Design and Synthesis of the Localization System for the On-site Construction Robot

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Abstract – Building tasks that carry out on the building façade, such as painting, cleaning, and maintenance are often to be described as dangerous, dirty, and demanding. Recently, researchers and institutes are developing autonomous and semi-autonomous On-site Construction Robots (OCR) for those aforementioned applications. The most of façade working OCR is either suspended or supported by the secondary structure. The biggest challenges for these types of methods are obtained stability while carrying out the task against external elements such as wind and inertia caused by the step motors. There are very limited resources that discuss positioning and stabilizing methods. In this paper, a novel localization system for OCR will be introduced, which is based on the on-site construction robot commissioned by The Construction Industry Council Hong Kong (CIC) and developed by the Chair of Building Realization and Robotics (br2) at Technical University of Munich (TUM). The research presents the preliminary concept of a stabilization method that can be adopted on most of the suspended OCR type. The proposed system will localize the initial position, alter the OCR into the correct working pose, and secure the system to place. At the time of this writing, it is only limited to the conceptualization and proof of concept of the system. The control scheme is validated in simulation. The proposed approach is expected to be expanded into other applications in the future.

Keywords –
Construction robotic; localization; Stabilization

1 Introduction

To adopt automation and robotic technology with the aim to augment human performance is not a new concept in the construction industry. In fact, since the late 1970s and the early 1980s, many research institutions, universities, and construction machinery companies have conducted research and development (R&D) initiatives. In the early 1980s, Japan's construction industry started to face a shortage of skilled workers due to the fact that working condition of conventional construction sites was considered dirty, dangerous and difficult by the young generation. The construction industry had begun to fall behind the manufacturing industry [1]. Until today, there are over 150 Single-Task Construction Robots (STCRs). Most of the systems were developed to be used on the construction site. Each type of robot was designed to focus on a particular on-site work task. In general, automation and robotic technologies are often referred to as a solution to solve many profound industry-related issues, such as declining productivity, skilled labour shortage, safety, and quality. The increased popularity of robots is expected with improved economic incentive and wider applicability [2]. Some construction processes can be automated while others not, even the one that can be automated in the other sector, such as manufacturing sector might not be realized in the construction context. For instance, the construction sector is fundamentally different from that in the manufacturing sector in many aspects. The difference can be reflected in the following characteristics including working environment, distribution of materials, the allocation of the robot and human function, skill sets, and information transformation [3]. Therefore, to develop a practical application for the construction industry the system designers must be proficient in traditional construction methods, building structure, engineering management and other disciplines, and understand the auxiliary knowledge about microelectronics, mechanical design, manufacturing, and automation, so interdisciplinary teaching and cooperation in the field of construction robotics is essential.

There are increasing demands of working in great heights, due to the popularity of high-rise buildings. Yet, high-rise construction often prone to issues that affiliated with working in great heights. In this paper, the author will use the multifunctional façade finishing robot that was developed through the consulting project commissioned by the Construction Industry Council Hong Kong (CIC) as a case study. When the proposed

OCR system is suspended in great heights and to be exposed in the external environment. It is vital for the system to maintain stability while operation, and to position itself securely and accurately. This paper will focus on the development of a practical solution that can potentially address the challenges associated with localization, stabilization, and positioning tasks in respect of the suspended type of OCR system. The method can be adjusted and adopted when executing a similar development.

2 Background

Many construction tasks require labour to perform repetitive motions while to be suspended in great heights. For instance, cleaning task for high-rise buildings fitted with glazing curtain wall system, painting for high-rise building façade, and various maintenance tasks that need to be carried out from building façade. As mentioned earlier, working in heights imposes considerable safety hazards. It may sound contradictory but in the construction industry, on-site operational health and safety are one of the most critical areas that the industry trying to improve and very often overlooked. Construction accidents are influenced by multiple circumstances, such as workplace organization, equipment, training, risk awareness, and individual attitude. Hence, in many cases, it is hard to predict or to prevent accidents from happening. According to research regards to contributing factors in construction accidents, falling from heights is one of the biggest contributors to construction-related accidents [4]. In addition, working in heights also increases the opportunities of suffering other types of injuries, such as slips, trips due to unpredictable working condition. Many tasks involve working in heights are usually physically demanding even for the fit and younger workers [5]. Evidently, many developed economies in the world experience the aging workforce due to demographic changes. For instance, in Hong Kong, approximately 25.83% of the workers are above 50 years of age. Compared to a younger worker, workers 50 years and over will expose themselves to a higher risk of injury [6].

