Robotic platform for the (semi-) automated assembly of façade panels

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Abstract

48% of total energy consumption in Europe is used in buildings and homes. These are therefore accountable for 35% of Europe's total CO_2 emissions.

To solve this problem in a sustainable way, the building stock would have to be thermally refurbished further. Currently, the annual thermal refurbishment rate is only 1% of the total building stock, but the sector is already at its production limit. One reason for this is the ongoing shortage of skilled labour. Robotic systems can help here. In collaboration with Fundermax GmbH, St. Veit/Glan, Austria, and KUKA AG, Augsburg, a concept was developed for a (semi-) automated assembly platform that relieves workers of the task of assembling heavy façade panels. Systems that have already been developed are dependent on a complicated setup. This makes it very difficult to use these systems on the construction site.

This research project investigates how existing processes can be expanded so that the threshold for using robotic systems on the construction site can be lowered further. To this end, this work analyses existing processes, derives a concept and then evaluates it using simulations.

Keywords –

Façade robot; Robotic refurbishment; Automation

1 Introduction

As a result of the energy transition, the topic of energy-efficient refurbishment of existing buildings is moving further into the focus of public discussion. Looking at the potential savings, the building sector accounts for 35% of Europe's CO_2 requirements. However, only just under 1% of the building stock is currently thermally refurbished each year, although a gradual increase in the refurbishment rate to 4% could save 14.4% of Europe's gas demand by 2025 [1].

However, modernisation is a cost-intensive measure [1]. There are various options for the subsequent thermal modernisation of a façade [2]. Solutions for the automated installation of ventilated rainscreen facades are being researched as part of the Enable Refurbishment 4.0 research project. Ventilated rainscreen facades are based on a combination of supporting structure, insulation and rain protection/optical covering [3]. The first step is to examine the extent to which the external façade panels, which serve as visual and rain protection [2] can be installed (semi-) automatically on the façade.

The individual façade panels, though, weigh up to 105 kg in some cases (see 2.1). Scaffolding currently has to be erected for the installation of the façade elements. The façade elements are then lifted to their destination by specialised personnel. The panels must be positioned very precisely, as deviations are easily recognisable in the later appearance. Assembly is currently still carried out exclusively by hand.

Working on the façade in particular involves a high risk for construction site personnel. Risks include: Danger of falling from great heights, increased risk of injury due to lifting heavy loads, changing weather conditions. Automation can minimise these risks [4] and counteract the ongoing shortage of skilled workers [5].

Automated activities in the area of façades include building maintenance (see 2.2). They can perform valuable work, particularly when cleaning large façades. Developed systems are guided to the desired position by a cable system, among other things. The system for this, however, requires a complex installation [4].

As part of the *Enable Sanierung 4.0* research project, an alternative approach is being developed with the aim of enabling the (semi-) automated assembly of façade panels. The concept developed utilises a tower crane as a lifting device, unlike existing solutions such as the *Hephaestus CDPR prototype* [6]. The project is based on a patented gyroscope development, which was developed at the *Centre Construction Robotics*, Aachen, Germany [7]. The process is exemplary for a range of activities in the field of façade modernisation and can be applied to other fields.

In the first step of this work, existing research work and its limitations are presented and the reader is given an insight into the functional structure of ventilated rainscreen facades. The requirements and the developed concept are then explained and subjected to an initial simulation using *Gazebo*. The results provide an initial assessment of the extent to which the concept can be implemented in a prototype.

