Pictobot

A Cooperative Painting Robot for Interior Finishing of Industrial Developments

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Human–robot collaboration (HRC) [1], [2] is a vastly developing field in diverse industries such as health care [3], industrial assembly [4], search and rescue, home service [5], and construction [6], [7]. Many researchers believe that robots will enhance human workers, not replace them, as they do not have the same capability to evaluate and correct their work in real time. Lee [8] introduces case studies on glazing robot technology for installing glass panels on construction sites. A human–robot dialogue system [9] has been developed in joint-action science and technology to solve a construction task collaboratively with a human. The use of immersive virtual environments is also reported in [10] to evaluate human trust and perceived safety in response to robot actions during a collaborative construction. Deploying robots in collaboration with humans is seen as an enabler of major changes in construction productivity for various tasks, such as interior finishing.

Industrial developments come with high ceilings to accommodate large materials and equipment. Currently, high-rise painting services are labor intensive and performed with conventional techniques, which are time-consuming and tiresome. Manual painting often results in uneven painting quality and safety risks due to the need for a scissor lift or scaffold to reach high elevations. Aside from the low efficiency in this particular sector, the need for construction and maintenance is growing around the world, while the industry is facing a future shortage of skilled workers and wage increases. Inefficient resource management and the use of unskilled workers can result in a considerable decline in quality and productivity. Robotic technologies can be applied in construction to boost productivity by focusing on quality, time, and cost saving as well as sustainability and safety.

An overview of the relevant state-of-the-art applications of construction robots indicates a lack of adaptable robots for interior finishing because very few robots were invented and developed with this task in mind. The feasibility analysis and economic impact of robotizing interior finishing services for productivity improvement were initially studied by Rosenfeld et al. [11] and Warszawski and Rosenfeld [12], [13]. Later, Kahane and Rosenfeld [14] developed a method to assess the effects of HRC for automating a construction task and examined the technique using the multipurpose robot TAMIR for block laying and wall painting Figure 1(a). The painting system comprises a commercial six degrees of freedom (6 DoF) robot arm mounted on a computer-controlled 3 DoF mobile platform. The robot was devised for research and development purposes, and it had an average reach access. Another

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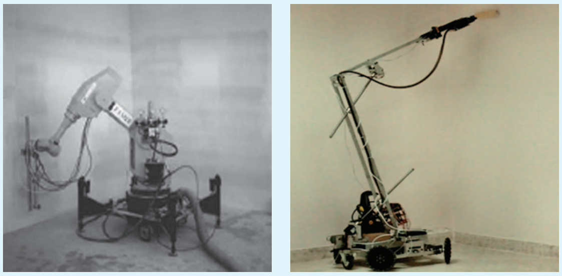
study by Naticchia et al. [15] introduced a scaled-down interior painting setup for laboratory use that consisted of a 6 DoF manipulator to be installed on a 2 DoF Hexapod for horizontal movement. The research also studied the reproduction of colored artworks by developing a multicolor spraying tool. A roller-based interior wall painting robot was proposed by Mohamed et al. [16], as seen in Figure 1(b), and includes a horizontally moving platform (3 DoF), and a painting arm (2 DoF) with a roller brush, attached to the end effector, which solely scans the walls vertically up to 2.7 m.

To the best of our knowledge, all of the existing indoor paint robots have a low (1.7 m) or average (3 m) reach access and are not capable of delivering desirable functionality for high-rise warehouses within a stand-alone system. Moreover, the previous works relied on the two-dimensional (2-D) range measurements by creating a 2-D map of walls to locate the robot's position, which is only suitable for painting flat surfaces. The implementation of three-dimensional (3-D) environment perception and robot–human collaboration in construction painting robots are not well studied in other works to deal with uncertainties in the build environment and errors in mobile robot positioning, and to paint walls with indentations or protrusions. The computer-aided design (CAD) model-based planning approaches previously deployed by conventional painting robots do not properly fit the interior finishing task due to the existence of less stringent 3-D models as well as the errors of mobile robot positioning. The traditional paint robots used in other industries, including manufacturing, automobile, and so on, are not meant to be operated with anyone nearby, and they can apply paint to objects with a precise CAD model (i.e., cars) that are fixed, relative to the robotic painters.

