.

2.2 Refurbishment systems of building envelopes

Currently, our buildings are responsible for 15% of CO_2 emissions. Due to the growing demand for increased efficiency in building envelopes, there is also a rising need for the thermal refurbishment of these envelopes. At present, these processes are primarily carried out manually, which leads to a backlog in renovations Liu et al. (2024).

There are two main methods for the thermal refurbishment of building envelopes. The first, the external thermal insulation composite system, consists of a multi-layer structure that is permanently bonded to the façade with adhesives and screws. During installation, the components must be trimmed on-site. The second method, the ventilated rainscreen façade system, consists of a substructure that is screwed to the façade, an insulation layer that is attached to the façade with screws, and a cladding layer made of panels that are also screwed onto the substructure Kepa Iturralde Lerchundi (2021). Currently, the installation of one panel takes between 15 and 60 min Liu et al. (2024). Moreover, scaffolding is typically required to bring the system to the façade, which, especially in densely built urban areas, blocks streets and sidewalks.

Automation has so far been implemented only to a limited extent in refurbishment processes. In the construction industry, there have been some attempts to apply automation to building refurbishment (see, for example, Maraje et al. (2019); Detert et al. (2017)). There are a few pioneering projects: for instance, Schlandt et al. (2017) demonstrated that by using a specially developed end-effector guided by a cable robot, the external thermal insulation composite system can be improved. In this approach, a textile is automatically applied to the façade instead of mortar, which is often susceptible to algae growth and cracking that compromise the façade's protection. Furthermore, Liu et al. (2024) investigated the use of cable-driven façade robots for the installation of ventilated rainscreen façade systems. However, significant challenges remain, particularly in ensuring the system can reach all areas of the façade.

Although initial systems are already in the theoretical development stage, no fully robotic solution for façade automation has yet been realized. This indicates a current research gap that is particularly important to address given the urgency of improving building envelope efficiency and reducing manual labor in façade refurbishment.

2.3 Façade robotics

Compared to mobile robotics, façade robotics remains a relatively niche field. Although the earliest systems were developed in Japan Bock and Linner (2017). However, recent advances in robotics have spurred numerous innovations in façade robotics Kepa Iturralde Lerchundi (2021). These innovations now span a broad spectrum of applications, including façade cleaning (Hortig et al. 2001), painting Asadi et al. (2018) and façade inspection Yoo et al. (2019).

Among these systems, cable-driven robotic platforms represent a distinct category, with several prototypes already developed (Pott et al. 2019; McDonald et al. 2023; Hahlbrock et al. 2022). In particular, research by Iturralde et al. (2022) has demonstrated that cable-driven parallel robots (CDPRs), as exemplified by the *Hephaestus* system, can effectively install heavy façade elements. This system employs eight actively controlled cables that are routed along the façade via cantilever arms mounted at the four corners. Designed to meet the assembly tolerances specified in DIN 18203-3, the system achieved absolute installation accuracies between 4 and 23 mm. Notably, fine positioning during bracket installation exhibited a repeatability of approximately 2 mm. The average installation time for a curtain wall module was reduced to about 31 min, and the complete bracket installation cycle was completed in around 11 min. To address the inherent workspace limitations, Liu et al. (2024) proposed an analytical approach to extend the operational workspace by optimizing the cable arrangement.

In summary, while the developed façade robotic systems offer a promising novel approach to automated assembly, they remain complex to deploy–partly due to the necessity for external cantilever arms–and are constrained by tight assembly tolerances and a limited operational workspace. This will probably have a negative effect on the cost-effectiveness of the CDPR by Iturralde et al. (2022), making it less attractive to be deployed. Additionally, when it comes to complex non-planar façades, the system's reachability is limited. Currently, none of the prototypes incorporate a cable-driven lifting device (such as a tower crane or mobile crane), which represents a significant area for further research.

3 Research methodology

The presented semi-automated robotic platform was developed using the Design Science Research (DSR) framework as defined by Ken Peffers and Tuure Tuunanen Chatterjee (2007). Ensuring a systematic and verifiable approach to the research, the process unfolded in the following six defined steps:

1. *Problem identification and motivation.* The Introduction highlights the need for (semi-) automated solutions for the thermal refurbishment of building envelopes and emphasizes the opportunities adaptive robotics offers to address the current state of the art in façade robotics.
2. *Objectives of a solution.* The research question is delineated in Section Introduction and further supported by the conclusions drawn in Section Related Work.

3. *Design and development.* Section Overall Concept presents the developed concept for the semi-automated robotic platform, divided into the hardware concept and the control concept. The subsequent Implementation section details the development of the robotic system.
4. *Demonstration.* Section Field Demonstration and Results is divided into indoor and outdoor demonstrations. First, the system was set up under controlled conditions to enable holistic testing of the different subsystems, followed by its deployment on a real construction site test bed.
5. *Evaluation.* In Section Discussion data gathered from tests conducted indoors and at a real construction site test bed are analyzed and discussed.
6. *Communication.* Lastly, the solution has been disseminated among an extensive network of academic and industry collaborators.

4 Overall concept

In this section, the concept of an adaptive robotic platform for mounting refurbishment panels is delineated. The demonstrator set-up and the crane system are described (Fig. 1).

4.1 Crane-setup

The *Jekko* crane [35] is a compact mobile mini crane. Its design facilitates its deployment in both indoor and outdoor environments, including the test bed. The crane's lifting capacity, contingent upon the configuration of its arm, ranges from 100 kg to 3200 kg. The kinematic system comprises four degrees of freedom, namely: θ_0 - the base encompasses one rotational degree of freedom; θ_1 - the joint facilitates the inclination of the crane; θ_2 - the telescopic joint facilitates the extension of the crane boom to a maximum length of 8.5 m (it is important to note that these three joints are interconnected and cannot be moved independently); and θ_3- the load is connected to the crane hook block and can be lifted.

In order to capture the mini crane's movement, rotational and linear encoders are integrated in all joints except θ_3. The positional data is read out over the internal CAN Bus Boland et al. (2021) interface. Therefore, the crane was previously transferred to a server. The mini cranes data is accessible via a 5 G router (1). An interface translates from TCP/IP Plonus (2020) to CAN bus. This allows external ROS 2 Quigley et al. (2009) commands to be sent to the crane.

4.2 Demonstrator

In order to create a realistic test scenario, a state-of-the-art renovation façade system from *Fundermax* [39] and *Spidi* [40] is chosen. The system, which can be seen in Figure 2,

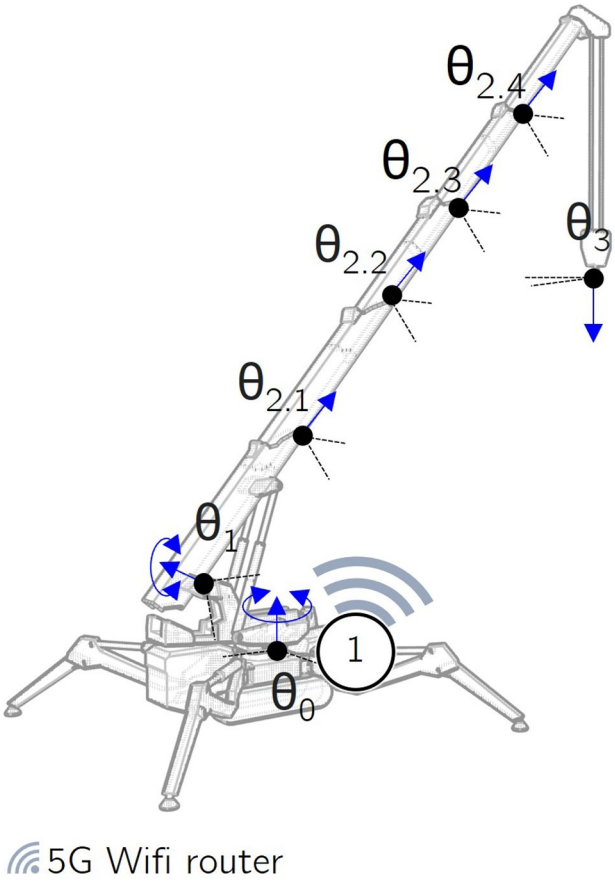


Fig. 1 Representation of the kinematic system of the *Jekko*. 1) 5 G Router and Raspberry Pi 4B [34] with CAN Bus Head

consists of three subsystems: 1) the mounting brackets are fixed to the façade with screws 2) the *Spidi* linear aluminum rails are precisely screwed vertically on the brackets to create a uniform flat layer and 3) then a refurbishment panel is mounted over two aluminum rails. The refurbishment panels are glued with special tape. To allow them to expand with temperature changes. They are mounted with a 5 mm expansion joint.

To facilitate the evaluation of the robotic system, two demonstrators were constructed, each using the mounting system described. For the indoor test scenario, a wooden frame was built to a height of 5 m, allowing for 8 rows of panels. For the outdoor test scenario, a designated test building was used that allows for the mounting of the brackets and linear rails by means of screws. Six rows of panels could be mounted.