2 State of the art

2.1 Conventional montage of the façade-system

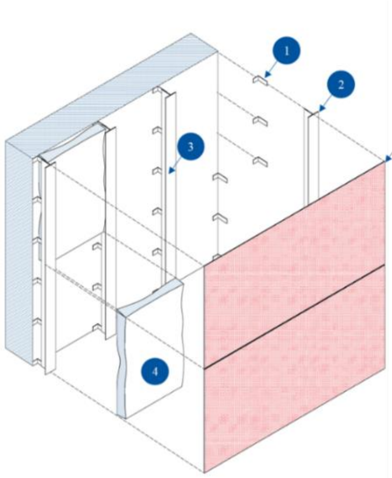


Figure 1. 1) Bracket for fastening the rail 2) T-shaped rail is screwed to the brackets 3) Fastened T-shaped rail 4) Rock wool is inserted into the intermediate areas 5) Visible panel is connected to the T-shaped rail (fastening method: screws, rivets, adhesive)

A variety of methods are available for the modernisation of façades [2]. This paper only considers the ventilated rainscreen facade system. The system can react flexibly to the respective requirements, e.g. insulation thickness [8]. This is a three-stage system consisting of a support layer, insulation layer and weathering cladding [3].

The façade system used in the research project is described below (see Figure 1):

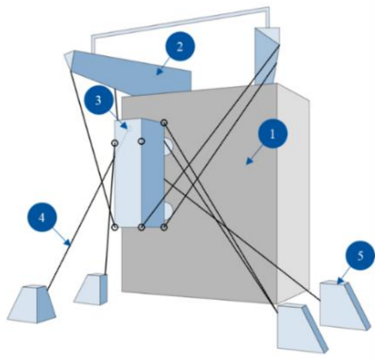
- Aluminium brackets are attached to a structural load-bearing layer (e.g. concrete or stone) at a fixed grid spacing (see Figure 1. point 1)
- The insulation can now be applied to the façade (see Figure 1. point 4). This can be done using a bolt setting tool, for instance
- An aluminium T-shaped rail is attached to the brackets. The rails can be used to level out any unevenness in the façade. The aim is to create a flat surface for attaching the cover panels [9] (see Figure 1. point 2)
- The façade panels are then attached to the T-shaped rails. Common methods of attaching the façade panels to the T-shaped rails are stapling, nailing, screwing and bonding [10]. In order to achieve a clean joint pattern, the components must be installed precisely. The required tolerance is an accuracy of ±20% of the joint width [11]. The weight of the façade panels is heavily dependent on the actual size of the components. Due to the relatively high density of 1450 kg/m3 of the façade panels, a common format of (280cm x 130cm) results in a weight of 105kg (see Figure 1. point 5)

2.2 Existing façade robots

The field of façade robotics covers a wide range of different tasks. These range from inspection tasks to assembly works. In general, the following four functional principles can be derived according to Kepa Iturralde [12].

2.2.1 Cable-guided robots

A cable-guided parallel robot is guided along the façade using actuators. An example of this is the Hephaestus Robot (see Figure 2). The cable robot, developed for the assembly of façade elements, has a high load-bearing capacity. However, it requires a complex set-up, as the developers highlight in [4].The time required to set up the system is currently the biggest obstacle to market readiness.



Graphic derived from: [6]

Figure 2. 1) Façade structure 2, 5) Tension point assemblies guide the cable system 3) Platform connected by the cable system 4) Cables for lifting the platform [6]

2.2.2 Crane-guided systems

Powerful lifting machines lift the robot to the desired position on the façade [12]. As part of the research project to develop a cable robot for the installation of curtain walls. Tests have shown that the developed cable robot has a positional deviation of 22 mm. However, this varied within the robot's working range. By recording the position with a total station, the error could be further reduced [4].

2.2.3 Cartesian moving systems

An assembly platform is lifted to the desired position using a linear system installed on the façade. Vertical overhead cranes are included in this group.

2.2.4 Other systems

This category includes systems and individual solutions [12]. One example is the wall-climbing robot developed, which can apply a maximum load of 35 kg using an electrically activated adhesive [13].

2.2.5 Conclusion

An overview of the solutions developed for façade robot systems reveals limitations in the handling of heavy panel components. The field of façade robotics covers a wide range of different tasks. These range from inspection tasks to assembly works.

The cable-guided robots in particular require a particularly complex assembly. Restrictions in the accessibility of the platform also complicate its use in existing building modernization [4]. The challenges mentioned above emphasize the need for further research and development in this area in order to develop more efficient and practicable solutions.