The robotic painter called *Pictobot* (pictor means painter in Latin) could work safely in close proximity to human coworkers performing the repetitious and troublesome task of painting at high elevations. Pictobot provides a way to combine the benefits of automation in construction with those of human dexterity and ingenuity. Thus, it relieves workers of the tiresome tasks and considerable climbing, bending, kneeling, and reaching, freeing them to paint walls at low heights and supervise the robot. By utilizing a modular system, the robot is designed as a stand-alone system with six primary subsystems: a 3-DoF mobile robot, a 1-DoF long-reach jack-up mechanism, a 6-DoF industrial robot arm, an airless paint pump, a painting head system, and a computer-controlled system. Pictobot is outfitted with a sensor-driven painting system via in situ 3-D scanning and spray-gun motion planning, which adapts to the uncertainties of inherent in construction environments and robot deployments from various positions. Moreover, we employ human perception to decompose a broad functional area to smaller workspaces and to position the robot at approximately anticipated locations with the help of both visual and data feedbacks. The human–Pictobot system works collaboratively, in which the worker's judgment and perception become the upper robot planner, and the robot adjusts the spray-gun path and the painting plans from various deployed positions. The robot is then successfully tested in two actual industrial developments. Pictobot enables achieving higher spraying transfer efficiency (TE) in comparison with manual spraying, resulting in reduced paint dust, paint waste, and human exposure to harmful chemicals. It also allows the existing workforce to achieve more with consistent coat quality and higher productivity.



(a) (b)

Figure 1. Previously reported works in interior finishing include (a) TAMIR: Kahane et al. [14] and (b) Sorour et al. [16]

Task Analysis

Approximately 45% [17] of the paint produced worldwide is used in the construction sector to paint new buildings or maintain existing ones, including residential, public, and industrial developments. Additionally, construction markets for paint coatings will be driven by the need for environmentally friendly paints with low volatile organic compounds (VOCs). Indoor high-rise painting is inevitable and common in building construction, especially in industrial workshops. Airless spray painting is preferred for painting large workshops and buildings, as it provides a fast and economical way to apply a broad range of coatings with high quality. Traditional high-rise painting is done manually by utilizing ladders or hydraulic lifts and often results in unreliable and uneven paint quality. It is difficult to obtain consistent quality because of the precarious working position and movement of the worker, thus yielding a big disparity in productivity due to the worker's skill level and experience. Moreover, spraying in high places will create potentially dangerous working conditions.

The main requirements of a reliable robotic system to interior finishing in industrial developments are briefly summarized as follows.

- The robotic system should be able to navigate and reach high elevations of up to three floors (9–10 m), i.e., the normal warehouse height.
- The robot should be adaptable to various deployed positions and shapes of different architectural surfaces with indentations/protrusions and concave/convex corners.
- Platform stability and safety are needed when at high elevations, and the load capacity of the robot should be sufficient to support the weight of the pump, paint and water reservoirs, hoses, and all the control tools, actuators, and mechanisms.

- The robot should work with various commercial paint products.
- The painting head should be capable of spraying efficiently, which would result in precise paint coverage and distribution with minimal paint dust.
- The robot should host an automated water flushing system to clean the spray-gun and tubes before and after operation.
- Environmental conditions and light variation in construction sites are crucial to the robot's operation, and the robot must be constructed to withstand high temperature, humidity, and dust.

Pictobot's Platform and Modules

A modular design is necessary to reduce the system complexity at the conceptual and technical levels. The Pictobot comprises six primary subsystems, as seen in Figure 2: a mobile robot is capable of carrying a heavy payload with zero-turn maneuverability, a commercial airless system is selected for high-volume spraying and aesthetic paint finishing and is also equipped with a distributed computer-controlled system [Figure 2(b)], the jack-up mechanism comprises a dual-mast telescopic device that is employed up and down to specific heights, up to 10 m, a 6 DoF collaborative robot arm (the UR10 by Universal Robots) is mounted on top of the jack-up mechanism to enable precise movement of the spray-gun, and the manipulator is outfitted with a painting head system that includes a time-of-flight (ToF) camera and paint protective housing together with an electrically actuated spray-gun that allows high-quality paint finishing. Moreover, the robot consists of several subsidiary modules such as a 13-m cable-hose suspension system, stabilizer legs, and diverse types of covers to protect the equipment and sensors against paint pollution.