4.3 Concept

As illustrated in Figure 3, the conceptual design of the semi-automated robotic platform is presented. The system is composed of three main subsystems:

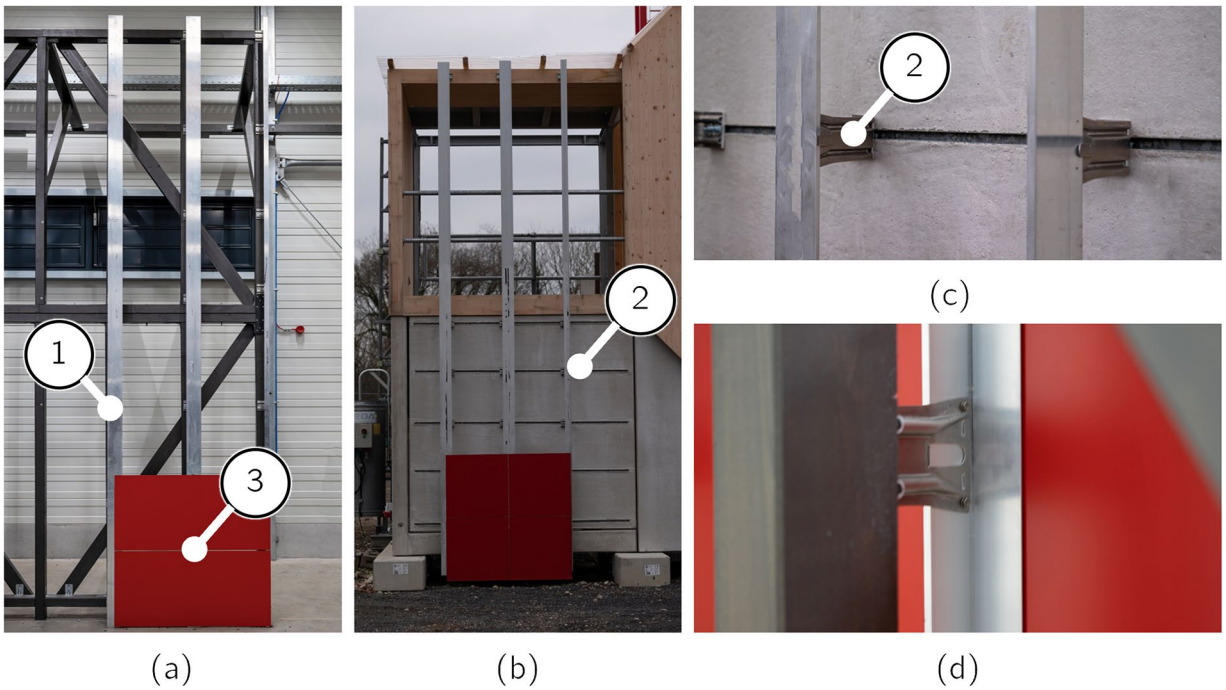


Fig. 2 Demonstrators with the mounting system of the panels. **a** Indoor demonstrator, **b** Outdoor test bed with the designated reference building, **c** Mounting of the brackets to the concrete wall, **d** Mounted panel on the aluminum linear rail. 1) Linear rails 3) Mounting brackets 3) Refurbishment panels

1. **Cable-Driven Lifting Device**: Examples include mobile cranes, tower cranes, or similar lifting machines.
2. **Semi-Automated Robotic Platform**: This platform integrates both rough and fine positioning systems Heuer et al. (2024).
3. **Custom Operator Interface**: A dedicated interface enables safe control of the system by a human operator from the ground.

The rough positioning system's main objective is to stabilize the mounting process. In contrast to contemporary methods, a minimalist setup approach is selected. As illustrated in Figure 3, the handling of loads by cranes typically entails six degrees of freedom (DoF). In contrast, the present design incorporates the rough positioning system to control five of these DoF with the help of a comprehensive gripping system.

Due to the system's inherent oscillatory behavior, the translational motion along the Z-axis cannot be directly controlled. For the remaining DoF, a distinction is made between active and passive control:

- **Active Control**: Actuators manage the platform's translational movement along the X-axis as well as its rotational movements around the ϕ, ψ axes.
- **Passive Control**: The other DoF (Y and θ) are not directly actuated.

This configuration ensures that, although the platform is not fully actuated in all directions, sufficient stabilization is achieved for effective mounting.

The fine positioning system consists of an articulated robot arm (Kuka KR 10 R900 [41]), a force-torque sensor (ATI Axia FT Sensor [42]), and a dedicated passive compliance end-effector with a single degree of translational freedom for mounting the refurbishment panels He et al. (2022). The robots use an adaptive robot control concept that combines active and passive compliance control to enable precise placement of the refurbishment panels in the complex and dynamic environment of the construction site. Therefore, a combination of force control and position control is utilized Niku (2011).

To mitigate the risk of falls and reduce physical strain during the assembly of the refurbishment panels, the worker is assigned the role of a quality control operator. A portable interface is designed to enable safe and precise control of the adaptive robotic platform from the ground, minimizing direct exposure to hazardous tasks.

5 Implementation

5.1 Control architecture

This section provides a detailed overview of the communication architecture in the adaptive robotic platform, as

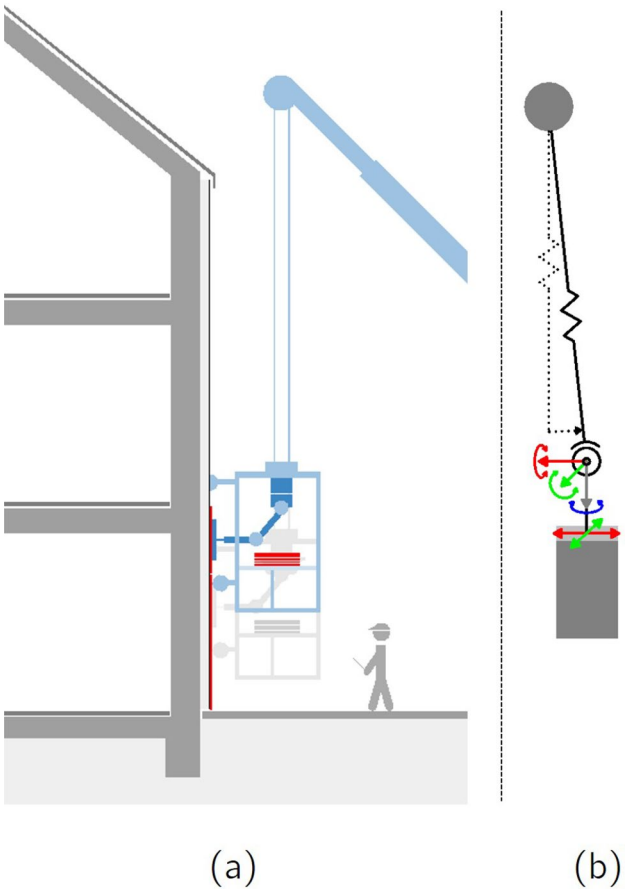


Fig. 3 Mechanical concept for the adaptive robotic platform. **a** Schematic representation of the set-up. **b** Abstract representation of the kinematic system

depicted in Figure 4. Four main communication clusters are employed: teleoperation, platform control, articulated-robot control, and crane control. For safe handling of the process, a worker assists the mounting procedure from the ground using a custom Node-RED web interface accessible via a tablet. Data from the interface is transmitted via MQTT to the platform's main embedded PC (Intel NUC). By means of the *mqtt_bridge* package in ROS, these MQTT topics are integrated into the overarching control system. A CAN bus establishes a link between the embedded PC and the IFM PLC, which drives the actuators (motors for the gripping mechanism (see Section 5.2), the translational load balancing system (see Section 5) and air relays (see Section 5.2)) and gathers sensor data (absolute encoders for closed-loop motor control and the laser sensors). In parallel, a wired connection links the embedded PC with the KR C5 micro, which actuates the articulated arm, processes force-torque data, and handles digital I/Os for the end-effector's air relays. Here the communication relies on RSI (see Section 5.1.1).

The Jekko mini crane has its own control unit, and the platform's embedded PC connects to the mini crane's 5 G-enabled router. By running ROS 2 in a Docker container on the embedded PC, velocity commands can be sent to the mini crans ROS 2 action server while external height information from the platform's depth laser sensor is provided to the crane control system.

5.2 End-effector for compliance control

The end-effector is a key component in the overall mounting process and grasps the refurbishment panels during installation. It is designed to compensate for delays in the adaptive robotic path planning, thereby preventing damage to the robot arm. It is based on the concept of passive compliance (see Heuer and Brell-Cokcan 2025) and has one degree of freedom in the direction of the vertical oscillation of the crane. Figure 6 shows the developed end-effector for the mounting of the refurbishment panels. The relative low payload capacity of the articulated robot (Kuka KR10) limits the weight of the end-effector and the gripped façade panel to 10 kg. It consists of four main subsystems. 1) The passive translational compliance device to compensate for the

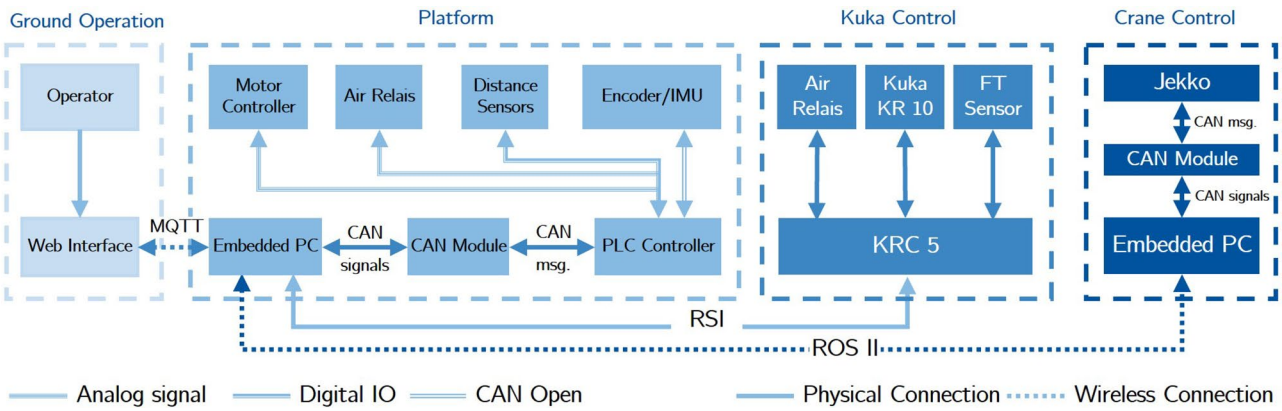


Fig. 4 Schematic representation of the communication architecture

dynamic positional error. 2) Aluminum profiles serve as the connector frame for the mounting of a laser distance sensor. 3) Laser distance sensor for the detection of the aluminum rails for an adaptive reliable path planning. 4) Six vacuum cups grip the refurbishment panels. Six vacuum cups grip the refurbishment panels. They can withstand a total shear force of 296.4~N.

