

A Large-scale Suction-based Climbing Parallel Robot for Wall Painting Application

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Abstract— This paper presents a large-scale climbing robot that employs a parallel mechanism with three translational degrees of freedom as its locomotion method. Using a robot frame having a triangular pyramid shape, the robot provides a good stability during the locomotion and task execution. Three suction cups, called the perimeter cups, are attached to the vertices of the robot's pyramid base, whereas three other suction cups called the middle cups, are attached to the end-effector of the parallel mechanism. The climbing motion is made by attaching and releasing the perimeter and middle cups one after another. The synchronization between the parallel mechanism's motion and the suction cups during locomotion, as well as the improved gait trajectory, was established to ensure successful climbing. The control scheme of the robot integrates the servo control, the suction control, and the application control in a modular fashion. The successful climbing of the robot proves the scalability of the proposed climbing robot using active suction cups with an optimized design. Finally, a painting application was presented to demonstrate the robot's capability to perform a wall painting task.

I. INTRODUCTION

Large structures having vertical or largely inclined surfaces, such as buildings, often require inspection and maintenance. Climbing robots can be effectively and efficiently used to perform both tasks. Nevertheless, climbing robots are considered a type of robot that is still rarely deployed in real-world applications, compared to other various types. One of the main reasons is the fact that making a climbing robot move safely and reliably is challenging. Climbing robots are typically classified based on two aspects: their locomotion methods and their adhesion methods. Surveys on crawling and climbing robots based on this classification can be seen in [1 - 5]. Any climbing robot always uses a specific locomotion method with a particular adhesion method. The locomotion methods include wheels, track wheels, translating/rotating frames, legs and arms, sliding (snake-like) mechanisms, wires, and rails. The adhesion methods include mechanical adhesion such as gripping and clamping, negative pressure (vacuum), magnetic adhesion, electro-adhesion, and chemical adhesion. A survey on these adhesion methods can be seen in [5 - 7]. The mechanical adhesion is typically convenient to climb on structures that can

be easily grabbed using grippers [8], claws [9], clamps [10], or another mechanical attachment device. Such structures include slender structures such as pipes and beams, perforated structures, and structures with protruded features across their surfaces. The magnetic adhesion methods include permanent magnets, electromagnets, and electro-permanent magnets. The magnetic adhesion can only be used on ferrous surfaces. Negative pressure adhesion can be considered the most convenient for buildings that often have surfaces from non-ferrous materials such as concrete/cement, wood, glass, and aluminum. The negative pressure adhesion methods include vacuum/vortex chambers and suction cups. The electro-adhesion and chemical adhesion methods require relatively low energy. The first type of electro-adhesion method is using electro-adhesive pads [7]. Another type of electro-adhesion method is dry adhesion [11], which employs microscopic fibrillae (hairy structures); however, this method is limited to very low payload. The chemical adhesion methods include the use of sticky tapes, thermal glue, and magnetorheological fluids. While the mechanical, magnetic, and negative pressure adhesion methods are theoretically feasible to be scaled up, there is still no clear evidence on the scalability of the electro-adhesion and chemical adhesion.

As mentioned earlier, negative pressure adhesion is convenient to be used for robots climbing on non-ferrous surfaces such as building facades. In a climbing robot with a vacuum/vortex chamber [12], a negative-pressure aerodynamic thrust is created by a vortex generator to maintain the robot in contact with the surface, while wheels are usually used to move the robot across the surface. The adhesion force generated is limited since the suction provided by such a mechanism is not air-tight. Therefore, such robots cannot perform high-load tasks; they can only perform light-load tasks such as inspection and cleaning. In a climbing robot with suction cups, the crawling action is typically performed by attaching and releasing the suction cups one after another. The suction cups can be either passive or active, as well as wet or dry. A passive suction cup [13] does not need an active vacuum generator. In contrast, an active suction cup requires an active vacuum generator (such as a vacuum pump and pressurized air with a vacuum ejector). The vacuum-based climbing robots can use various locomotion methods, including wheels [14], translational frames [15], rotating frames [16], multi-legs [17], rotating chains [18], and serial arms [19, 20].