The overall architecture of the control system is depicted in Figure 2(b). The robot is equipped with distributed control subsystems and two on-board personal computers (PCs), as well as a remote control system with data and video feedback. The two control PCs, PC-I and PC-II, are attached to the mobile base and the jack-up mechanism, respectively. The feedback system streams the robot's workspace with the overlaid high-frequency distance measurement to a smartphone or first-person view (FPV) monitor placed on the remote controller [Figure 2(c)]. The software on the two PCs interacts with each other via transmission control protocol/Internet Protocol communication and with the remote controller to share sensory data and feedbacks, which are briefly summarized as follows.

- The robot operator is provided with both visual and data feedback, high-frequency distance measurement [Figure 2(c)] that eases mobile base positioning within an acceptable distance, and orientation range. The camera and rangefinder are mounted on a three-axis Gimbal, placed close to the manipulator stand.
- PC-I software receives the Bluetooth signal from the remote controller operated by the human operator and sends feedback of its actions to PC-II. It also performs the control of the mobile base (Figure 3) and receives control signals from PC-II to apply the jack-up mechanism action.
- PC-II communicates with PC-I, the manipulator controller, and the painting head system to conduct the automated spray painting. It performs the high-level task of planning and execution as well as 3-D understating of structure layout and motion planning of the robotic arm and the jack-up mechanism by processing the sensor readings and action's status in real time.

Cooperative Task Automation

Replacing on-site workers with fully autonomous robots is not affordable with current technologies due to the challenges of developing robotic capabilities that evaluate and correct a robot's work in real time. However, the productivity of many construction tasks could be significantly leveraged through human and robot cooperation.

We propose combining the benefits of automation with the deployment of Pictobot and human skill/ingenuity for the interior finishing of industrial developments to minimize the tiresome part of this type of work while maximizing the spraying efficiency and coat quality.

Considering a space with high walls, we could reduce the functional painting area to several vertical strips with certain widths and lengthy heights from the ceiling to the floor, in which each vertical section comprises multiple rectangle patches at different heights (Figure 4). The Pictobot is designed to autonomously spray paint one vertical area from top-to-bottom through a combined motion of a 6-DoF manipulator and a 1-DoF jack-up mechanism. The 3-DoF mobile base is then teleoperated (Figure 3) to the next working station in stepped courses. A mobile base motion requires a rapid movement with low precision, while a spray-painting task needs precise robotic arm motions with relatively slow speeds to provide a proper paint thickness. Accordingly, the allocation of tasks between the operator and the robot are as follows.

- The human operator is primarily responsible for setting painting requirements, e.g., selecting a proper spray nozzle, or paint type, or adjusting parameters such as spraying pressure or paint thickness on the user-defined finishing needs. This preparation is a one-time setting of parameters, and the values are selected from a predefined library for different paints and specifications; however, the operator must have a basic knowledge of spraying to verify the output quality as well as to take care of fine-tuning the pressure or refilling the system during the robot operation. For instance, sprayer tail, i.e., paint that is not being evenly atomized at the edges of pattern, might occasionally happen when initializing the system if there is any dirt inside the nozzle or the pressure is less than optimal.
- The operator also teleoperates the navigation of Pictobot between adjacent workstations to cope with a changing work environment (Figure 3) with the help of visual and data feedback as seen in Figure 2(c). This method enables the benefits from a human's perception and cognition to reduce complex working environments to smaller, less-complicated workstations, while the operator also has the safety and convenience of joystick teleoperation of the robot. The robot must be

