Development of a Modular End Effector for the installation of Curtain Walls with cable-robots

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Abstract
The installation of façade enclosures is a manual, dangerous, and time-consuming construction task. However, thanks to the capability of automated systems, the application of automation in construction is increasing, and therefore, manual work and risky situations can be avoided. Despite this, only a few robotic systems are capable of spanning such a vast work space, i.e. the façade of a building. Among these systems is the cable driven parallel robot (CDPR). Furthermore, the CDPR could carry heavy loads such as unitised curtain wall modules (CWM). Nevertheless, the tools and devices required for installing the CWM need to be innovated. Firstly, in order to cover that research gap, the current manual procedure was analysed in detail. After that, the development team evaluated several options for performing the tasks. Finally, an optimal solution was chosen: the so-called modular end-effector (MEE). The MEE comprises several tools in order to achieve various tasks. Mainly, these tasks are: drilling the concrete slab, bracket installation, and CWM handling and positioning. In addition to the aforementioned tasks, the MEE should accurately fix all elements with a desired tolerance less than 1 mm. Meanwhile, the MEE should compensate for the perturbation movement due to external forces such as wind that affect the system. As part of the study, a detailed workflow for the automated installation of CWMs was elaborated. The drilling step of the workflow was tested and the result is presented in this paper.

Keywords
Modular end effector, Cable robot, Construction robotics

DOI 10.7480/jfde.2018.2.2067

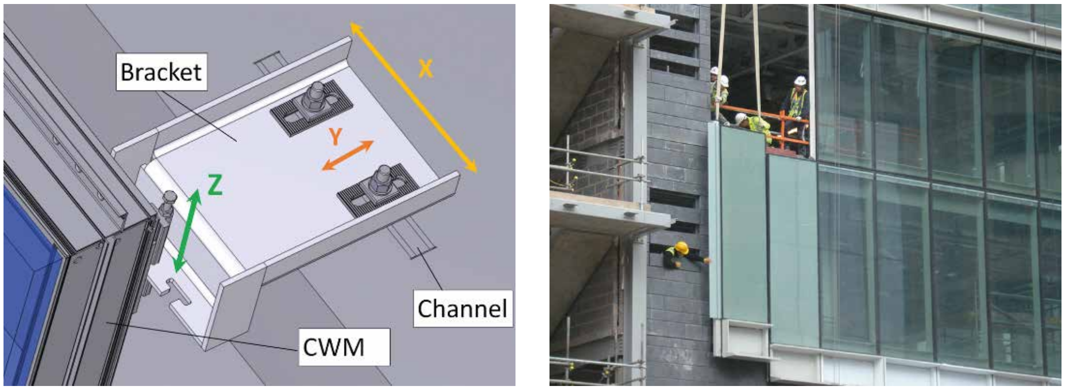

FIG. 1 Left: Bracket and CWM level adjustment. Two possible directions of bracket adjustment (X & Y) and one direction of CWM adjustment (Z). Right: Conventional installation of a CWM, possible dangers for labourers (e.g. falling) and the number of workers involved in the installation process. (Images by FOCCHI SPA-2017)

1 INTRODUCTION

The existing conventional CWM installation is a manual procedure that is based on two major steps: bracket fixation and installation of the CWM. Installing a CWM on a building requires the prior installation of an interface, or bracket. As of now, these brackets get anchored to the edge of the concrete slabs, thanks to cast-in channels. Apart from hosting and holding the CWM load, these elements are designed to cope with deviations between theoretical and actual construction geometries. The groove in these channels, in combination with the slotted cuts in the bracket plate, allow the manual adjustment of the location and orientation of the bracket itself. See Fig. 1 (Left).