In large structures with vertical surfaces such as buildings, some maintenance tasks such as deep cleaning, drilling, and coring require high rigidity. For this reason, a climbing robot employing parallel kinematics is a good candidate as it has a high stiffness-to-weight ratio. As a preliminary work, this

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paper presents the use of a newly developed climbing parallel robot for painting applications. Due to the high rigidity of the parallel robot, the future applications of the developed robot will include high-rigidity tasks, as mentioned earlier.

This climbing robot is an improvement of our previous robot [21] which requires only three main actuators. While the previous robot demonstrates its capability to crawl on horizontal and inclined surfaces only, the robot currently discussed in this paper demonstrates its capability to climb on a vertical surface. This climbing capability requires an adapted mechanism's motion planning that enables a reliable attachment to the climbing surface. While its predecessor can move translationally and rotationally, the climbing robot proposed in this paper will only move by translating. This is because the rotational gait in its predecessor is performed by having a slip with the attachment surface, while such a slip is not safe in a climbing application.

Moreover, most of the developed climbing robots have small to medium sizes. In fact, building maintenance does not only involve tasks requiring small payloads or application forces such as inspection, surveillance, and non-destructive testing, but also tasks requiring large payloads or application forces such as cleaning and sanding. For this reason, the climbing robot proposed in this paper is developed at a large scale to be able to handle large payloads and application forces. Some applications such as painting and cleaning can also be completed faster when a robot with a large size is used. In this case, the robot can paint or clean a larger area in a single robot position. Furthermore, this large-scale development also assesses the scalability of the proposed robot design. We aspire to not only mimic a climbing gecko but also a climbing crocodile or a climbing elephant. This is among the reasons we make a machine: to do something a living being cannot do. In other words, to surpass the capability of a living creature in some useful aspects.

Since our previous paper [21] already discussed the novel design of the proposed robot, the contribution of this paper is to demonstrate that the robot at a large scale can successfully climb a vertical surface and perform a useful task namely painting. Furthermore, the differences between the currently proposed robot from its predecessor can be summarized as the following: 1) While its predecessor demonstrates a capability to crawl on horizontal and minimally inclined surfaces, the current robot demonstrates a capability to climb on vertical surfaces, 2) While its predecessor can translate and rotate, the current robot is intended to only translate, 3) While its predecessor is mainly designed for on-structure machining tasks, the current robot is designed for building maintenance tasks such as exterior wall painting, and 4) The current robot is larger than its predecessor, but its weight is optimized by using lighter materials.

The remainder of this paper is organized as follows. Section II discusses the topology, kinematics, and design of the robot. Section III discusses the synchronization between the robot motion and the suction cup control. Subsequently, Section IV discusses the improvement of the end-effector trajectory for the gait motion to provide better attachment. Section V presents the control scheme of the robot. Section VI presents the use of the robot for painting applications. Finally, Section VII concludes the paper.

II. TOPOLOGY

The topology of the proposed climbing robot, depicted in Figures 1 and 2, is similar to that of the crawling robot [21] previously developed by the authors, with a few differences to be described soon in this section. Having the shape of a triangular pyramid, the body frame of the robot provides several advantages. First, the pyramidal body frame creates a spatial truss-like structure with a closed structural chain. As a result, the loads exerted on the frame members are mainly tension and compression. Second, the pyramidal body frame leads to a natural placement of a minimum number of suction cups to provide good stability of the robot. In this case, three suction cups are placed at the vertices of the pyramidal body frame. These cups are called the perimeter cups. Three other suction cups are placed at the vertices of a triangular holder attached to the parallel mechanism's end-effector. These cups are called the middle cups. Third, the pyramidal body frame also provides excellent stability as the cross-section (footprint) area decreases from the base to the apex of the pyramid. The placement of the actuators that have a significant weight close to the robot's base also improves further the stability of the robot and reduces the gravity-induced moment exerted on the robot. The proposed climbing robot has three main actuators. However, some auxiliary actuators with smaller sizes and lower cost can be added for an application such as painting or cleaning. The manipulation and gait kinematics using the 3PRRR parallel mechanism (3 = number of limbs, P = prismatic joint, R = revolute joint) is identical to that in its predecessor. Hence, it will not be repeated here for conciseness. The kinematic model is extensively discussed in [21]. Furthermore, the "hopping" gait of the robot is useful for avoiding a significantly thick protrusion on the climbing surface. A specific design of the holder of the middle cups and a specific motion planning are required to enable this protrusion avoidance capability. However, a discussion on this protrusion avoidance is not the scope of this paper.