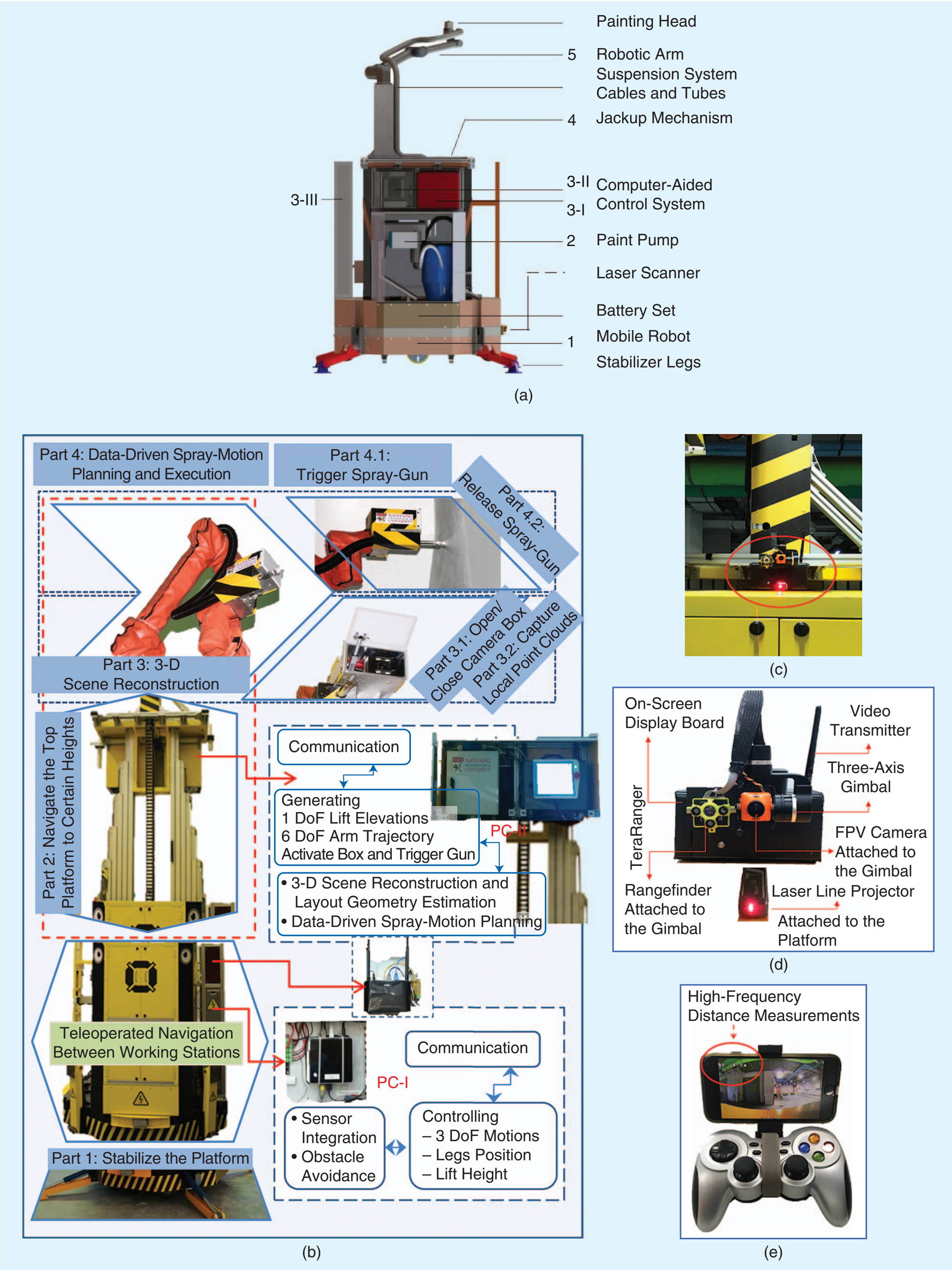


Figure 2. The hardware and software design of Pictobot: (a) The hardware design of Pictobot, (b) the overall workflow of the computer-aided control system, parts 1–4 refer to the sequence of actions, (c) the attachment of a video pilot system to the platform, (d) the integration of both the FPV camera and rangefinder to the Gimbal (the range data and video stream are integrated through an on-screen display board), and (e) a remote controller with an FPV display (smartphone).