However, when considering their use by automated systems, it not only becomes cumbersome, but redundant, as automated systems can eliminate or reduce the variation between actual and theoretical states in previous CWM installation stages. This can be achieved by using another correct, but less popular, method for CWM interface installation: slab drilling and setting of expansion anchors. This method allows for the preparation of the structure and work in the correct location right before the installation of a CWM without the need for further adjustments. Aside from the ease of automation, a relevant advantage of drilling (over cast-in channels) is the reduction of complexity during the design, planning, and concrete casting of slabs. Furthermore, using expansion anchors allows the installation of CWM on new construction sites as well as on existing ones that require renovation work.

Once all brackets are installed, and adjusted in their locations with a tolerance of 1 mm, the CWMs are transported to the desired building level with aid of a crane or elevator and, finally, are manually located, mounted, and fixed in the planned position. Fig. 1 (right) shows the CWM being lifted up using a crane, and several workers, who are working in a dangerous situation. The amount of labour work, danger, and required time is considerable. Workers could use the adjustment screw to level the CWM in the Z-direction (Fig. 1 (Left)). Automating the CWM lift and installation will increase the safety of labour. In foresight, the higher installation speed could be reached, while maintaining the required accuracy.

1.1 PREVIOUS ROBOTIC EXPERIENCES FOR INSTALLING ELEMENTS AND MODULES IN CONSTRUCTION

The automation level of different industries has been increased notably in the last decades. Although the construction sector has been demanding the use of automation and robotics in recent times (Bock T. , 2015), the presence of proper automatic systems is rare (Hastak, 1998) (Vähä, Heikkil, Kilpelinen, Jrviluoma, & Gambao, 2013). As an example of robotics working in the construction industry, a prototype of a moving platform hosting a modular end effector for an overhead (ceiling) nailing system was developed by the company Lindner and the Technical University of Munich (Bock & Linner, 2016). Another commercial robot for drilling the ceiling was produced by the company nLink in Norway (nLink, 2018). The corresponding required features of the robot, such as flexibility, heavy duty, reliability, and big workspace should be deeply considered when developing automation systems in the construction sector (Moreira, et al., 2015). For instance, the installation of the automatic Curtain Wall Module (CWM) requires a large work space (the façade of the building), heavy payload (The CWM weight is about 300 kg), and it happens in an outdoor environment. Several automatic systems for CWM installation have already been proposed. For instance, the patented technology from Brunkeberg Systems AB (USA Patent No. US8695308, 2014) is in use. It brings the railing system into action just for their dedicated CWM. Alternatively, a mobile robot that installs the CWM from inside the building is used by Yu et al. (Yu, Lee, Han, Lee, & Lee, 2007). This method automates only the CWM installation and not the bracket installation. A telescopic, tele-operated hydraulic system was designed and tested to nail the sandwich panels from outside the building by (Cinkelj, Kamnik, Cepon, Mihelj, & Munih, 2010). The system is also designed to work only with specialised panels. As previously mentioned, these systems have their own limitations. The CDPR provides the big workspace and high payloads. This makes the CDPR a proper solution for construction automation and especially for CWM installation. Therefore, within the call ICT-25-2016-2017 (EU, 2017) from the European Union, the HEPHAESTUS project (HEPHAESTUS, 2018) was founded. The project, as well as the subject of this paper, focuses on CWM installation using Cable Driven Parallel Robot (CDPR).

1.2 SUB-SYSTEMS AND TASKS FOR CWM INSTALLATION

To automate the CWM installation, the system in the HEPHAESTUS project is divided into three subsystems: 1) CDPR, 2) MEE, and 3) controlling system. This paper addresses the challenges of the MEE design in detail. The requirements for the MEE were carefully analysed and considered as:

- Drilling the concrete
- Installing the bracket (the interface between the CWM and building)
- Positioning and mounting the CWM on the installed brackets

Moreover, the MEE should be able to work outdoors and provide required accuracy for the system. It means that the system should be stable in case of environmental loads and vibration caused by, for example, wind, and that the bracket should be installed with a tolerance of 1 mm.