Consequently, researchers have been developing OCRs that provide full or partial replacement of the tasks that used to perform entirely by human. Automation does not offer all the solutions to the identified challenges, yet can provide an alternative method that enhances human performance and improve on-site operational [7]. In principle, façade OCRs can be divided into three main functions include rendering, cleaning, and inspection. The examples of some of the applications can be seen in Table 1 .

Table 1. Examples of the applications in on-site construction robot

Manufacturer	Robot	Country	Application	localization method	Façade type
Taisel	Exterior wall painting	Japan	Rendering	Guide rail	Vertical, flat
Kajima	Façade inspection robot	Japan	Tile façade inspection	Parapet, wall clamps and supported by cables	Vertical, flat
Fraunhofer, SIRIUS	Glazing curtain wall cleaning robot	Germany	Façade cleaning	Wheels and cables	Protruding
Louvre, Robosoft	Glazing curtain wall cleaning robot	France	Façade cleaning	Vacuum cups	Vertical, flat

The aforementioned systems also demonstrate various localization methods that have been adopted for a diverse range of application. Each system were tailor made for a specific configuration of building design that means the system is not applicable to be used for other buildings. Along with high operational costs, and complexity, many systems are not be able to commercialize successfully.

CIC commissioned the Chair of Building Realization and Robotics (br2) at Technical University of Munich (TUM) to research and develop construction robots and automation strategies that are tailor-made for the Public Housing Construction (PHC) sector in Hong Kong. As part of the project, the project team have to identify the requirements of the stakeholders, functional, non-functional requirements, and the circumstances of the construction site. There are other factors could also influence on the final decisions, such as technological, social, political, and economical. The project has been divided into six stages. The first phase consists of initial research, literature review, preselection, and proposing use case scenarios. The second stage includes an online survey, questionnaires, and on-site visit. The third stage is co-creation workshops. The fourth stage is concept development and detailed design of the proposed system. The fifth stage includes the construction of the mock-up and discussion of dissemination and exploitation strategies. The final stage is to develop a roadmap that provides a guideline on how to execute the remaining project a short-, mid-, and long-term basis. In the end, the Multifunctional Façade and Exterior Finishing Robot were chosen to be developed as a stimulator to the PHC industry. During the development stage, the project team have identified numbers of issues, in which the system positioning, stabilization imposes serious implication on the overall performance of the proposed OCR.

3 Research challenge and objective

Diverse localization methods were adopted in the façade application OCRs that have been developed in the past. However, they were designed to operate on the specific type of building façade. For instance, the Taisel exterior wall painting robot is positioned with guide rails. The guide rails are not an additional fixture for the building, yet the architect was made aware that the exterior wall painting robot will be equipped, hence the guide rail was included as part of the design feature of the façade to accommodate the robot. Evidently, the façade OCRs is tend to be developed and operated on specific type of façade and to manage unique configuration and material.

According the research, the project team realised that the existing façade OCRs are not applicable to the PHC façade type. This is due to the complexed geometry shape of the façade design. The external façade is constructed with prefabricated concrete panel. As shown in Figure the prefabricated concrete façade (PCF) element consists of two major protruding sections, both are designed to support air-conditioning equipment. The edge at the bottom of the panel overshadowing the floor level below, especially during the hottest hour of the day. Another function of the overhanging edge is to divert rainfalls during the subtropical monsoon seasons in Hong Kong. The advantage is that the PCF is identical for every elevation of the building.

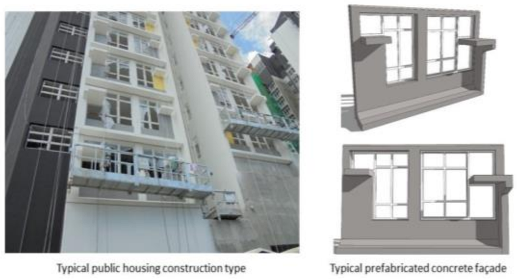

Figure 1. Typical public housing construction type

Because of the complexed shape, a high level of accuracy is required for the painting task, in particular to keep an even paint coverage throughout every sections of the PCF. When dealing with a flat surfaces, this requirement is achievable even with the conventional supporting solution, such as suspended working platform that is often referred as gondola. The gondola is suspended by cables, which supported by wall clamps that installed to the parapet wall. When hanging in mid-air, it is very difficult to keep the gondola in absolute stable motion, due to wind, inertia, and movements caused by the operator. In the case of CIC project, as part of the design requirement, the proposed OCR was developed based on the conventional gondola platform that is widely used in Hong Kong construction industry for various façade tasks. The system need to be stable and retain levelled with the reference wall surface prior to carry out painting task and to ensure the required functional performance can be achieved.