The passive translational compliance along the Y-axis effectively buffers the delays that are needed for the trajectory calculation of the articulated robotic arm. In addition, it adjusts for unplanned motion caused by robotic platform oscillation, thereby preventing damage to the articulated robot arm. Without the spring-loaded translational axis, the adaptive controller cannot respond fast enough to position changes of the robotic platform to prevent damage to the articulated robotic arm. During the outdoor tests (see Heuer et al. 2024) a frequency rate of 0.5 Hz was measured. The test was performed on a *Liebherr L1-24* fast-erecting crane with a reference weight of 1000 kg. The ROS framework deployed on the embedded PC (see Fig. 8) has an cycle rate of 100~Hz. Therefore, the system has to have vertical passive motion range of around ~2 mm enabling the system to react to the changes, without causing damage to the articulated robotic arm. The system had an vertical amplitude of ~50 mm.

In order to prevent undue stress on the platform's gripping devices, it is imperative that the center of gravity be perfectly centered to allow for vertical swinging. The implementation of a balance system is therefore essential to counterbalance disparate load factors. Figure 7 illustrates the developed balancing system.

5.3 Translational load balancing system

The system comprises two translational degrees of freedom (X-axis and Y-axis) and is designed primarily to shift the crane chain attachment point. To facilitate this, two slides can move independently along each axis. Each axis is driven by a designated NEMA 34 stepper motor. The motors actuate the slides via a threaded rod, while linear rails and corresponding linear housing blocks ensure precise, linear movement. To enable closed-loop control for each axis, a laser distance sensor (*ifm OMH554*) is mounted to guarantee sub-millimeter accuracy.

To adjust for any load shifts, a service node in the internal control framework is implemented (see Section 5.1). Using the installed IMU (*ifm JD1111*) (see Figure 7(1)), the current rotation around the ϕ and ψ axes is measured with an accuracy of $\pm 0.5^{\circ}$. The service comprises a velocity controller that continuously balances the platform horizontally by moving the two translatory axes. Once the platform is balanced, the service stops.

5.4 Human–robot interaction for adaptive process control

A shift from discrete to non-discrete conditions occurs in the assembly of refurbishment panels in a dynamic construction site environment. Therefore, a combination of control concepts (position control and force control) is integrated to handle the different requirements. The articulated robot arm, which mounts the panels is controlled by a custom-written program within the ROS 1 framework (see Quigley et al. (2009)). The program runs on a portable computer installed on the platform.

Figure 8 represents a schematic representation of the communication structure developed to enable the real-time control of the articulated robot. The main system consists of the three subsystems. The robot arm; the KRC 5 controller [46]; and the embedded PC. To control the movement of the robot arm, the following steps are performed: first, the Kuka KR 10 robot (1) sends its current arm position to the KRC 5 controller. In addition, the FT sensor (2) sends the current force and torque values to the controller via the EtherCat protocol. Next, the data is translated into an XML format to be sent via the Robot Sensor Interface (RSI) [47] (a similar setup is described in Schöpfer et al. (2010)). The User Data Protocol (UDP) Al-Dhief et al. (2018) is used to transmit the data to the embedded PC. The ROS Industrial [50] hardware interface translates the incoming data into a Joint State Msg, which is then used in the C++ program to compute the inverse position motion planning of the robot. Additional sensor data is read in to extend the sensing range (see section 5.1.1). The computed new axis values of the robot are then published and received by the hardware interface. The data are then transmitted to the KRC 5 via RSI. The KRC 5 executes the commands. As an extra precaution, any inverse miscalculations are performed. In order to avoid any damage to the robot, the movement of the robot has been limited by a defined work area to avoid a contact with the platforms frame. Section 5.1.1 describes in detail the control methods developed for the individual application steps.

5.4.1 Hybrid position control

This section provides a detailed explanation of the robot's movement, building on the system described in Section 5.1. To enable precise placement of the refurbishment panels in a non-discrete construction site environment, a combination of control concepts (position control, hybrid force-control) is implemented to account for the dynamic influences of the construction site environment. An abstract representation of the two different approaches is given in Figure 9. The placement of the panels is structured into seven event-driven transitions, which are described in detail and illustrated in 5.1:

(a) *Picking up the Panel* To activate the articulated robot, the RSI connection (see Section 5.1) must first be initialized by starting the program on the teaching pendant (see Figure 8). The worker sends the activation command to the ROS Quigley et al. (2009) robot service node using the web interface. Next, to eliminate sensor drift or the effect of tool weight, a calibration offset is subtracted. Therefore, 1000 samples are collected to calibrate the FT sensor. The robot then moves vertically to the panel storage location (see Figure 10 (10)) using a position controller. To account for the changing load at the storage location, the controller switches to force control to detect the first refurbishment panel. It moves vertically until a significant force is measured. The vacuum is then activated to grip the panel. With the panel attached, the robot switches back to position control and moves along a fixed trajectory parallel to the façade.

(b) *Locating the Sub-Structure* Once the refurbishment panel has been moved into the approximate mounting position, the robotic arm travels with constant velocity parallel to the façade. Meanwhile, the panel is aligned orthogonally to the façade plane, with its lower edge slightly angled forward to prevent the applied glue from contacting the aluminum profile. A laser sensor (see Figure 6 (b)) detects the contour of the sub-structure. On reaching a certain distance to the façade, the control node sends a notification to the robot service node, prompting a switch to the next sequence. This step is necessary because the platform and the rough positioning system can introduce slight positioning inaccuracies. For the panels to meet the sub-structure with a tolerance of 2 cm, it is essential to locate the sub-structure accurately. The first contact point is planned to be roughly 20 cm above the lower panel row.

(c) *Locating the Sub-Structure* A hybrid force-control strategy is now applied to establish contact between the panel and the sub-structure. At this stage, the control transitions from a discrete to a continuous mode. The articulated robotic arm moves toward the sub-structure with a constant force. Compliant motion enables adaptive contact along the panel's lower side, allowing rotation around θ so that the end-effector can conform to the two aluminum profiles. The force deviation, derived from the measured force vector (from the FT Sensor), is translated into a motion specification in cartesian space and then converted into an axis-specific velocity command. The control loop reduces the error between the target force and the actual force. If the deviation remains below 0.2 N for ten consecutive cycles, it is deemed stable, thus preventing misalignment of the panels. Once this condition is satisfied, the state machine proceeds to the next task.

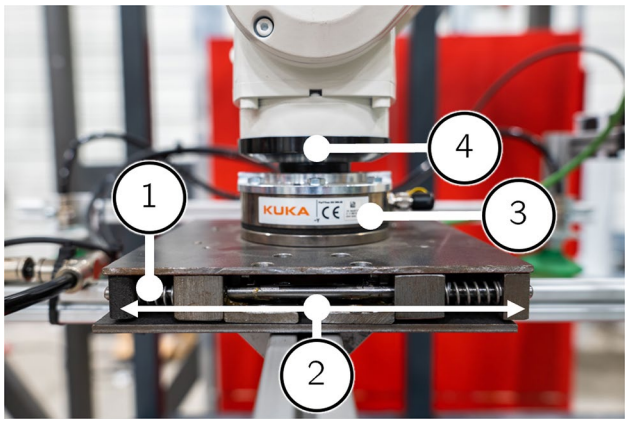


Fig. 5 Passive compliance system of the end-effector. 1) Spring 2) FT Sensor 3) Tool attachment point of the robot

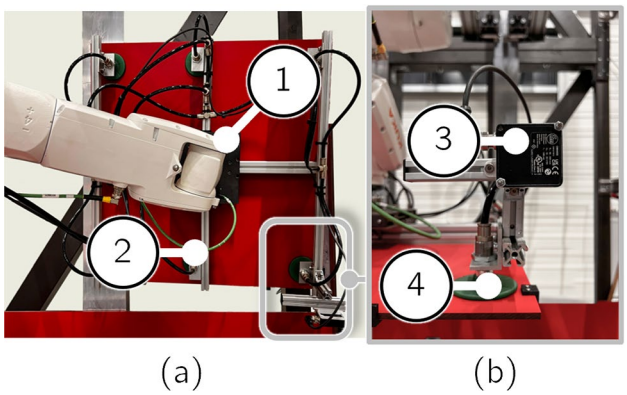


Fig. 6 End-effector design for the adaptive robotic platform. **a** End-effector with gripped refurbishment panel. **b** Distance laser for the detection of the sub-structure

(d) *Locating the Lower Edge* As described in step (b), the robot is currently about 20 cm above the lower panel row. The compliant motion control system now carefully drives the robot toward the lower reference with