3 Robot-Assisted montage approach

3.1 Process requirements

The most important aspects resulting from the catalogue of requirements developed are explained in the following chapter.

3.1.1 Lifting devices

The maximum weight of the platform is determined by the permissible lifting capacity of the crane. A tower crane (L1-24) from *Liebherr-Components Biberach GmbH, Biberach an der Riß, Deutschland,* is used to lift the façade plattfom. With a maximum outreach of 25 metres, the crane can lift 950 kg at the top. The load is picked up via a crane hook block. The advantage of the crane is its quick assembly on site and the general availability of finished crane systems [14].

The dynamic forces and the inertia properties of the construction crane generate oscillations in the vertical direction when a load is moved. The oscillation varies depending on the weight, wind, trolley position and acceleration (see 4.1).

3.1.2 Rough and fine positioning

The principles of rough and fine positioning should serve as the basis for the development of the façade robot, which was already developed in previous project at the *Centre Construction Robotics*, Aachen, Germany. According to that the platform should first be navigated to its rough position on the façade. Once this predefined position has been reached, the *KUKA robot (KR 10)* should carry out fine positioning and place the façade panel at its destination. The integrated force-torque sensor can help to find the desired alignment. The selected robot initially limits the panel weight to less than 10 kg.

3.1.3 Assembly process of the panels

For an initial test of the façade robot, a fixed panel format of horizontal: 125cm vertical: 62.5cm was selected. The façade element was then glued to the T-shaped rail. The advantage of gluing as a fastening method is that the panels can be prepared in advance with the adhesive and can be applied directly to the T-shaped rails by the robot without any further intermediate step. The fastening method involves two adhesives. A double-sided adhesive tape from *Innotec GmbH & Co. KG* is applied in such a way that it is later centred on the T-shaped rails. An even strip of silicone adhesive is applied to each side. The purpose of the adhesive tape is to hold the façade panel in position until the silicone adhesive has cured. The bonding process requires compliance with fixed process boundary conditions such as temperature, humidity and surface cleanliness [8].

With a centre-to-centre distance of the T-shaped rails of 62.5 cm, each façade panel rests on three T-shaped rails. This results in a shear load (0.28 N/mm²) of 6,300 N and a breaking load (0.28 N/mm²) of 8,640 N for each façade panel [15]. In addition, the manufacturer of the façade system specifies a permissible horizontal compressive force of 2.0 kN/m², which results in a maximum load limit per façade panel of 1.5 kN [8].

3.2 Concept description

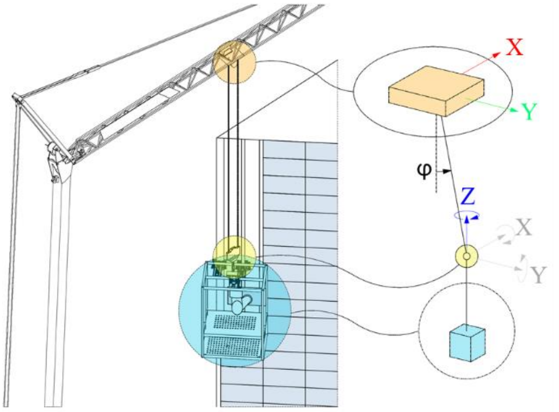


Figure 3. Display of the degrees of freedom of the robotic system. The axes that are greyed out cannot be controlled. The development is based on the patent [7]

The following section explains the overall system concept and how it fulfils its function of façade panel positioning under these constraints. The basic elements of the system and their task as well as a description of the assembly process are then presented.