Although the topology of the climbing robot is similar to its predecessor, several modifications were made to adapt to the climbing application. The proposed climbing robot having parallel mechanism with 3T motion (translational motions in three directions) will only move by translating, whereas its predecessor can also move by rotating besides translating. This is because the rotational gait performed by taking an advantage of slip between the suction cups and the attachment surface is not safe in a climbing application. Consequently, while the perimeter cups in the predecessor robot are connected to the

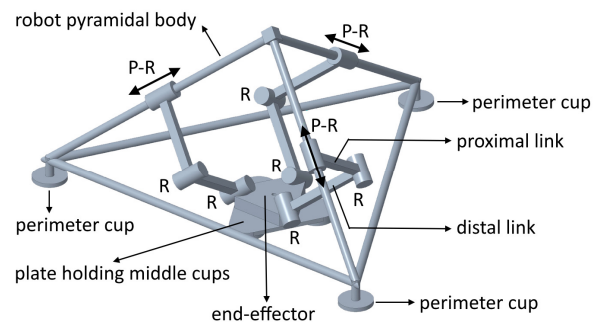
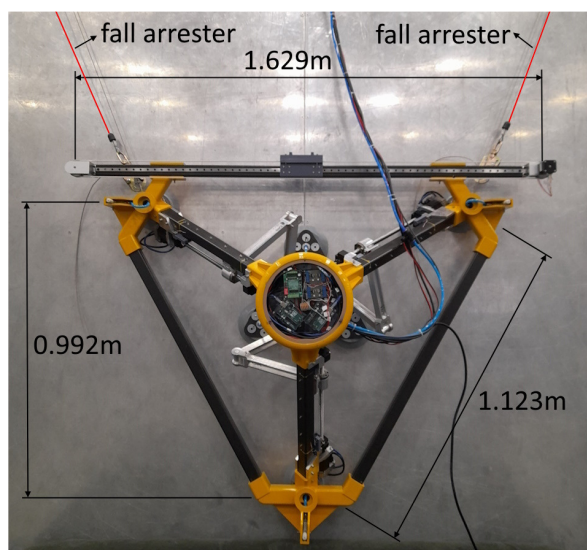
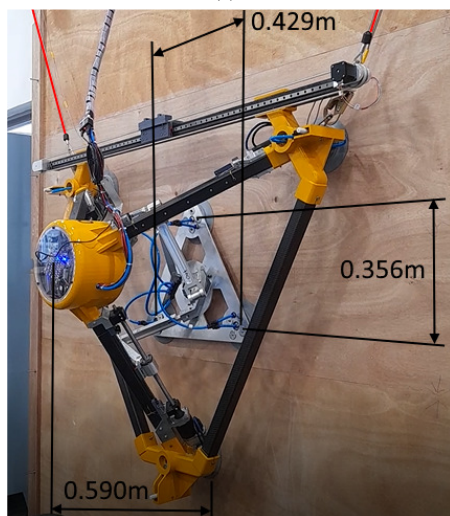


Figure 1. Topology of the proposed climbing robot, with P and R indicate prismatic and revolute joints, respectively



(a)



(b)

Figure 2. Prototype of the proposed climbing robot attached to (a) an aluminum vertical surface and (b) a wooden vertical surface

pyramidal body through spherical joints, the perimeter cups in the currently proposed climbing robot are directly fixed to the robot's pyramidal body.