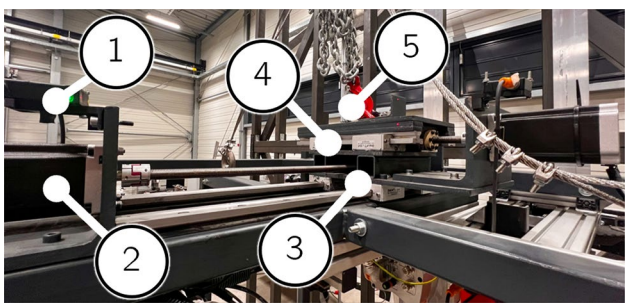


Fig. 7 Transitional load balancing system. 1) Distance sensor for the X-axis. 2) NEMA 34 stepper motor. 4) Translational slide for the X-direction. 5) Translational slide for the Y-direction. 5) Crane hook attachment point

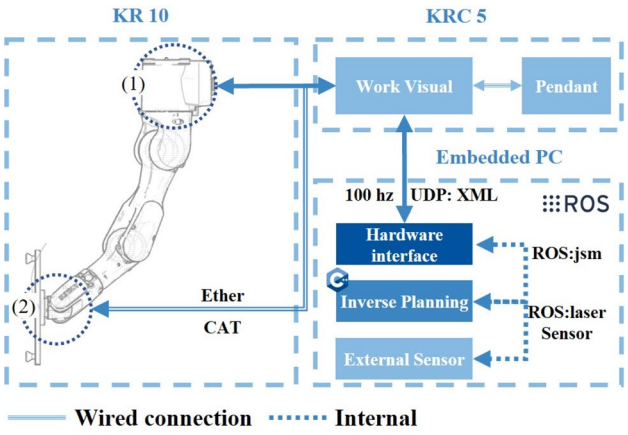


Fig. 8 Communication design of the robot

a constant force of (Y: 5 N, Z: 3 N) (see Figure 10). In contrast to the translational axes, which use defined force set-points, the rotational DoF are not regulated by active torque. Instead, the end-effector can rotate passively about θ and ϕ, allowing it to adapt to the lower edge. Additionally, to compensate for the near-sinusoidal vertical oscillation (Section 4), a passive vertical translation along the Y axis (see Figure 10 (5)) is permitted. This accommodates low-frequency motion of the panel and ensures stable contact. The concept remains constant for the following steps (*e, f*) Unlike the previous steps, the worker must confirm event-driven transitions to ensure precise placement.

(e) *Side Alignment* The refurbishment panel is positioned against the adjacent side panel using the same control approach as in step (d). A steady force of (X: 3 N, Y: 3 N, Z: 5 N) is applied, and the panel is tilted by 10° around the Y axis so that it touches the side panel at the lower corner (see Figure 12 (1)). A torque arises between the robot flange (see Figure 5 (4)) and the lower contact point, so the passive rotational movement is blocked to avoid uncontrolled rotation around the Z axis. When contact with the side panel is established, the worker confirms the next event.

(f) *Mounting the Panel* This step covers gluing the refurbishment panel. Here, the 10° inclination around the Y axis must be adjusted. In contrast to the previous steps (b, c), *active* translational compliance and *passive* rotational compliance both come into play. With a force of (X: 10 N, Y: 3 N, Z: 7 N) and passive rotation around ϕ, the panel is pressed against the sub-construction. Because bonding is a critical task, the worker must confirm the transition to the starting position.

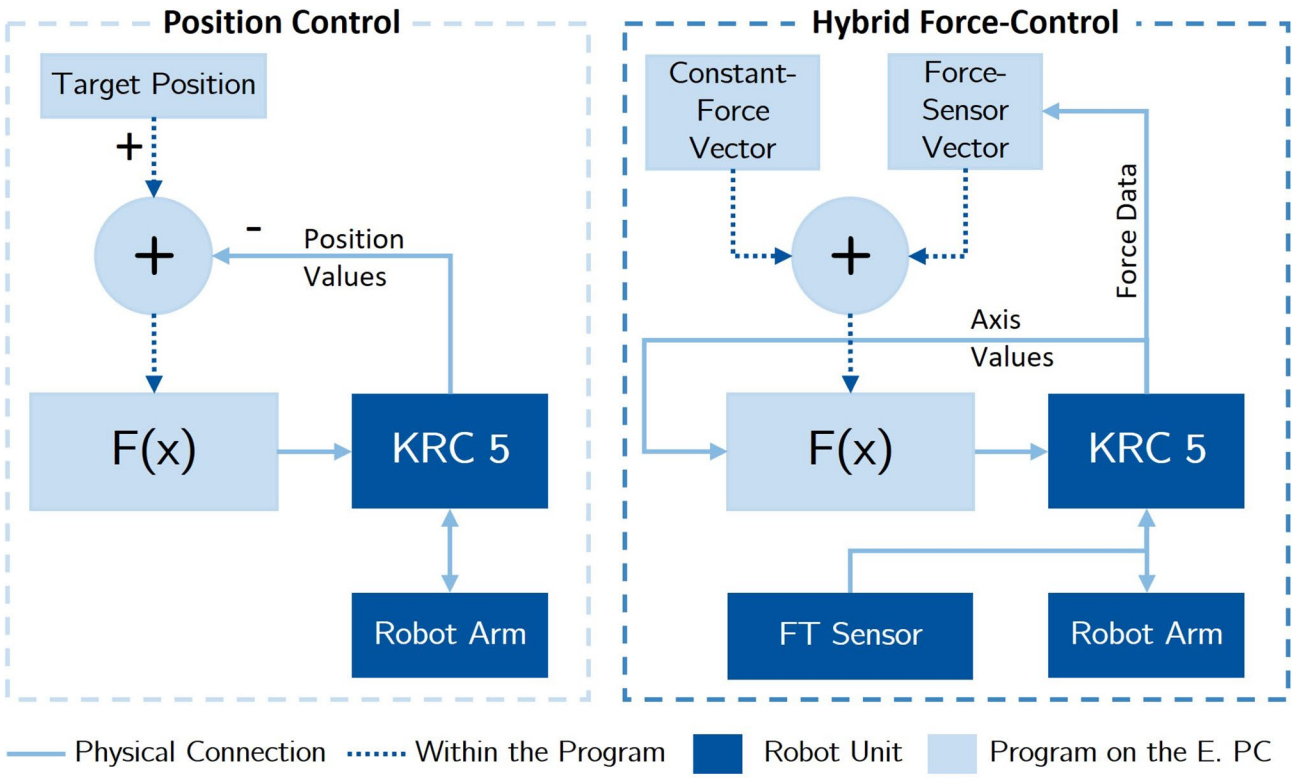


Fig. 9 Simplified schematic representation of the position control and the hybrid force-control

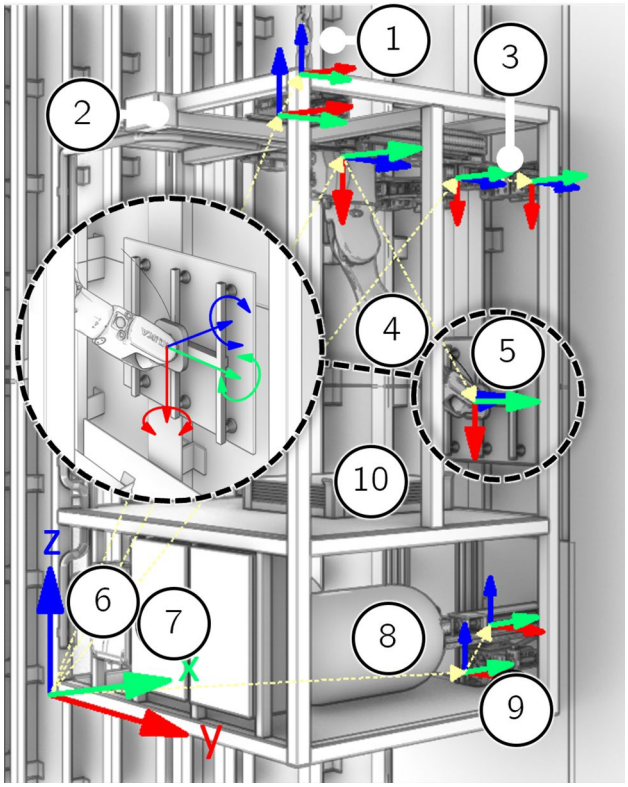


Fig. 10 Robotic platform with developed kinematic system. 1) Attachment point for the crane hook. 2) Metal frame. 3) Gripping system for stabilizing the platform. 4) Kuka robot 5) End effector with compensation system. 6) Robot controller. 7) Control computer with PLC and motor drivers. 8) Vacuum system for the grippers. 9) Vacuum foot for fastening and guiding the vertical movement of the platform. 10) Panel storage location

(g) *Restart / Transition to the Next Panel* Finally, the vacuum grippers are released, and the robot, under position control, moves back to the starting position.

The complex hybrid control architecture is designed to accommodate the changing non-discrete construction site conditions to ensure a safe and precise mounting process.

5.5 Stabilizing gripping-mechanisms for platform control

Following the concept of the rough and fine positioning system, the gripping mechanisms encompasses two sub-mechanisms as shown in Figure 3. The upper pair of articulated rail-guided gripping mechanisms holds the sub-structure and allows the platform to oscillate in the vertical direction by controlling the other DoF. The lower articulated pair of vacuum-guided mechanisms grips the newly installed panel row by means of vacuum grippers. Through a force-driven spring mechanism vertical oscillation is enabled.