2 DEVELOPMENT OF THE MODULAR END EFFECTOR

The end-effectors are tools that are attached to the robotic manipulator, and interact with the environment. In the case of the HEPHAESTUS project, this end-effector operates within the platform of the cable robot and it is modular, meaning it contains several devices including the end-effectors. In this project the main task is to install a Curtain Wall Module (CWM). Within the task, there are four main requirements. First, the MEE should perform tasks such as drilling, fixing a bracket and handling the CWM. Second, the MEE should fulfil the tasks accurately. The issue is that the cable robot does not provide the required accuracy. Therefore, the MEE must re-adjust to the location. A secondary robotic device will be necessary for the completion of this subtask. The third requirement is that the MEE needs to be stable while performing these tasks and the outdoor hazards, including their forces, need to be neutralised. A fourth and final requirement is that the CWM module needs to be lifted and fixed into its correct position.

For each of the requirements of the MEE, several possible options were considered. These options were analysed carefully and evaluated. In the selection method, careful considerations occurred for the following indicators:

- The preferred option should fulfil the requirements of the system completely with smallest risk of failure.
- It should be safe.
- Its design and manufacturing should be possible within the available resources of the HEPHAESTUS project.

Once the analysis was carried out, an optimal solution for each of the requirements was selected. The evaluation process and the selected solutions are explained in the next sub-chapters.

2.1 SECONDARY ROBOTIC SYSTEM

The cable robot is expected to have an accuracy of about 40 mm, thus a secondary robotic system is required to achieve the 1 mm positioning need for the different tasks, from the structural preparation of the building to the installation of necessary mounting hardware. That is, the cable robot will achieve a 'macro' positioning throughout the building façade plane, and the secondary robotic system will do the 'micro' positioning of tools and components at the required locations. Once the coordinates for the CWM and the anchors' design locations are known, it is possible to locate the cable robot frame in a nearby position, where the anchor points are accessible to the tooltip of the robotic arm.

A thorough consideration of options for this secondary system included: Cartesian system, Pyramid based movement, Hexapod, and finally, a serial arm robot. To evaluate these options, sub-tasks and useful end-effector tools were analysed for completing the tasks. For example, a drill with a rotary hammer was considered. Given the tasks, tool availability, and project resources, it was defined that the most appropriate option for a secondary system is a 10 kg payload serial robotic arm. This system will then manipulate off-the-shelf tools that are adapted and mounted at the robot head via pneumatic or electric tool changers, which allow for fast and automated swapping throughout the CWM installation process. Universal Robots UR-10 is tentatively the system to be integrated.

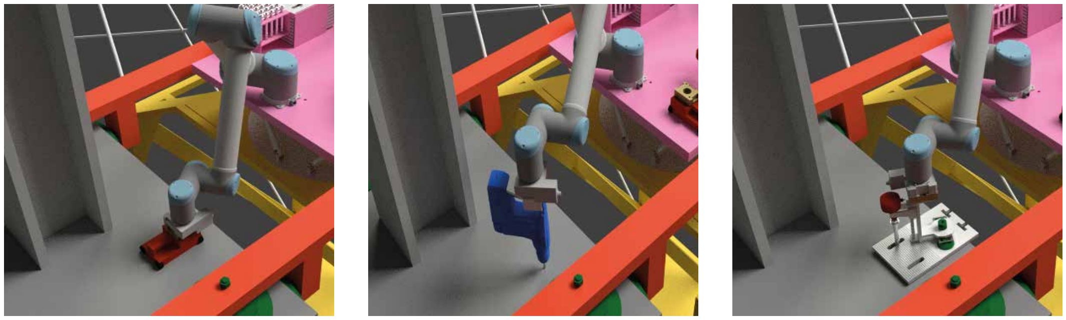

FIG. 2 Robotised Bracket installation process. Left: Rebar scanning, rebar scanner in red colour is handled by serial arm robot and scan a specific area to check if there exist a rebar or not. Centre: Drilling, the driller in blue colour is handled by serial arm robot to do the drilling. Right: Bracket adjustment and installation, a gripping tool is handled by serial arm robot.