The footprint of the developed climbing robot is given by the area of the pyramid's base which has an equilateral triangle shape with an edge length of 1.123 m. The height of the pyramidal body frame is 0.590 cm. To minimize the weight, the segments of the pyramid use carbon fiber square hollow beams, whereas the vertices and the apex of the pyramid are made from 3D-printed polymer. These 3D-printed components integrate all the carbon fiber hollow beams into a closed, pyramidal structural chain. With this closed structural chain, the carbon fiber hollow beams perform well as they are mainly subjected to tension/compression loads. The apex of the pyramid has a hollow cylindrical shape which serves as the onboard control cabinet in which all the electronic boards and an onboard computer reside. The 3PRRR parallel mechanism is actuated by three linear actuators that use three AC servo motors with steel ball screw mechanisms. The links of the parallel mechanism are machined from 7075 aluminum. This

material provides an excellent trade-off between the weight and the strength of the moving links of the mechanism that carry the pyramidal body frame during the climbing motion. The vacuum cups are made from nitrile butadiene rubber (NBR) with a rigid core from aluminum. Each cup has a diameter of 160 mm when it is unattached and 170 mm when it is fully attached, with a stroke distance of 8 mm. Each cup can provide a suction force of 975 N. For a better suction performance, the vacuum generators are placed close to the suction cups. The pneumatic hose and all the power cables are tethered to the robot. The overall mass of the robot is 37 kg. With the robot volume of 0.01563 m^3 , the robot has a mass-to-volume ratio of $2,367 \text{ kg/m}^3$. A comparison with its predecessor and some animals is shown in Table I.

TABLE I. COMPARISON OF MASS, VOLUME, AND MASS-TO-VOLUME RATIO

Aspect	Approximate mass (kg)	Approximate volume (m^3)	Approximate mass-to-volume ratio
Current robot	37	0.01563	2,367
Predecessor robot [21]	40	0.00899	4,450
Gecko	0.1	0.00075	133
Crocodile	800	2	400
Elephant	4,000	8	500
Human	62	0.062	1000

Table I shows that a gecko which has a capability to climb on a smooth surface has a much lower mass-to-volume ratio compared to human and other animals that do not have similar climbing capability. Labonte et al [22] suggested that a gecko is the size limit of a land animal capable of climbing on a smooth surface using sticky footpads. Furthermore, they concluded that 40% of a human body surface should be equipped with sticky pads to be able to climb on a smooth surface like a gecko. The investigation implies that the climbing capability of animals on a smooth surface is not scalable. For this reason, we use active suction cups to make our large-scale robot capable of climbing on smooth surface. Although Table I shows that the currently proposed robot has a much larger mass-to-volume ratio compared to the non-climbing land animals, we demonstrated that the proposed robot can climb well on a smooth surface. The active suction cups are selected over magnetic pads and mechanical attachment mechanisms as the former works for a smooth non-ferrous surface having a large area, such as a building wall and a building facade. Furthermore, Table I also shows that the currently proposed robot has a smaller mass-to-volume ratio compared to its predecessor. As mentioned earlier, this is achieved by using lighter materials to build the robot. The reduction of the robot's mass-to-volume ratio is a way to reduce the force requirement of the suction cups. The current robot prototype shown in Figure 2 demonstrated a successful climbing up and down at a speed of 0.75 meters per minute, with a distance of 0.1 meters in each climbing step. This is the speed at which the robot prototype was tested, not the maximum speed of the robot prototype.

For safety purposes, the currently proposed robot is equipped with two fall arresters in its testbed, as shown in Figure 2. These fall arresters will stop the robot falling motion not more than approximately 20 cm after an attachment failure. Not only such a safety feature is required in a test setup, but it is also required in a real deployment to ensure the safety of the robot's operation.