In addition to stabilizing the mounting process, they play a crucial role in guiding the transition between mounting tasks. Therefore, a complex walking sequence has been developed to ensure constant contact with the façade while moving to the next row, reducing the risk of positional loss.

Figure 13 illustrates the upper rail-guided gripping mechanism, which consists of three main degrees of freedom:

1. *Adjustable Distance to the Façade:* The articulated clamping mechanism is designed to securely attach the system to the linear rail. The first DoF controls the distance between the platform and the façade (a). For precise adjustment, the articulated clamp mechanism is equipped with a closed-loop linear axis (1). This allows for adaptive positioning, ensuring continuous contact with the structure while compensating for variations in façade geometry. In addition, this axis plays a key role in decoupling horizontal oscillations, preventing unintentional load on the gripping system.
2. *Articulated Clamping Mechanism:* It consists of parallel kinematics (b) actuated by a closed-loop stepper motor. When the two arms of the gripper open to detach from the base, the spring-loaded bearings (2) are retracted. In the closed position (a), the spring-loaded bearings (see Figure 14 (1)) guide the platform vertically, ensuring stable movement along the rail. In addition, the mechanism facilitates the decoupling of vertical vibrations, reducing external disturbances and improving system stability.
3. *Manual Adaptation for Different Sub-Structure Grids:* The third mechanism (see Figure 13 (2)) allows for manual adjustment along the metal frame, ensuring compatibility with different sub-structure grids. This flexibility is essential for adapting the system to varying construction conditions while maintaining structural integrity. By allowing manual repositioning, the system enhances its versatility without compromising on precision.

Figure 15 shows the articulated pair of vacuum-guided mechanisms, which comprises three main subsystems:

1. **Articulated Arm:** The articulated arm (1) establishes the connection between the four vacuum cups and the vertical axis. A linear, closed-loop driven axis makes it possible to adjust the distance between the façade and the platform(2). The array of vacuum grippers (3) are controlled directly via a relay.
2. **Vertical Axis:** The vertical axis includes an additional degree of freedom (4) to facilitate vertical adaptation. It decouples the vertical oscillations while ensuring precise vertical positioning of the articulated arm. To enable this decoupling, an active force control system compensates for the arm's weight. A closed-loop stepper

motor (5) with active force regulation applies a constant upward force via a leadscrew (6). When the vacuum gripper is detached from the façade, the motor switches from the force control to a position control, allowing the arm to move to the lower position (see Figure 16 a) to b)). This transition enables the platform to move to a new location.

5.5.1 Safe position shift of the platform

In order to ensure a safe position shift between the two panel placement positions, a motion sequence has been developed to ensure a stable, safe three-point contact during the position shift.

Figure 16 displays the developed walking transition from the lower row to the next mounting position. During the transition, three of the four mechanisms remain in contact with the façade to prevent uncontrolled movement of the platform. The system performs a walking sequence as follows:

1. As displayed in Figure 16, both systems are moved separately from the lower end (a) of the linear axis to the upper end (b) by the position-controlled motors (2). A special trajectory planner is implemented to track the seams between the refurbishment panels using an integrated laser sensor. Similar to the end-effector's laser sensor (see Figure 12 (2)), this sensor creates a profile of the façade, allowing the program to directly detect the seams. The trajectory planner then calculates an optimal position for the lower gripper (see Figure 17 (1)) .
2. Once both systems are engaged, the position-controlled motors switch to a passive compliance mode (see Figure 12 (1)), which allows the two grippers to move as required. A signal is sent to the crane's action server to initiate the platform lift.
3. A two-phase controller uses the distance between the platform and the ground measured by the lower laser (see Figure 15 (1) and Figure 17 (2)) to control the crane's lifting velocity, ensuring that the platform reaches the next target position.

This process is repeated until the final row position is reached.

6 Experimental results

The following section details the demonstration of the adaptive robotic platform described in Section 5. Testing was conducted under controlled indoor conditions as well as in a realistic construction site environment on the test-bed. Initially, the system's precision is evaluated under controlled conditions (see Figure 2 (a)). Next, the generated forces are measured, and each sub-step is time-tracked to provide accurate timing feedback. In addition to panel placement, the walking concept is also assessed.

Finally, the entire process is repeated under outdoor conditions on the large test-bed (see Figure 2 (b)), offering a realistic perspective on the procedure's field performance.

6.1 Indoor evaluations

6.1.1 Evaluation of the mounting process

Figure 18 illustrates the test setup, which comprises the lifting device (*Jekko-crane*) (1), the build demonstrator structure with its sub-structure (2), and the adaptive robotic platform (3). A crucial aspect of the platform's performance is its accuracy; only a precise image of the joint seams enables the system to be deployed under real-world conditions. Accordingly, 10 tests were conducted in which the system mounted both the right and left panels. Figure 19 (*1 = Lower left (LL), 2 = Lower right (LR), 3 = Right side (RS)*) shows the three measurement points recorded to determine the deviation.

The results summarized in Table 1 demonstrate the high relative placing accuracy achieved by the system. Here the gap between the lower panel and the 3D printed spacer was measured, with a resolution of 0.05 mm. In particular, the lower-right (*LR*) and lower-left (*LL*) positions exhibit no deviation from the target position, while the side-right (*SR*) position shows a slight average deviation of 0.178 mm.

The proposed adaptive robotic system is in particular depending on the right interaction between the different force and torque values, set-in the system. Figure 20 represents a mounting sequence. The following observations were made during the mounting process:

1. As shown in Figure 20(1), the force on the relevant axis suddenly increases to approximately 80 N, indicating that the system was able to reliably grasp the panel. However, subsequent assembly errors occurred due to inaccurate placement of the panels at the storage location. In particular, when the refurbishment panel was shifted along the Y axis at the storage location, the substructure was sometimes missed, resulting in an aborted process.
2. As described in Section 5.1.1, the use of a laser sensor (see Figure 12) enabled a reliable mounting process. In the absence of the laser sensor, initial mounting errors were observed when the robot, while approaching the substructure, missed one of the two aluminum rails.
3. Step (d) illustrated in Figure 11 required precise parameter tuning. The system must distribute the force evenly at the contact points shown in Figure 19 (1 and 2), a task aided by the passive rotational compliance. A balance is

necessary between excessive compliance in the rotation about the Z axis and insufficient compliance. An overly high compliance value caused oscillations, prompting the torque monitoring to halt the robot's movement. When the compliance was insufficient, the contact deviation occurred. Additionally, Figure 21 details a persistent oscillation (1) around the *Y* axis observed when both contact points on the lower panel were engaged. Although this oscillation did not adversely affect the mounting quality.

4. The lateral placement of the refurbishment panel (see Figure 19(3)) posed a challenge during mounting. Due to the moment between the robot flange and the 3D-printed spacer, the panel became susceptible to an undesired rotation about the Z axis, which led to a loss of accuracy at the UL contact point. This behavior resulted from play in the passive translational compliance along the Z direction (see Figure 6(a)). By reducing the lateral force and executing a targeted, short translational movement along the Y axis, the inaccuracies were effectively compensated.