2.2 STABILISING THE MEE

It is considered that the HEPHAESTUS robot works under wind conditions with a maximum speed of 15 m/s; this point initially brings the stiffness characteristic of the cable robot into consideration. The stiffness of the cable robot could be translated as the relation of the applied external force and the resulting movement. It is a parameter that can be considered during design of the cable robot. However, there are some limitations, since higher stiffness needs higher cable tension, while the other factors remain constant. For higher tension in the cables, there are cost and technical constraints. The stiffness of the cable robot influences the accuracy of the performance of the MEE, since external loads imposed on the cable robot and its platform (e.g. wind) will cause the cable robot to move, which consequently means the movement of the MEE. The MEE is the final performer of the task on the building and it should be stable during the performance. A driller is an example of a final tool performing the task on the building, which should not move due to external loads while drilling. For filling the gap between the stability of MEE and the stiffness of the cable robot, the stabilising system was designed in this project. In the system, the MEE will grip the building in order to be stabilised during the performance of the task.

2.3 PERFORMING TASKS ON THE BUILDING

In order to mount CWMs, the first requirement is to install the CWM mounting bracket on the edge of the slabs at each level of the building. The sequence for this interface installation can be defined by three main phases: Structural Preparation (steps 1 and 2), Bracket Installation (steps 3-5), and Quality Assurance (step 6), which consists of 6 steps in total:

1. Rebar Scanning: To avoid structural damage or potential drill bit jamming, it is imperative to scan the slab surface to detect embedded reinforcement bars. This task will be performed by adapting and manipulating an off-the-shelf manual rebar scanner. Fig. 2 (left) shows the concept of the automated method of rebar scanning in this project.

2. Drilling: Following the identification of optimal drilling locations, the actual drilling takes place using a rotary hammer tool. This operation needs to be followed by, or include, an integrated dust management system to leave the hole ready for further steps. Fig. 2 (centre) shows the concept of automated drilling in this project.

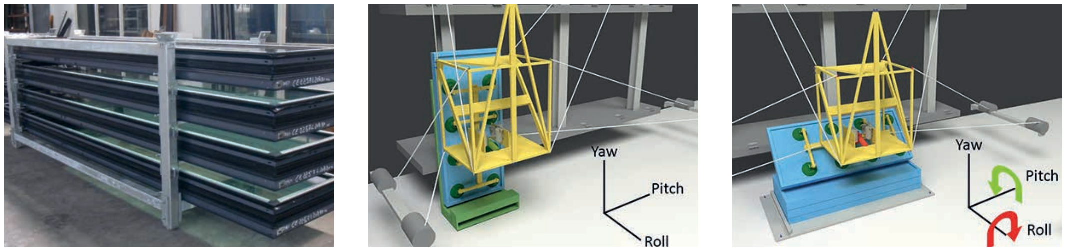

FIG. 3 CWM handling. Left: CWM crates [Picture rights: courtesy of FOCCHI SPA]. Centre: Picking up the CWM vertically with no rotation, green is the reference bed and blue is the curtain wall module. Yellow is the cable robot frame. Right: Picking up the CWM horizontally, two degree of rotation in roll and pitch direction is implemented.

3. Expansion Anchor setting: Setting an anchor requires a gripping mechanism to manipulate the anchor from a magazine onto the drilled hole. Once the location is locked, a hammering device (e.g. rotary hammer with hammering-only function) inserts the element down into the hole. This operation is done for two anchors: the first anchor with the bracket plate (see next step), and the second anchor alone to secure bracket plate rotation about the Z-axis.