3.2.1 General parameters

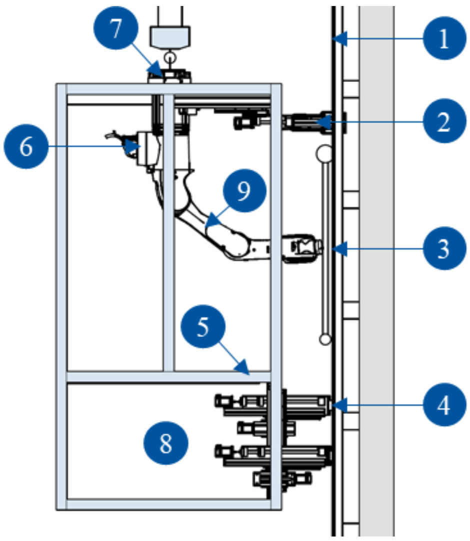


Figure 4. Function diagram of the facade robot. 1) T-profile rail 2) Upper gripper assembly 3) End effector 4) Lower vacuum grippers 5) Frame of the coarse positioning unit 6) KUKA robot (KR 10) 7) Adjustable load fastening point 8) Rough-positioning-unit 9) Fine-positioning-unit

When positioning an object in space using a construction site crane alone, all six degrees of freedom are in principle indeterminate with regard to the accuracy required here, as will be explained below. The concept of how these degrees of freedom are controlled is then presented. The crane cable results in two pendulum axes, which results in an approximate linear degree of freedom in the X and Y directions for the object on the crane hook. In addition, high loads result in spring pendulum-like movements in the Z direction (see Figure 4). A construction site crane controls the Z-position of the load basically by the length of the crane rope (see Figure 3), but as described in the tests in (see 4.1), it was shown that this positioning in the Z-direction does not meet the requirements defined by the process. The vibration measurements showed that a sinusoidal carrier frequency is found here, which is overlaid by smaller vibrations that represent a disturbance variable of the positioning. Initial measurements showed that a sinusoidal beam frequency is present here, which is superimposed by smaller oscillations (see 4.1)

There is also a rotational degree of freedom around the Z axis and minor influences due to rotational movements around the X axis and the Y axis, resulting from the unguided pendulum motion of the mass, which are not considered further in the following analysis due to their minor influence on positioning (see Figure 3). To summarise, there are three linear degrees of freedom and one rotational degree of freedom that need to be controlled.

One of the main aspects of this project is to utilise existing structures of the façade in order to reduce the number of degrees of freedom and the complexity of the task while maintaining the required high positioning accuracy. To this end, the T-shaped rails used in this façade system are utilised as linear guides. By means of two sliding grippers (see Figure 4. point 2), the entire rough positioning unit slides along the T-shaped rails in the Z direction, which are already firmly bolted to the wall, while the weight is still almost entirely taken by the crane.

This concept determines all open degrees of freedom with the exception of the translational degree of freedom in the Z direction, which is affected by the sinusoidal oscillation of the crane. This disturbance is detected and compensated for with high positioning accuracy by the KUKA robot (KR 10) and a specially developed end effector.

By determining the degrees of freedom in this way, the weight force and thus the main load of the system continues to be borne by the crane and only lateral forces caused by wind or vibration superimposition are absorbed by the T-shaped rails.

3.2.2 General design

The following section explains the individual assemblies and how they work.

Upper grippers: The main task of this assembly is to secure the rough positioning unit to the T-shaped rails while maintaining the mobility of the entire system with low friction in the Z direction in order to minimise the load caused by the weight of the system on the profile rails. This assembly also ensures lateral guidance of the system on the façade. (Figure 4. Point 2)

Vacuum grippers: This assembly uses vacuum grippers to ensure permanent contact with the already installed elements of the lower row of façades during the installation process, whereby it should be noted that the following façade elements are always installed in the positive Z direction. It is installed in the rough-positioning-unit so that it can move in the Z direction by means of a spindle with a movement thread, thus allowing the crane to oscillate periodically without losing contact with the wall surface and still remaining controllable (Figure 4. Point 4). By controlling the torque of the stepper motor that drives the linear module, the weight of the gripper is compensated as far as possible so that the force required to move the carriage along the linear guide is minimised.