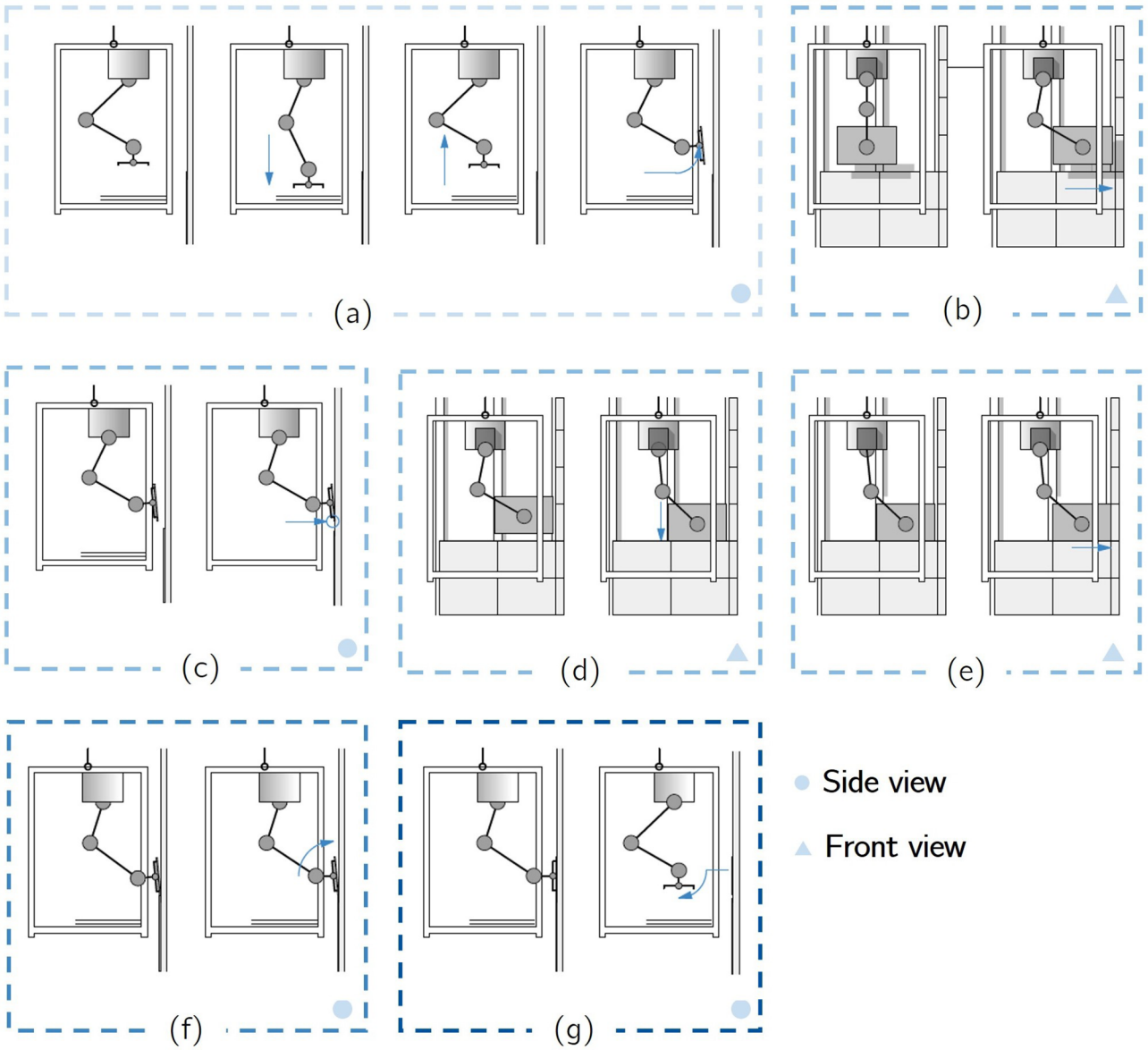


Fig. 11 Schematic representation of the robot trajectory: **a** Picking up the panel from the storage, **b** Locating the sub-structure with the help of the distance laser, **c** Creating contact between the sub-structure and the panel, **d** Vertical movement towards the upper edge of the lower row, **e** Sideways movement to create contact with the right side of the panel, **f** Creating full contact between the panel and the sub-structure; double-sided tape holds the panel, **g** The vacuum is turned off, and the robotic arm moves back to the starting position

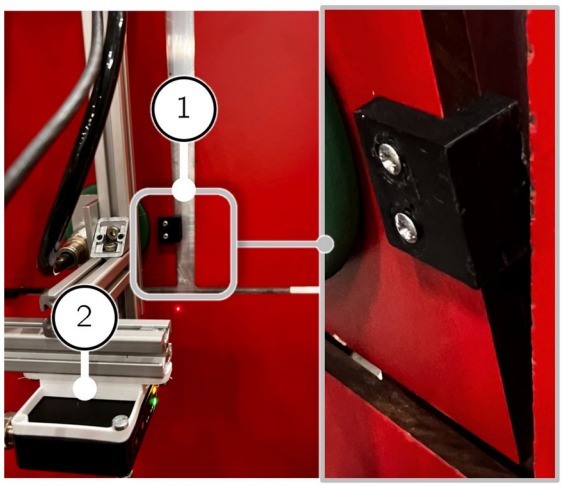


Fig. 12 Refurbishment panel being aligned to the adjacent side panel. 1) A 3D-printed spacer, screwed onto the panel, ensures a uniform and clean seam between panels. 2) A laser distance sensor detects the sub-structure behind the façade, enabling accurate placement of the panel at the designated target position

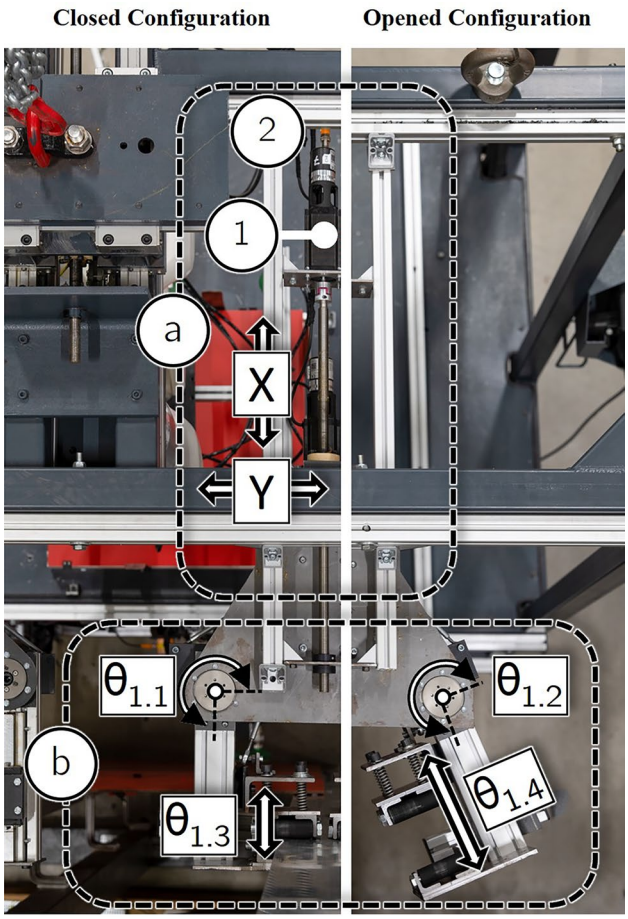


Fig. 13 The upper rail-guided gripping mechanism. Top-view of the upper gripping mechanism in opened and closed configuration. 1) Closed loop stepper motor 2) Manual adaption along the X-axis

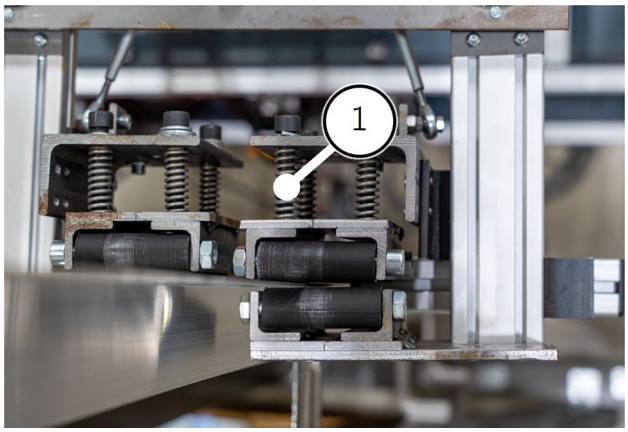


Fig. 14 Spring loaded bearings attached to the sub-structure. 1) The springs presses the guidance bearings with a constant force

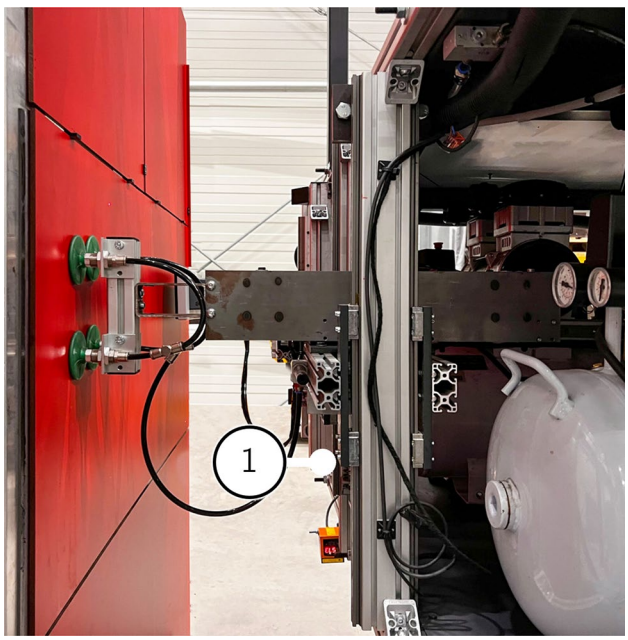


Fig. 15 Lower vacuum-gripping mechanism. The mechanism comprises four vacuum cups. A vacuum tube connects them to the main vacuum generator (1) on the lower side of the vertical axis

The assembly time plays a crucial role in the system's viability on a construction site. The following analysis, however, represents the mounting process of a panel row. In the following, the mounting of the refurbishment panel is examined; this process is divided into individual substeps based on the structure shown in Figure 11. There was a small time difference between the two sides, with the right side taking an average of 275 s, while the left side was slightly faster at about 255 s due to the shorter trajectory.

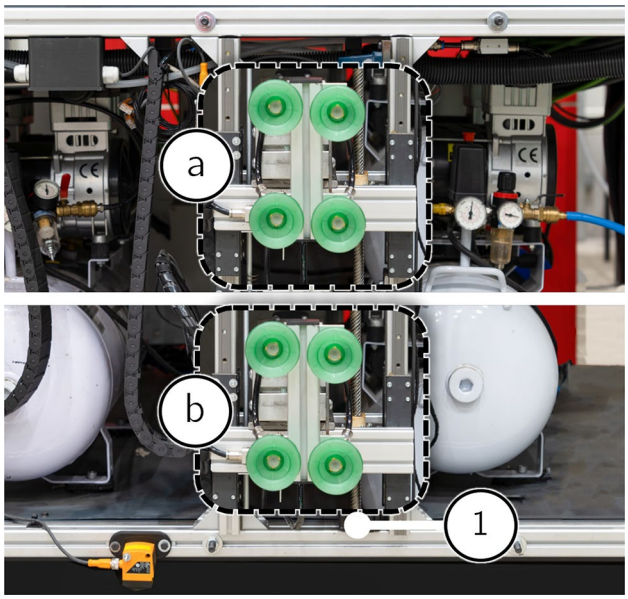


Fig. 16 Front view of the lower vacuum-gripper mechanism. a, b) Lower and upper configuration of the vacuum-gripping mechanism 1) CAN-Bus controlled stepper motor