The main challenge faced by the proposed OCR is how to design a system that is capable of self-diagnose the position, and to keep the working platform stable during operation. The primary design objectives of the system are, first, the system is to be expected to come to a stop once the system reaches the correct position. Second, after stopping, the system needs to remain stationary and to keep perfectly horizontal to the building façade. Third, the system should able to detect moments caused by either the external force or the momentum of itself. Once displacement has been detected, the system is required to correct the position automatically.

The proposed localization method presents the following improvements to the existing method. The design will not require any temporary or permanent additional fixtures and fittings other than the one has been used in a conventional manner. With a minor adjustment to the design, the system can be adapted to a large variety of building façade. The improved stability will accommodate a variety of automated applications, which demands an immobilized working condition. In terms of semi-automated application, human labour will also benefit from a stationary working platform to avoid the risk of occupational injuries. The next section will describe the development method in detail [8].

4 Method

The proposed Multifunctional Façade and Exterior Finishing Robot is based on the design of conventional gondola, the additional frame below the gondola hosts the robot end-effector, the space between the frame structure constitutes the robot working trajectory. Supported by the common roof supporting system, the robot can descend from the top to the bottom of a high-rise building while executing a task. Two electric motors near the hoisting devices on top of the robot are used to actuate the up and down movement. Through the addition of various sensors, the ultimate goal is to achieve a fully automated façade processing robot system. The robot system is highly modularized, meaning that the shape and size of the robot can be easily changed in accordance with the design of the target buildings, see Figure 1.

The localization system compresses of counterbalance design. It is compatible with all types of prefabricated façade panels used in Hong Kong PHC sector. The system consists of three subsystems, which include a detection system, stabilization system, and final positioning system [8].

1. **Detection system**: equipped with two linear actuators that provide moment along X and Z-axis. A limit switch module is installed at the end of the X-axis.

2. **Stabilization system**: consists of three rotation servo actuators interconnected with counterbalance bars. At the tip of the final link a clamping device along with pressure sensors are installed. In addition, an inner industrial vacuum suction device is equipped in between the clamps.

3. **Final positioning system**: comprised off two retractable vacuum suction cups, they are able to secure the system to the final position. They are also able to withstand wind loads under normal circumstances.

All three subsystems can be adjusted when applied to another building and only minimum setup time is needed.

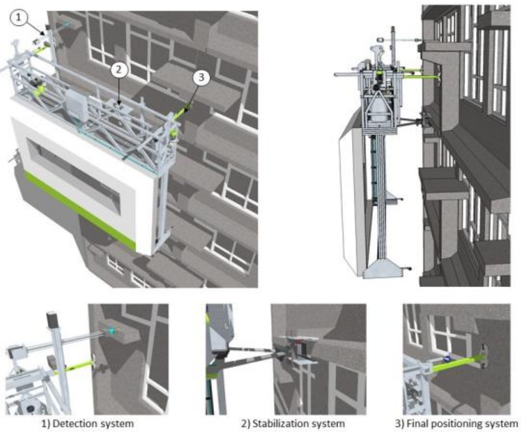

Figure 1. The design of the localization system

4.1 The design of the localization system

4.1.1 The mechatronic design and the kinematics of the system

The kinematic model of the localization system is shown in Figure 2. Based on the Denavit-Hartenberg (D-H) convention, the coordinate transformation between two consecutive link frames $\{i-1\}$ to $\{i\}$ can be defined as:

$$^{n-1}T_n = \mathrm{Rot}_{x_{n-1}}(\alpha_{n-1}) \cdot \mathrm{Trans}_{x_{n-1}}(a_{n-1}) \cdot \mathrm{Rot}_{z_n}(\theta_n) \cdot \mathrm{Trans}_{z_n}(d_n), \quad (1)$$

where $\mathrm{Rot}_{x_{n-1}}(\alpha_{n-1})$ defines a rotation of angle α_{n-1} around the x_{n-1} axis, and $\mathrm{Trans}_{x_{n-1}}(a_{n-1})$ defines a translation of a_{n-1} along the x_{n-1} axis. The transformation matrix $^{n-1}T_n$ is a composition of rotations and translations to move from a frame $\{i-1\}$ until it coincides with the frame $\{i\}$.