Adjustable load fastening point: The adjustable load fastening point of the system is actively controllable along the X and Y axes and, in combination with a force sensor at the contact points with the façade and an inclination sensor on the outer frame of the system with the façade in the form of a closed control loop, ensures that any load on the substructure that could occur due to uneven loading or dynamic forces is minimised by moving the adjustable load fastening point so that the entire system is aligned parallel to the façade and the forces in the contact points are minimised. (Figure 4. Point 7).

Robot: The KUKA robot (KR 10) has the task of compensating for the movement of the permanent spring-pendulum-shaped oscillation of the crane and installing the façade elements at the desired location with the required accuracy. (Figure 4. Point 6)

3.2.3 Process description

For the process presented here, it is necessary that the substructure of brackets and aluminium T-shaped rails is already attached to the wall. Furthermore, at this stage of the project, it is necessary to assemble both the bottom row and a lateral vertical row of façade elements in advance, which serves as a reference point for the system shown here and as the first contact point for the two lower vacuum grippers (see Figure 5).

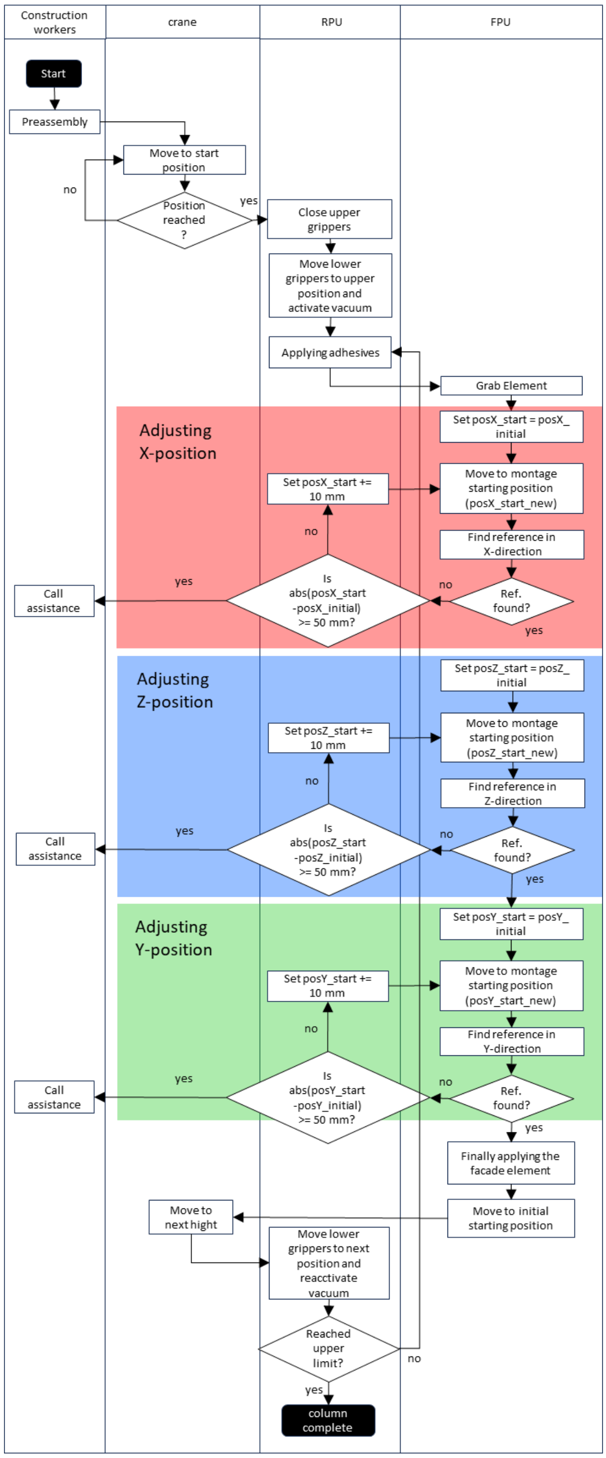


Figure 5. Flowchart of the installation process

The assembly process begins with the movement of the rough positioning unit by the construction site crane to the starting position. The façade robot is guided to the starting position by the site personnel. To ensure the lowest possible load on the substructure, the entire rough positioning unit is aligned using the adjustable load fastening point, as shown in the module description.