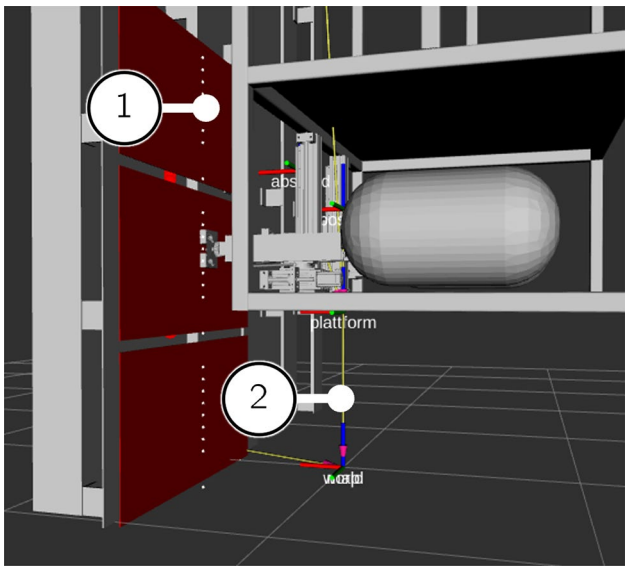


Fig. 17 View of the robotic platform in RVIZ [51]. 1) Visualization pre-plant placing positions for the left foot 2) Transformation between the ground and the platform

6.1.2 Evaluation of the load balancing system

The developed load balancing system was able to horizontally balance the platform as planned, as the translatory axes (X and Y) had sufficient play to counteract the load shift. In this process, the service node–directly activated through the web interface–assisted in the balancing. It was, however, critical to ensure that the platform was freely attached to the crane. If this was not the case, changes in the control loop did not result in any adjustments, and the system shifted uncontrollably.

Additionally, the system was found to actively improve both the lifting and mounting processes. When the translational X-axis was moved toward the façade, the vacuum grippers were passively pressed against the lower installation row, thereby improving the grip.

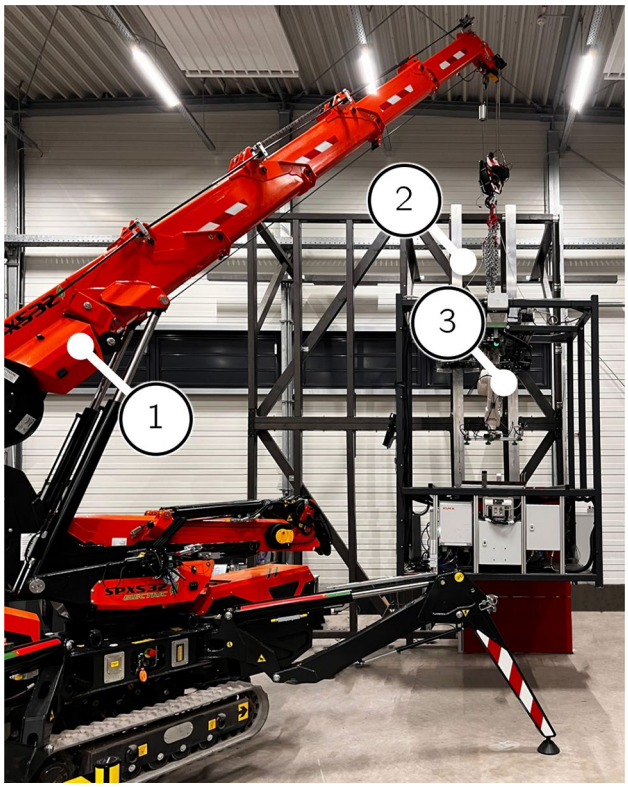


Fig. 18 Adaptive robotic platform under controlled conditions. 1) Jekko-crane 2) Sub-construction 3) Adaptive platform

Table 1 Performed evaluation of the platforms placing precision (N=10). Scale in mm

Measurement	LR	LL	RS
Average	0	0	0.178
Median	0	0	0.1

6.1.3 Evaluation of the stabilizing gripping-mechanisms for platform control

In this section, the evaluation of the stabilizing gripping-mechanisms process is described, including the achieved speed and the issues encountered. The developed gripping systems are an essential component of the rough positioning

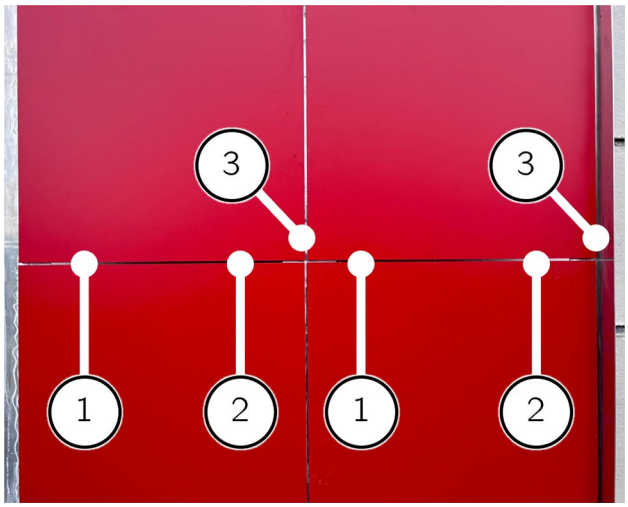


Fig. 19 Measured contact points. 1) Left spacer 2) Right spacer 3) Side spacer

system. It secures the mounting process by preventing uncontrolled oscillations of the platform.

When the platform was balanced the platform could be lifted with the help of the mobile crane. To control the position of the mobile crane a remote controller is used. Next the articulated clamping mechanism has to be opened in order to grip the face, the worker carefully guides the platform towards the façade. When the gripper positioned on the sub-structure, the web-interface is used to send a command to close the grippers. This process step can be executed by a worker. Once gripped to the façade, the system could be freely moved along the sub-structure to target position. A fix distance was used to align the lower and upper gripping system on the façade. Both synchronized, the rough positioning system could rotate around θ and ϕ.

The walking sequence was used to transition the platform from the lower to the upper row. The described sequence (see Section 5.2) performed as intended, although the stepper motor of the vertical axis, in combination with the high lead on the lead screw, resulted in a low transition speed. This led to an average transition time of around 9 min to switch between the two rows. To enable a faster transition, the lower row can be retracted while the platform is guided

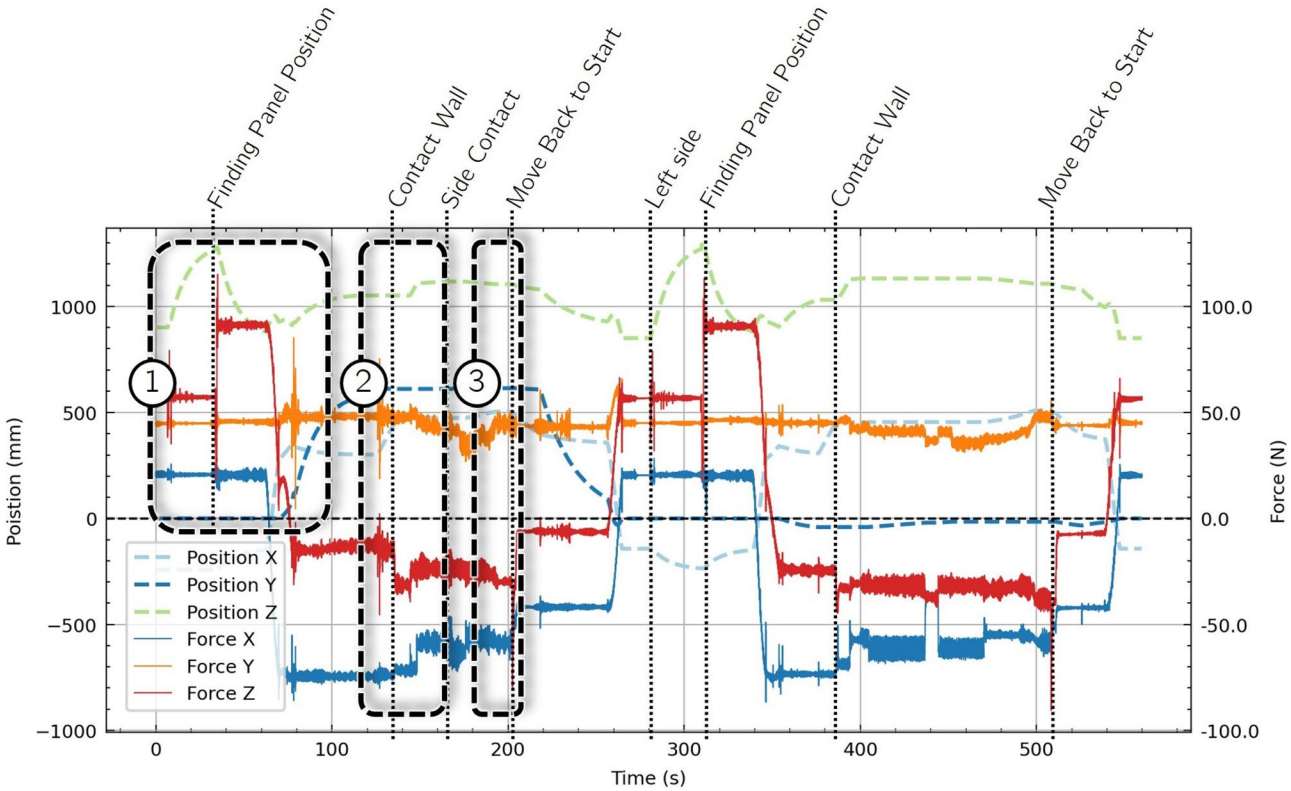


Fig. 20 Measured force and position data of the robotic arm during one full placement cycle. To overlay position and force data, the left Y-axis displays the position in mm, and the right Y-axis displays the measured force data in Newton (N). 1) Picking the refurbishment panel from the storage location 2) The refurbishment panel makes contact with the sub-structure 3) The robot moves back to the starting position