Accordingly, the D-H parameters for this model is shown in Table 2, where d means the offset along previous z to the common normal, θ means the angle about previous z, from old x to new x, a means the length of the common normal (Assuming a revolute joint, this is the radius about previous z), and α means the angle about common normal, from old z axis to new z axis [8] and [9].

Table 2. The D-H parameters of the localization system model

α_{n-1}	a_{n-1}	θ_n	d_n
$-pi/2$	0	0	d_1
$pi/2$	0	$-pi/2$	d_2
$-pi/2$	0	0	d_3
$pi/2$	0	$\theta_4 + pi/2$	0
$pi/2$	0	θ_5	0

With the D-H parameters, the transformation matrix from the robot base frame to the end-effector can be calculated using joint variables. The end-effector pose can be obtained by multiplying the transformation matrix as follows:

$$^0T_e = {}^0T_1{}^1T_2{}^2T_3{}^3T_4{}^4T_5{}^5T_e, \quad (2)$$

where $^{n-1}T_n$ is the transformation matrix as shown in (1).

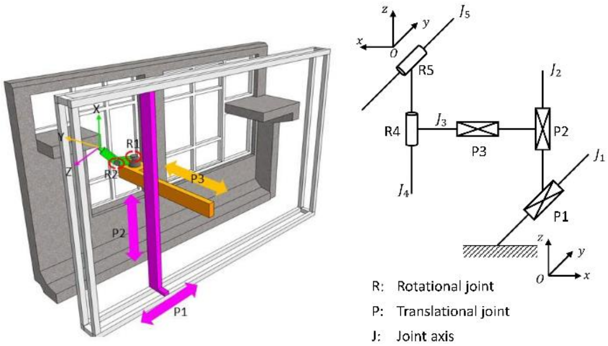

Figure 2. Kinematic structure of the localization system.

4.1.2 The work principle of the design

The localization process can be divided into six steps.

Step 1: Robot descends along the cable operated by the conventional step motor. The system will stop descending when the limit switch make contact with the protruding feature of the PCF.

Step 2: Due to inertia and external forces, at this moment the system may swing swiftly. The system is designed so the stabilization system is aligned with the overhanging edge of the PCF. The stabilization system will be reaching out and press onto the surface of the edge. Once the pressure sensor detects even force has been distributed across the sensor the clamping device will retract and form a firm grasp to the edge, while the inner suction cup secures the system in place [8].

Step 3: once the system is stabilized, the stabilization system detects if the position is horizontally aligned with the PCF façade, if it is not, then the system will correct the position by using impedance control method.

Step 4: The robot extends the retractable vacuum grippers toward the wall at the proper length, then to grasps the wall to fix its position.

Step 5: the robot will detect any deviation between the real position and the ideal one. If there is any deviation the system will offsets, and the step three and four will be repeated.

Step 6: after the painting application has been complicated. The vacuum suction cups and clamps will be unfastened. The system is ready to decent to the lower floor level.

4.2 The control of the localization system

To achieve the above processes, several controllers for the localization system should be designed. Based on whether the robot will interact (have contact) with the target building, the controllers are divided into two categories: position controller and force controller. The former guides the robot to a precise position, while the latter attempts to maintain a compliant contact between the robot and the environment. We take the stabilization system as the example to illustrate how to achieve the stabilization with the abovementioned controllers.

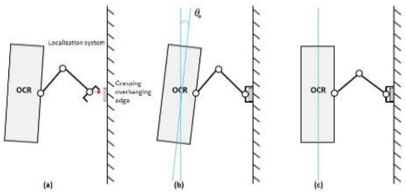

Figure 3. The three phases of the localization system (LS) for stabilization. (a) The LS moves towards its front direction to get in touch with the building wall; (b) The LS attaches its end with the wall and fixes its pose; (c) The LS eliminates the pose error.

As shown in Figure 2, the goal of the stabilization system is to find the wall, attach the gripper with the wall and finally adjust the pose of the robot. To achieve that, the following control laws are adopted [8].