The first contact with the façade substructure is established by aligning and closing the upper grippers. The lower vacuum grippers are then activated, thus reaching the starting position for assembly. Next, the KUKA robot (KR 10) starts the assembly process of an element. As soon as this is complete, first one vacuum gripper of the lower assembly is released and moves upwards in the Z direction by means of a linear guide within the rough positioning unit, while the other gripper continues to ensure a fixed connection to the façade and the rough positioning unit is connected to the wall at at least three points at all times in order to minimise process disruptions caused by influences such as wind. When the suction pad has reached its upper end position, it is reactivated and the second suction pad moves upwards in the same way as the first. The entire rough positioning unit is now moved up one element height by the construction crane and the lower vacuum pads can remain attached to the façade thanks to the linear guide, so that the fine positioning unit can continue the assembly process with a new façade element.

4 Simulation

The developed rough-positioning-unit now needs to be tested for functionality. For this purpose, the developed system was implemented in *ROS* and *Gazebo*. *Gazebo* [16] is a powerful physics simulator that can be used in combination with *ROS* (Robot Operation System). *ROS* is a framework in which complex and robust robot behaviours can be implemented [17]. In *ROS*, the individual axes were virtually equipped with force and acceleration sensors. This allows the corresponding data to be recorded in the *Gazebo* simulation for later evaluation and prototype design. It was also possible to include the recorded oscillation data from the preliminary tests in the simulation

4.1 Recording the oscillation amplitude

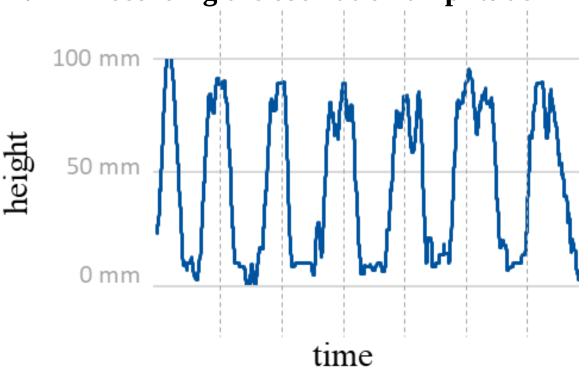


Figure 6. Results of the vibration tests. The vertical movement was recorded via the distance sensor. The frequency was recorded via a video capturing

In order to be able to estimate the oscillation amplitude of the platform for the simulation, a weight of approx. 1000 kg was attached to the construction crane. A distance sensor was attached under the component, which measured the vertical movement of the component over time (see Figure 7 and). It can be seen that the component has a oscillation amplitude of 50 mm and an oscillation frequency of approx. 0.5 Hz.

Figure 7. 1) Component weight ~1000 kg 2) Distance sensor, which measures the distance to the floor, to record the oscillation

4.2 Implementation

A *URDF* file (Universal Robot Description Format) was then generated from the *CAD* model. The properties of the components and joints can be precisely defined. In addition, the required sensors for recording the process forces can already be implemented [18]. The joints were implemented in *ROS* with the help of *ros_control*.

Gazebo also enables the implementation of vacuum grippers [19]. The two surfaces of the suction pads could be provided with the corresponding function in the *URDF* file.

For the simulation, the ventilated rainscreen facades also had to be integrated into the simulation environment. For this purpose, the original dimensions of the T-shaped rails and façade panels used in the project were modelled. The façade panels were installed according to the specified dimensions. The façade system was successfully integrated into the simulation environment.