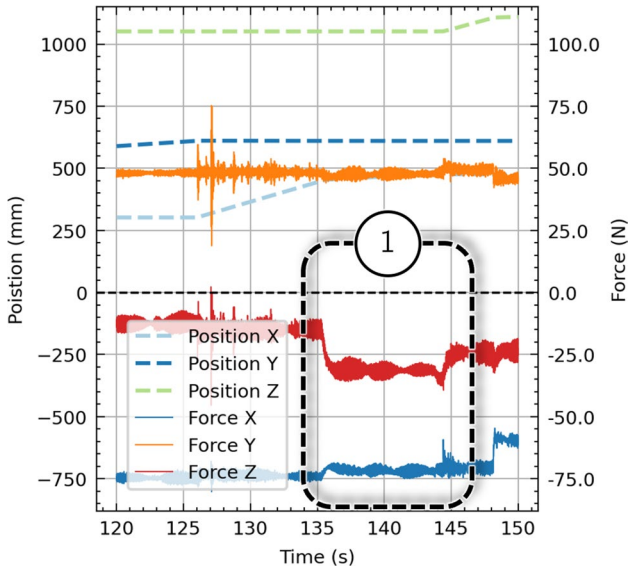


Fig. 21 Measured force values during the panel placement

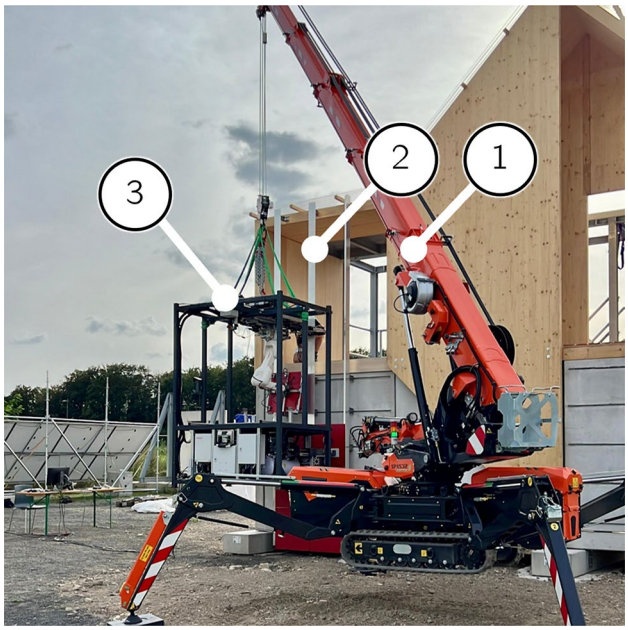


Fig. 22 Adaptive robotic platform on the outdoor test-bed. 1) Jekko crane 2) Sub-construction 3) Adaptive platform

by the upper grippers. Although this approach results in shorter transition times, it also increases the risk of position loss, which could limit the fine positioning system's ability to accurately place the refurbishment panels.

6.2 Outdoor evaluations

Figure 22 shows the developed system on the large-scale test-bed. As in the indoor tests, the system comprised the mobile Jekko crane (1), the sub-structure mounted on a reference building (2), and the adaptive robotic platform (3). The objective of the experiments was to determine whether the developed system could successfully attach a series of panels under outdoor conditions. It was found that the system reliably brought the refurbishment panels to the façade, and no significant influence from external forces, such as wind, was observed.

7 Discussion

In summary, the novel concept for an adaptive robot platform for façade renovation shows promising results. The development is based on the research question of whether it is possible to develop an adaptive robotic platform which, unlike existing methods, can use a construction crane or similar cable-supported system and be deployed quickly and flexibly, and is controllable using adaptive control methods. In the following, the results recorded in Section 6 are compared and classified with the data and results of comparable projects and procedures (see Section 2).

The assembly accuracy is a key indicator of the practical suitability of the developed system. The Internationale Föderation (2020) serves as a reference here, which defines the required assembly accuracy depending on the component size. For the highest requirements (class 3), a maximum position deviation of ± 1.5 mm is specified. In contrast, the developed platform achieves an average assembly deviation of $Y = 0.17$ mm and $Z = 0.0$ mm, and is therefore well within the required target range. However, a vertical oscillation of about 2 cms was detected. In comparison, the cable-guided robot platform presented in Section 2 (see Iturralde et al. (2022)) achieves assembly tolerances between 4 and 23 mm. This shows that the chosen approach not only has significantly lower tolerances, but also enables a more uniform installation accuracy over the entire façade surface. In contrast to the cable robot, the developed solution is characterized by a homogeneous accuracy — a decisive advantage of the newly developed system.

Another critical comparison concerns process time. In contrast to the manual process - which, as Liu et al. (2024) indicates, typically requires an average installation time of between 15 and 60 min - the presented solution differs significantly in its overall approach. In particular, the developed system does not require the assembly of scaffolding, which is usually an essential part of the manual process and contributes significantly to the overall time and cost. Furthermore, compared to existing cable-operated robotic systems (see Iturralde et al. (2022)), the presented approach eliminates the need to construct and mount the cantilever structure (see Section 2). This advantage allows the system

to be operated either with an existing site crane or with a mobile site crane (e.g., the *Jekko crane*), thus reducing the set-up time. In the evaluation of the process, the placement of the two refurbishment panels took on average 8 min.

The transition time of approximately 9 min should be further reduced to speed up the process. If the crane lifts the platform without the lower vacuum clamps engaged, the lifting time can be reduced to around 9 s. It should be noted that this configuration may result in misalignment of the platform.

The hybrid control architecture proved capable of responding dynamically to both indoor and outdoor environmental changes. By leveraging real-time sensor data–such as from laser sensors (see Figure 6), the system continuously updated its positional model to account for shifts in the substructure, thereby maintaining accuracy despite varying conditions. The integrated active and passive compliance mechanisms effectively compensated for errors introduced by the rough positioning system, ensuring that any minor discrepancies were corrected during operation. Nevertheless, several challenges remain: the force control showed some uncontrolled oscillations, and the system still relies on external inputs to determine when to transition between control states.

Taken together, these findings indoor and outdoor of the test results indicate that the platform is a promising solution in terms of both accuracy and process time. The data clearly shows that the system achieves significantly tighter tolerances and competitive cycle times compared to existing methods. Further testing in the construction site environment could help provide insight into the behavior in scenarios affected by wind and other variable environmental factors. This will be essential for future development of the adaptive robotic platform.

8 Outlook

Building on the existing results, future work should focus on improving the control architecture. Currently, the system is optimized for placing refurbishment panels of the same size. Descriptive programming and the integration of planning data could help create a more flexible panel placement process. With integrated concepts such as descriptive programming, the fine positioning system could independently detect panel sizes and avoid errors by using the integrated FT sensor and tactile fiducials built into the platform.

Future work should focus on increasing the mounting velocity, since the average mounting time could hinder the system from being broadly deployed. In the current configuration, the velocity of the robot is limited within the program for safe testing, but with further improvements, the overall mounting time could be reduced. In addition, by integrating stronger motors, the transition time of around 9 min could be significantly reduced.

In the scope of the work, the operator is an essential part of the operation. The operator oversees the process and corrects the robot's mounting process. It's part of the approach that the operator is an essential part of the operation. Currently, as shown in the indoor testing, the program is not always able to differentiate between the friction of the sub-structure and the final placing position. In addition, the integration of the worker into the platform control could be improved. When lifting to great heights, integrated sensing must be implemented to monitor the process from a safe distance.

Currently, a worker is required for control, but future work could help streamline multiple processes to increase worker efficiency. Here, the operator is still needed to confirm the final placing. When the system is further improved, the worker's role could be to oversee multiple processes at once.

At present, the adaptive process has been tested on the semi-automatic panel assembly use case. Next, the process should encompass the entire assembly of the ventilated rainscreen façade system (mounting of the brackets, applying the insulation layer, and installing the substructure). This will require the existing stabilizing gripping mechanisms to be made more adaptable to different surfaces. Additionally, the system's awareness is currently limited in detecting different surfaces. The work already explained the use of a distance laser to detect the seams of the refurbishment panels. In the future, a LiDAR in combination with a camera could significantly improve the system's adaptation to different building geometries.

Since the system doesn't need a complex cable setup, it could be used for the maintenance and construction of high-rise buildings. A crane system could be placed on top of the building to lift the robot façade platform. The crane chain can be considered as a spring-like element whose flexibility increases with length, making vertical oscillations more pronounced and the role of passive compliance of the robotic façade platform even more important. New requirements come into play: strong wind, and a new transport chain for the building components has to be designed. Data transmission is also becoming more important. Given the long distance, the 5 G network must be tested for this use case to verify the stable control of the robotic façade platform.

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information for writing. In addition, Aaron Lentes' interal documentation of the end-effector was a reference source for the description of the end-effector section. Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work the authors used DeepL and ChatGPT in order to improve the readability and overall grammar. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Author Contributions Christoph Heuer wrote the manuscript. All authors reviewed the manuscript.

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Availability of data and materials No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest We would like to note that Prof. Sigrid Brell-Cokcan serves as Editor-in-Chief of the journal. To ensure an impartial and transparent peer-review process, a different Editor was assigned to handle our submission.

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