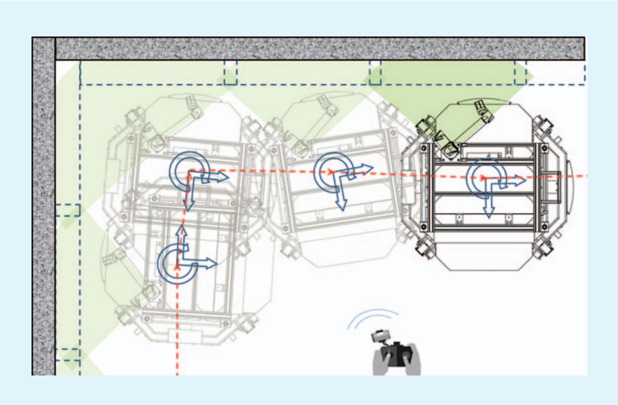


Figure 3. Route planning and execution by a human operator.

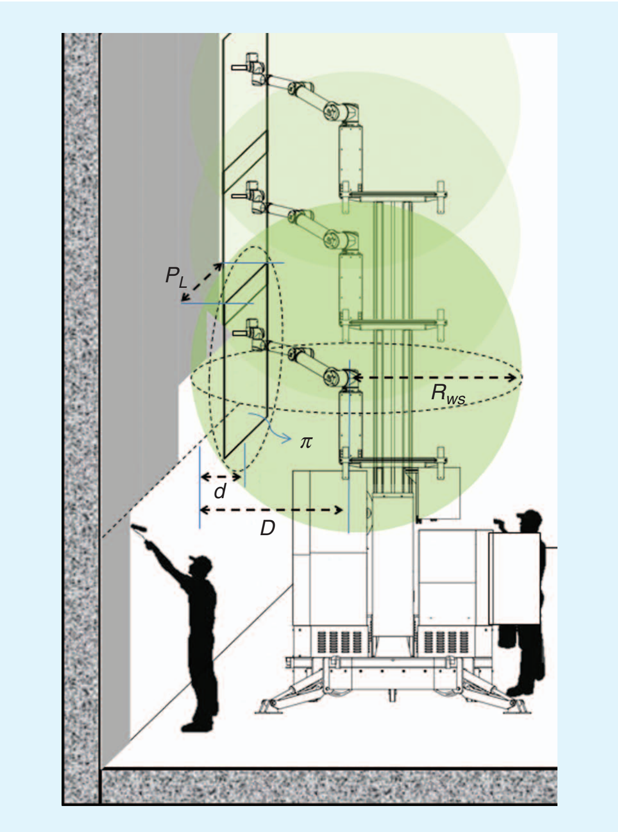


Figure 4. An HRC for interior finishing.

moved along a wall in stepped courses with displacements less than the maximum allowable painting length, which is noted as P_L and expressed in (1). Thus, the worker's judgment and perception become the upper robot planner, while the robot will autonomously adjust the plane-to-plane spray-gun position and painting plans from various deployed positions using the sensor-driven method.

- The Pictobot works safely when close to workers performing repetitive painting processes independently at high elevations, relieving human workers of tiresome tasks and much of the climbing, bending, kneeling, and reaching associated with this type of work. Pictobot is outfitted with a sensor-driven spray-painting solution, in which the steps include in situ scene reconstruction and 3-D layout understanding, automated height control of the jack-up mechanism, and coverage spray-gun arm motion planning and execution.
- The workforce could also help with painting walls at low heights or finishing details close to the edges of windows or doors simultaneously, with the robot performing work on high walls.

A schematic workspace of the 6-DoF robotic arm adjacent to a wall surface is illustrated in Figure 4 as a sphere with a certain radius, i.e., R_{ws}. The combined movement of the manipulator and 10-m jack-up mechanism enlarges the workspace to cover a cylinder with the R_{ws} and a 10-m height. However, painting requires the use of the spray-gun at a fixed plane-to-plane distance, d, and perpendicular to the wall surface that is defined as a spray-gun constraint plane, π. This constraint plane intersects with the cylindrical workspace, with R_{ws}, in a circle with the radius of a. Thus, the length P_L of the region to be painted successfully from a particular deployment distance is considered equivalent to the side-length of the largest square that lies in this circle.

$$P_L = \sqrt{2} \times a = \sqrt{2 \times (R_{ws}{}^2 - (D - d)^2)}, \tag{1}$$

where D is the distance between the arm base and the wall.