4.2.1 The proportional-derivative (PD) control law

The dynamics of the robot system can be described in the form of the equation

$$M(\theta)\ddot{\theta} + C\big(\theta,\dot{\theta}\big)\dot{\theta} + N\big(\theta,\dot{\theta}\big) = \tau, \tag{3}$$

where $\theta \in \mathbb{R}^n$ is the set of configuration variables for the robot and $\tau \in \mathbb{R}^n$ the torques applied at the joints, and M, C, and N are the inertia, Coriolis and gravity-related matrix, respectively. In practice, the robot is controlled by τ.

Before the localization system starts to act, and after it holds the wall firmly, the system should always keep a high precision for the movement or keep itself exactly where it is. This could be achieved with the PD controller:

$$\tau = -K_v\dot{e} - K_p e, \tag{4}$$

where $e = \theta - \theta_d$, and θ_d defines the desired configuration of the robot. K_v and K_p are positive definite matrices indicating the coefficients of the PD controller. For second-order systems, the relationship between K_v, K_p and the damping D of the system can be described as

$$D = \frac{K_d}{2\sqrt{K_p}}, \tag{5}$$

which helps to provide an initial value to adjust the expected response of the system [8].

4.2.2 The impedance control law

During the states where the robot and the wall are in contact, the robot should prevent rigid collisions between itself and the wall. In that case, the PD controller, which only targets at moving to the goal position in joint space, will not fulfil the requirement. We need to redesign a controller to provide a compliant force in the task space. When contact occurs, the robot should handle the contact in a soft, compliant way.

In such case, the dynamics of the robot system in the task space can be rewritten as

$$M_x(\theta)\ddot{x} + C_x\big(\theta,\dot{\theta}\big)\dot{x} + N_x\big(\theta,\dot{\theta}\big) = J^{-\top}\tau + F_a, \tag{6}$$

where x is the pose of the end-effector in task space, J is the Jacobian and F_a is the external force applied to the end-effector. The postscript of M_x, C_x, and N_x indicates that the matrix is an equivalent of the matrix expressed in task space with

$$M_x(\theta) = J^{-\top}M(\theta)J^{-1} \tag{7}$$
$$C_x(\theta,\dot{\theta}) = J^{-\top}C(\theta,\dot{\theta})J^{-1} - M_x(\theta)\dot{J}J_a^{-1} \tag{8}$$
$$N_x(\theta,\dot{\theta}) = J^{-\top}N(\theta,\dot{\theta}). \tag{9}$$

Still, the robot is controlled by τ:

$$\tau = J^{\top}(\theta)\left[M_x(\theta)\ddot{x} + C_x(\theta,\dot{\theta})\dot{x} + N_x(\theta,\dot{\theta}) - F_a\right]. \quad (10)$$

Then the desired acceleration trajectory $\ddot{x} = a$ can be designed in the task space. Regarding the contact force, a dynamic impedance model can be expressed as

$$M_d(\ddot{x} - \ddot{x_d}) + D_d(\dot{x} - \dot{x_d}) + K_d(x - x_d) = F_a, \quad (11)$$

where $x_d(t)$ and $x(t)$ are the desired/real motion, respectively. M_d, D_d, and K_d are the desired inertia, damping and stiffness, respectively. In this case, if a soft and compliant contact is desired, it can be achieved by choosing

$$a = \ddot{x}_d + M_d^{-1}[D_d(\dot{x}_d - \dot{x}) + K_d(x_d - x) + F_a]. \quad (12)$$

Substituting Eq. (10) into Eq. (12), there will be

$$\begin{aligned}\tau = M(\theta)J^{-1}(\theta)\{\ddot{x}_d - \dot{J}(\theta)\dot{\theta} &+ M_d^{-1}[D_d(\dot{x}_d - \dot{x}) \\ &+ K_d(x_d - x)] + C(\theta,\dot{\theta})\dot{\theta} \\ &+ N(\theta,\dot{\theta}) \\ &+ J^{\top}(\theta)[M_x(\theta)M_m^{-1} - I]F_a\}.\end{aligned} \quad (13)$$

Further, if M_d is chosen as

$$M_d = M_x(\theta) = J^{-\top}(\theta)M(\theta)J^{-1}(\theta), \quad (14)$$

then the control law becomes

$$\begin{aligned}\tau = M(\theta)J^{-1}(\theta)\{\ddot{x}_d - \dot{J}(\theta)\dot{\theta}\} + C(\theta,\dot{\theta})\dot{\theta} &+ N(\theta,\dot{\theta}) \\ &+ J^{\top}(\theta)[D_m(\dot{x}_d - \dot{x}) \\ &+ K_m(x_d - x)],\end{aligned} \quad (15)$$

which do not require the contact force F_a feedback anymore. With Eq. (15), the compliant motion which limits the contact forces at the end-effector could be achieved [8].