4. Bracket plate setting: The bracket plate, which will create the interface between the building and the CWM, will be gripped, manipulated, and positioned on the slab at the correct location. Here, it will be locked by the 1st installed expansion anchor (from previous step). Fig. 2 (right) shows the robotic procedure of the bracket adjustment and installation

5. Nut tightening: To fully secure the interface hardware, the nuts from both previous anchors must be tightened to the right torque. For this operation an impact driver is used.

6. Installation quality: Prior to installing the CWM using the installed bracket, the correct installation of components needs to be verified. For this a 3D camera is utilised to remotely verify all components are in place and ready to take the panel load.

The six steps above describe the installation of bracket plates and required hardware. The combination of a robotic arm manipulator, tool changer, and off-the-shelf components conveniently allows the change or addition of tools. This feature benefits the utilisation of the same configuration for other applications such as façade washing or painting. e.g. mounting a spray paint nozzle onto the robot arm and moving it across the building exterior walls for painting complex surfaces.

2.4 HANDLING THE CWM

The transportation and arrival of the CWM is achieved using racks, with which the CWMs are transported horizontally to the construction site, as shown in Fig. 3 (left). For the CDPR, the necessary manoeuvres could be minimised if the CWMs were transported vertically (Fig. 3 (centre)), but that would decrease the optimisation of the transportation of the modules. At this point, it was decided that the CDPR needs to pick up the CWMs from the horizontally stacked position, and must then mount them in a vertical position parallel to the building façade. For solving this issue, a two-directional rotary handling system with suction cups has been preconceived as a preliminary solution (Fig. 3 (right)).

FIG. 4 Drilling test. Left: Serial arm robot UR10 mounted hosting a driller with integrated dust suctioning system. Centre: Drilling with a 16 mm drill bit into sample concrete. Right: Showing the quality of a drilled hole.

2.5 INITIAL PROOF OF CONCEPT

In order to initiate the validation of the developed MEE, the secondary robotic system, the process, and the tools to be used, an initial test experiment was set up. A rotary hammer with a 16 mm diameter drill-bit installed was mounted on the serial arm UR-10 and driven into a concrete box that simulated the structure found in the slabs of a building. In parallel, the tool was equipped with a vacuum cleaner hose to remove dust during the drilling process. The test was successful and the resulting hole proved to be ready and useful for the installation of an expansion anchor, by following the procedure in the workflow defined in Chapter 2.3 of this paper. Fig. 4 shows the process and result.

3 CONCLUSION

Current practices for the installation of curtain wall modules imply several adversities, including the safety of workers. In order to achieve a more automated process, ongoing research based on an adaptation of a cable driven parallel robot will focus on this topic. This paper describes the elaboration process of a novel robotic modular end-effector or tool system that, in the near future, should perform the tasks for installing a curtain wall. First, several options were gathered and evaluated. Then a final solution was selected based on achievability criteria. The chosen modular end-effector integrates and makes use of market-ready solutions that can sufficiently perform the set of tasks involved in the installation of CWM. This development approach enabled the accessibility to a high feasibility-rate scenario, where it is possible to validate the concept in small and progressive steps without the need to develop completely new concepts and technology. Validating the system solution as a whole will enable further refinement of the solution itself. It will also enable continual abundance of automation solutions to the construction industry, which can address its most recurrent issues, such as inefficiency and safety.

For progressive movement towards the full construction and use of the CWM installation system, the different sub-tasks and tools will be tested individually in a similar way to the experiment described in Chapter 2.5. Some of these experiments will comprise mounting tools on the serial arm UR-10 to prove the effectiveness of the workflow defined in Chapter 2.3. In order to refine the design, and validate the function of the bigger MEE elements (e.g. building gripping damping system), digital simulations and physical experiments will follow. Finally, after designing and validating the MEE, it will be manufactured and the system will be tested on the real building together with cable robot.

Acknowledgements

The research leading to these results has received funding from the European Union's H2020 Programme (H2020/2014-2020) under grant agreement n° 732513.

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