III. SYNCHRONIZATION BETWEEN ROBOT MOTION AND SUCTION CUP CONTROL

The robot's gait consists of two main stages, namely the pyramid-lifting stage and the recovery stage. The sequence of the robot's gait is illustrated in Figure 3. The suction in the perimeter and middle cups should be controlled in a timely manner to ensure that the robot's gait can be performed well without a failure. While the states of the cups' suction are illustrated in Figure 3 along with the robot's gait, they are also summarized in Table II. As illustrated in Figure 3(a), the pyramid-lifting stage starts with initiating the attachment of the middle cups to the climbing surface while the perimeter cups are already attached. Before the middle cups initiate contact with the climbing surface, their suction should be activated. Once the middle cups are attached, both the perimeter and middle cups are attached. This is called the attachment overlap phase that ensures the safety of the robot operation. Without this phase, i.e., detaching the perimeter cups right away when the middle cups start their attachment, the robot may fall. Only after the middle cups' attachment is established well, the perimeter cups are detached after deactivating their suction, and subsequently, the lifting-pyramid motion is performed. The pyramid-lifting stage ends when the pyramid is landed back to the climbing surface. Before the landing, the suction of the perimeter cups should be activated. Once the perimeter cups are attached, both the perimeter and middle cups are attached. This is another attachment overlap phase, to ensure the safety, before the robot makes a recovery motion that returns the end-effector's position to an initial position for the next pyramid-lifting motion. Before making the recovery motion, the suction of the middle cups should be deactivated.

Besides showing the suction state during locomotion, Table II also shows the suction state during an application motion. In an application requiring the end-effector's motion, such as deep cleaning performed using the end-effector's motion, the middle cups are detached to enable the end-effector's motion while the perimeter cups are attached to fix the robot's body to the climbing surface. In an application that does not require the end-effector's motion, the best attachment strength is achieved by attaching both the perimeter and middle cups.

IV. END-EFFECTOR TRAJECTORY FOR THE GAIT MOTION

The end-effector's trajectory during the gait motion of the currently proposed climbing robot is improved from that of its predecessor robot that only crawls on horizontal and minimally inclined surfaces. While the predecessor robot has a triangular end-effector's trajectory for both pyramid-lifting and recovery motions, the current robot adds a motion perpendicular to the climbing surface at the beginning and end of both the pyramid-lifting and recovery motions, as shown in