4.3 Simulation of the proposed system

4.3.1 Setup of the simulation

The proposed localization system is verified in robot simulation environment ROS (Robot Operating System) + Gazebo. Gazebo is an open-source 3D robotics simulator, which is widely applied in robotics research area. In this simulation, it is hoped that the validity and effectiveness of the design could be verified.

4.3.2 Process of the simulation

To proceed, a simplified robot model is firstly established in Gazebo. Following the link-joint relationship of the robot, the model is expressed in sdf format [10]. The size of the model and the corresponding inertia property are set as the measured value in the CAD designing software. Finally, a Gazebo plugin is programmed to send the joint commands from the controller to the simulator. A framework structure is depicted in Figure 3.

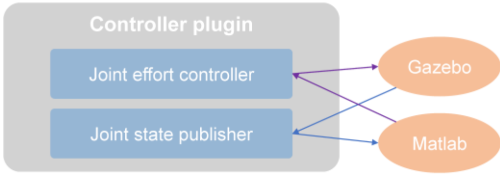

Figure 4. The framework structure of the simulation. The simulation is implemented in Gazebo. The controller is designed in Matlab. Using ROS communication mechanism, Matlab receives the current joint states from Gazebo, determines the joint efforts and sends them to Gazebo to achieve the final movement.

4.3.3 Data analysis

For the first stage, after fine-tuning the parameters for the PD controller, it could drive the localization system (LS) to the standby state fast and steady. For the second stage, the impedance controller could guide the robot to the right direction and achieve the contact with a very soft impact, see Figure 5.

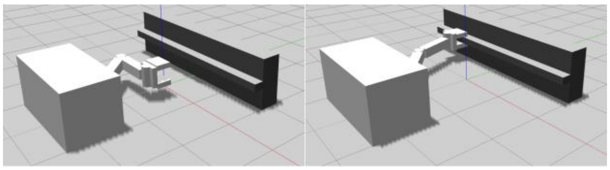

Figure 5. The localization process in the simulation. Left: the standby state. Right: the grasping process.

5 Future work

At the time of this writing, the proposed stabilization system is still under the Proof of concept (PoC) stage. There still many tasks and will take time and extensive tests to develop them into a practical application. The following tasks need to take into consideration when further developing the proposed system.

- For the detection system: to select the appropriate sensor technology for the specific construction operation environment. For example, a laser sensor may be sensitive to dust particles or reflective surfaces such as glazing and metal, but on the other hand, a gyroscope sensor may require high precision of the reference façade.
- For the stabilization system: it is necessary to develop an active and passive compliant control method to eliminate the external influence (i.e. the

wind, an unexpected collision).

- For the final positioning system: it is necessary to develop a robust position controller to guide the end-effector docking position.

It is crucial to test the localization system before the final pilot runs to reduce the risk of system failure, damage, or safety hazards. To test the effectiveness of the localization system, it is necessary to build a fully functional simulation or prototype that can be used for laboratory testing as well as pilot testing [8].

6 Conclusion

The paper proposed an innovative localization system for the Multifunctional Façade and Exterior Finishing Robot that developed in the CIC project. The proposed system consists of three subsystems, which include a detection system, stabilization system, and final positioning system. The objectives of the localization system including to assist the robot to localize the initial position, current the robot's position into the accurate operation pose, finally to grasp the façade and secure the robot to place. In order to achieve a fully functional application, several controllers for the localization system should be designed. As a PoC, two controllers were developed and described in the paper: position controller and force controller. The localization system was developed based on PD control law, the impedance control law was used to avoid rigid collisions between the robot and the façade. The controllers are designed in Matlab. Using ROS communication mechanism method, and simulated by using Gazebo simulator. As mentioned earlier, at the time of this writing, the proposed localization system limited to the conceptualisation. A fully functional robot application and extensive pilot testing are necessary to develop the PoC further.

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