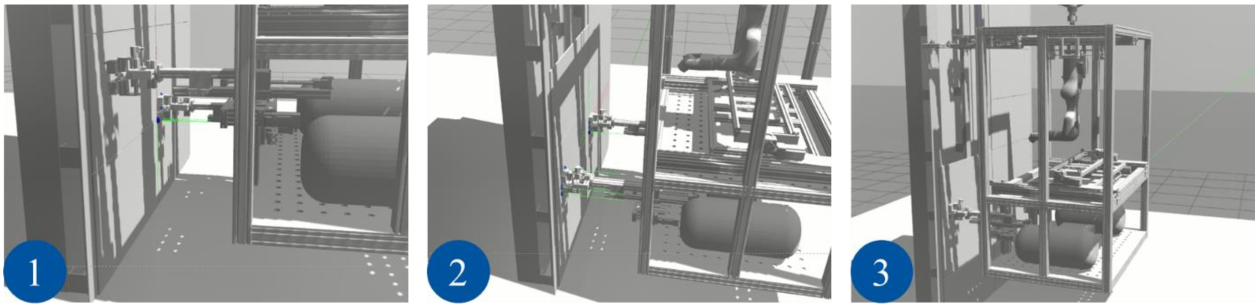


Figure 8. 1) Placement of the vacuum gripper 2) Stabilisation of the platform 3) Simulation of the platform with the determined oscillation amplitude

4.3 Simulation results

The simulation was performed using the internal physics engine of the Gazebo simulation software. The interpretation of these results is therefore purely indicative of the system design specification. The results of the simulation provide an initial assessment of the system. The following issues were identified by the simulation:

Compensation of crane oscillations: A key aspect is the ability of the system to compensate for the oscillations in the Z direction caused by the crane. Both gripping systems were able to keep the rough positioning unit constantly controlled. Due to the linear guide on the vacuum gripper, the forces were not transferred to the gripping system (see Figure 8. 1) Placement of the vacuum gripper 2) Stabilisation of the platform 3) Simulation of the platform with the determined oscillation amplitude. Point 1). As assumed, it can be seen that the torque control can compensate for the static weight force and the remaining forces are absorbed by the facade.

Precise positioning of the vacuum grippers: The precision of the system in positioning the vacuum grippers is a critical quality factor (see Figure 8. 1) Placement of the vacuum gripper 2) Stabilisation of the platform 3) Simulation of the platform with the determined oscillation amplitude. Point 3). The vacuum grippers could be released individually from the wall and moved to the next position accordingly. It is important to precisely coordinate the vacuum activation and movement of the motors so that the grippers do not shear off the façade panel in an uncontrolled movement.

Gripping the T-shaped rails: Gripping the T-shaped rails is a complex challenge. The grippers must be moved precisely to the target position and then closed firmly so that the subsequent movement process along the T-shaped rail runs smoothly. In the simulation, the T-shaped rails were successfully gripped and the rough positioning unit was guided along them.

Balance control using the adjustable load fastening point: The simulation showed that the adjustable load fastening point was able to successfully shift the centre of mass relative to the attachment point as described in chapter 3.2.2 in order to minimise the load on the gripping systems.

5 Conclusion and future work

The results achieved in this study show promising results. The solution approach of vertical motion decoupling clearly stands out from previously developed systems and offers a simplification of existing cable robots. In further steps, the results of the simulation can be analysed in greater depth in a future publication of the project results. This becomes relevant when the right components are assembled for the first prototype.

Particularly in the field of building envelope renovation, significant growth potential is forecast for the coming years [20], and the (semi-) automated solutions developed could represent an important addition to the construction industry, which is still heavily characterised by manual labour [21].

The next steps in this project will be

- Incorporating the simulation results into the prototype
- Simplification of the gripper kinematics
- Coordination of the individual subsystems of the platform, because only if the systems such as the vacuum gripper and actuators work in coordination with each other can it be guaranteed that the platform moves safely on the façade
- Construction of a first prototype

In addition to the development of the rough positioning, the development of the fine positioning is crucial. As described under (see chapter 3.2.3), the Kuka robot should detect and compensate for vertical movements and positioning inaccuracies with the help of force-torque sensors. Accordingly, an end effector must be developed for the robot, which grips the façade panels and brings them safely to the façade while working in coordination with the robot controller.

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