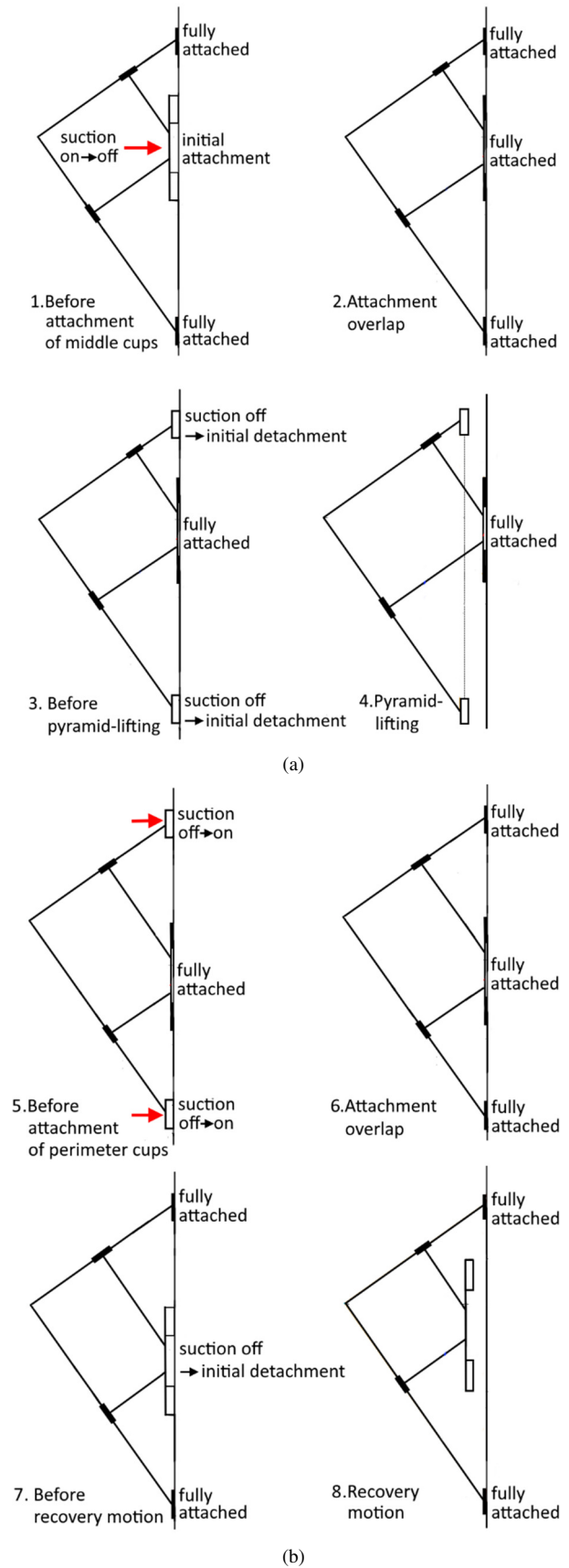


Figure 3. The states of the suction cups during locomotion: (a) in the pyramid-lifting stage and (b) in the recovery stage

TABLE II. STATES OF THE SUCTION CUPS DURING THE CLIMBING ROBOT'S LOCOMOTION AND APPLICATIONS

	Locomotion			
	Attachment overlap 1	Pyramid lifting	Attachment overlap 2	Recovery
Middle Cups	attached	attached	attached	detached
Perimeter Cups	attached	detached	attached	attached

	Application motion	
	End-effector manipulation for application	Application with extension mechanism
Middle Cups	detached	attached
Perimeter Cups	attached	attached

Figure 4. Added at the beginning, the perpendicular motion makes a perpendicular separation of the cups from the climbing surface after the suction is deactivated. Added at the end, the perpendicular motion makes a perpendicular approach of the cups to the climbing surface. This will ensure an ideal development of the cups' contact and vacuum.

For simplicity, the end-effector's trajectory for both the pyramid-lifting and recovery motions is made symmetric. Referring to Figure 4, this symmetry is indicated by $h_{w1} = h_{w2}$, $h_{r1} = h_{r2}$, $d_{w1} = d_{w2}$, and $d_{r1} = d_{r2}$. The maximum heights of the trajectory with respect to the climbing surface in the pyramid-lifting and recovery motions are D_w and D_r , respectively. The step distance of the pyramid-lifting motion, $h_w = h_{w1} + h_{w2}$, represents the distance climbed in a single locomotion step. The step distance of the recovery motion, $h_r = h_{r1} + h_{r2}$, in general should be equal to h_w if another identical pyramid-lifting motion is going to be performed in the next step.

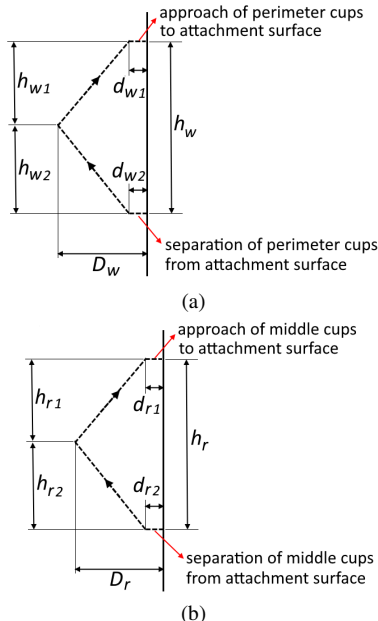


Figure 4. The end-effector's trajectory: (a) in the pyramid-lifting stage and (b) in the recovery stage

V. CONTROL SCHEME OF THE CLIMBING ROBOT

The control scheme of the climbing robot with an application included is depicted in Figure 5. The main components of the robot's control are the parallel mechanism's servo system and the suction system's control. The robot control software architecture is built on Robot Operating System (ROS) middleware that runs on an onboard Intel NUC computer. The ROS middleware allows modularity in the control architecture. The onboard computer and all the electronic boards are placed inside the cylindrical head of the robot.

The servo hardware consisting of the AC servo motors, encoders, drives, and controller are interfacing with ROS through *Servo ROS Driver*. The servo system is a PID-based closed-loop system that moves the parallel mechanism based on motion trajectories created by a motion planner. Vacuum generators that create vacuum in the suction cups are controlled through an Arduino microcontroller. To conveniently control the servo and suction systems, each is controlled through a ROS service. A single ROS node controls the servo and suction systems as both must be synchronized as discussed in Section III. Optionally, an independent node that controls the suction system alone can be created to control or test the suction system independently when required. The robot is tele-operated by using a gamepad.

It is worth mentioning that the suction cups used in the robot at hand have suction and blow-off capability. The former creates vacuum in the suction cups, whereas the latter blows pressurized air to the suction cup to release the cups from the climbing surface. Without the blow-off capability, the suction cups remain attached to the climbing surface although the controller deactivates the suction.

Figure 5 also shows that an application using stepper motors and DC servo motors is added to the system. This particular application will be discussed in detail in the next section. Both the stepper motors and DC servo motors are controlled through another Arduino microcontroller. A ROS node for the application controls the application hardware using ROS services.

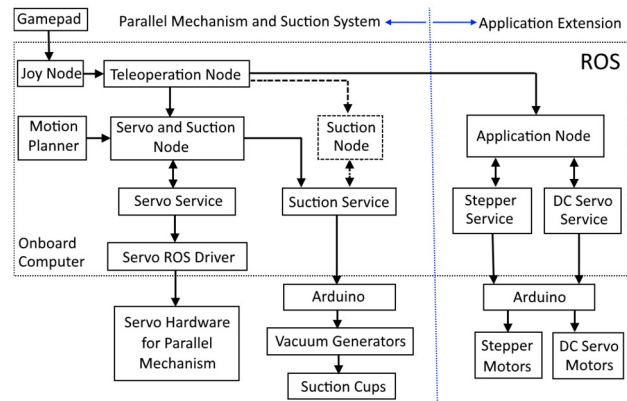


Figure 5. Control of the climbing robot with an application included

VI. PAINTING APPLICATION

A painting application extension was built and integrated with the climbing robot to demonstrate the robot's capability to perform a building maintenance task. This extension is

modular; it can be easily disassembled and replaced with another extension, depending on the required application. As shown in Figure 6, the extension is attached to a sliding cart namely the X-cart that travels back and forth along a rail attached to one of the pyramid's base segments. For painting application, two types of painting extension were developed, namely a 1-degree-of-freedom (DOF) painting extension, depicted in Figure 6(a), and a 2-DOF painting extension, depicted in Figure 6(b). In both types, a paint spraying gun is used to spray the paint to an intended surface. While spraying the paint, the robot is stationary as it is attached to the climbing surface on both the perimeter and middle cups. In the 1-DOF painting extension, the painting gun is attached to a fixture fixed to the X-cart. Hence, the painting path is a straight line with a length of L . In the 2-DOF painting extension, the painting gun can travel in both the X_p and Y_p axes, since it moves on two carts namely X-cart and Y-cart. Accordingly, the extension can paint a rectangular area with the length L and width H . Using this 2-DOF painting extension, a larger area can be painted in a single position of the robot. Figures 7(a) and 7(b) show the climbing robot prototype equipped with the 1-DOF and 2-DOF painting extensions, respectively. The 1-DOF painting extension has a length of $L = 1.45$ m, whereas the 2-DOF painting extension has a length of $L = 1.45$ m and a width of $H = 0.35$ cm.

The X-cart is moved by a timing belt-pulley system driven by two equally sized stepper motors installed at the two ends of the rail. The two stepper motors are controlled to move in

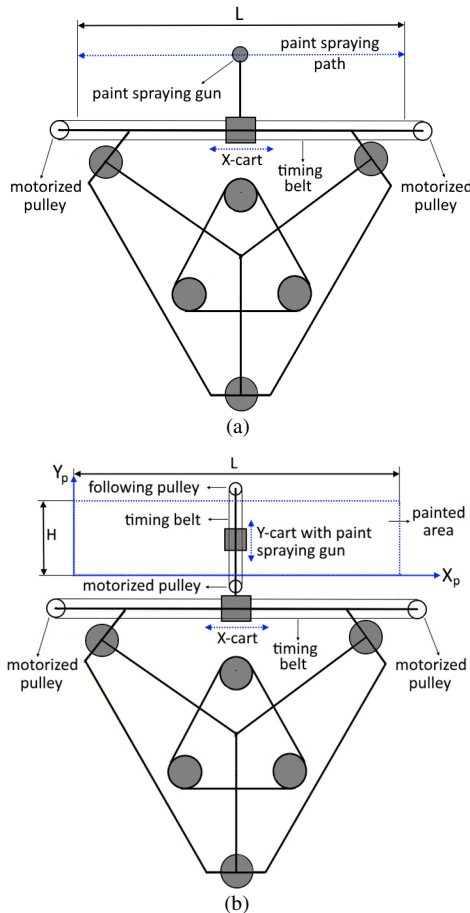


Figure 6. The schematic of the climbing robot with (a) the 1-DOF painting extension and (b) 2-DOF painting extension

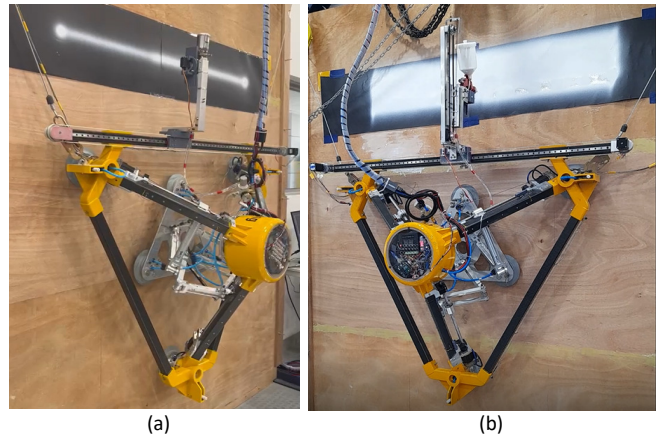


Figure 7. The climbing robot prototype with (a) the 1-DOF painting extension and (b) 2-DOF painting extension. White paint was sprayed on a black sheet of paper attached to the climbing wall.

the same direction at the same speed. In the 2-DOF painting extension, another timing belt-pulley system driven by a DC servo motor moves the Y-cart on which the painting gun is mounted. Having two stepper motors installed symmetrically at both ends of the rail provides a better robot balance. The painting gun used in our experiment is off-the-shelf. The gun's trigger is switched between *spraying* and *no spraying* states by using a cam mechanism moved by another DC servo motor. Using pulleys actuated by stepper motors having a size of $42 \times 42 \times 60$ mm and a torque of 0.65 Nm, currently the 1-DOF painting extension has a painting speed of approximately 6 meters per minute whereas the 2-DOF painting extension has a painting speed of approximately 7 minutes per square meter. The painting speed is expected to increase with the use of stronger motors that move the pulleys.

VII. CONCLUSION

It was shown that the proposed climbing robot, built at a large scale, can successfully climb on a vertical surface. This involves a synchronization in the control and motion planning between the parallel mechanism's motion and the suction system, as well as the improvement of the end-effector trajectory for the gait motion. It was demonstrated that the robot design conveniently allows an application for building maintenance, namely painting, to be performed efficiently due to the capability to cover a large area in a single position of the robot. In the future, the static and dynamic theoretical analyses of the robot along with experiments to obtain more quantitative results will be performed. Furthermore, the horizontal motion of the robot will be tested in the future. A rotational DOF can be added to the robot to make the robot able to rotate when climbing. This rotation capability can be used to compensate a possible angular deviation made by the robot during climbing. Vacuum sensors can also be added to the vacuum cups to indicate a successful attachment. This will increase the safety and reliability of the robot. Finally, high-rigidity applications such as cleaning of a building façade and drilling/coring of a vertical concrete wall will be developed to demonstrate the capability of the robot to offer high rigidity as an advantage of its parallel kinematics.

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