Stabilized Visual and Range Data Feedback

By mounting a rangefinder [22] and a camera on a three-axis Gimbal, as seen in Figure 2(c), the stabilized visual and distance feedbacks are integrated and streamed to assist the operator. The setup is deployed in two different modes. In pan mode, both the camera and rangefinder, attached to the Gimbal, will follow the pan movement of the base while the roll and tilt angles are locked. Thus, the point–point distance to the surrounding environment is measured and displayed. In lock mode, the operator locks the Gimbal both the camera and rangefinder perpendicular to the target wall. Therefore, the setup always measures point-to-plane distance, d, independent of the robot orientation that eases the operator effort to position the robot at the correct distance range. Moreover, the deviation between the projected line by the laser and the center of the video stream indicates the orientation between the y axis of the mobile base and the normal axis of the wall surface.

Pictobot Safety Features

The nonsimultaneous operation of painting execution and base movement brings operation safety to a higher level. To ensure the safety of the workmen, we incorporate several features.

- The mobile base is equipped with two laser scanners; one looking front and the other looking left, facing the target wall. Both scanners are incorporated for autonomous obstacle avoidance during the teleoperated maneuvering and parking.
- Two upward-mounted sonar sensors on the top of the jack-up mechanism are employed for autonomous obstacle avoidance when the mechanism lifts the robotic arm by real-time tracking of distance relative to the ceiling.

- Pictobot includes a collaborative manipulator with its safety system to perform a protective stop in case an arm accidentally hits a structure or a human. Also, a safety zone is established by defining five virtual planes in the arm workspace that ensures the robot movement only inside an area smaller than the footprint of the base platform and above a height of 2.3 m. The end effector could reach beyond the Pictobot footprint from only one side at the left, where the side-mounted scanner is used for monitoring the space between the robot and the wall; if a worker or object enters this zone, the protective stop will be automatically activated to stop the manipulator as well as spraying.
- Furthermore, the in situ generated 3-D point clouds are utilized for arm collision checks and safe spray-gun motion planning.

Sensor-Driven Interior Spray Painting

The CAD model-based planning approaches previously deployed by conventional painting robots does not fit the interior finishing task, which adequately copes with challenges that are present in a changing environment and the errors of implementing a mobile manipulator. The tolerances of construction models are also less stringent than manufacturing. The model-based planning solution suits applications that involve painting similar objects of standard size with high-precision models, in which it is possible to preprogram the trajectories of the spray-gun.

The Pictobot deployment is subject to variations of base position and orientation within different workstations, due to human teleoperation and changes in ground and wall evenness. Incorporating an automated base-leveling system that uses a dual-axis inclinometer and stabilizer legs to compensate the tilt-angle of the base if the ground is tilted between 0.5 to 2°, and avoids raising the platform on a slope more than 2° for safety reasons is essential to the successful deployment of the system. Pictobot also performs in situ scanning of an actual structure for spray-gun motion planning. Geometric and architectural features, such as surface normals and intersection lines, are mapped out for adjusting the gun position with an eye toward the variations in wall evenness and robot deployment from various locations. Unlike the CAD model-based painting methods, sensor-driven spray painting (Figure 5) is deployed, which incorporates manipulator motion control with the vision system.

Task-Oriented Scene Reconstruction and 3-D Layout Understanding

A part of the as-built structure to be painted is scanned and processed in situ by a 3-D camera coupled to the end effector. A ToF camera is among the best technologies to obtain scene depth and intensity images simultaneously. Low weight, compact design, and robustness to illumination changes make a ToF camera an affordable solution to perform in light-varying conditions, such as buildings under construction. In this article, an eye-in-hand configuration is preferred to optimize the scene acquisition and processing through manipulator

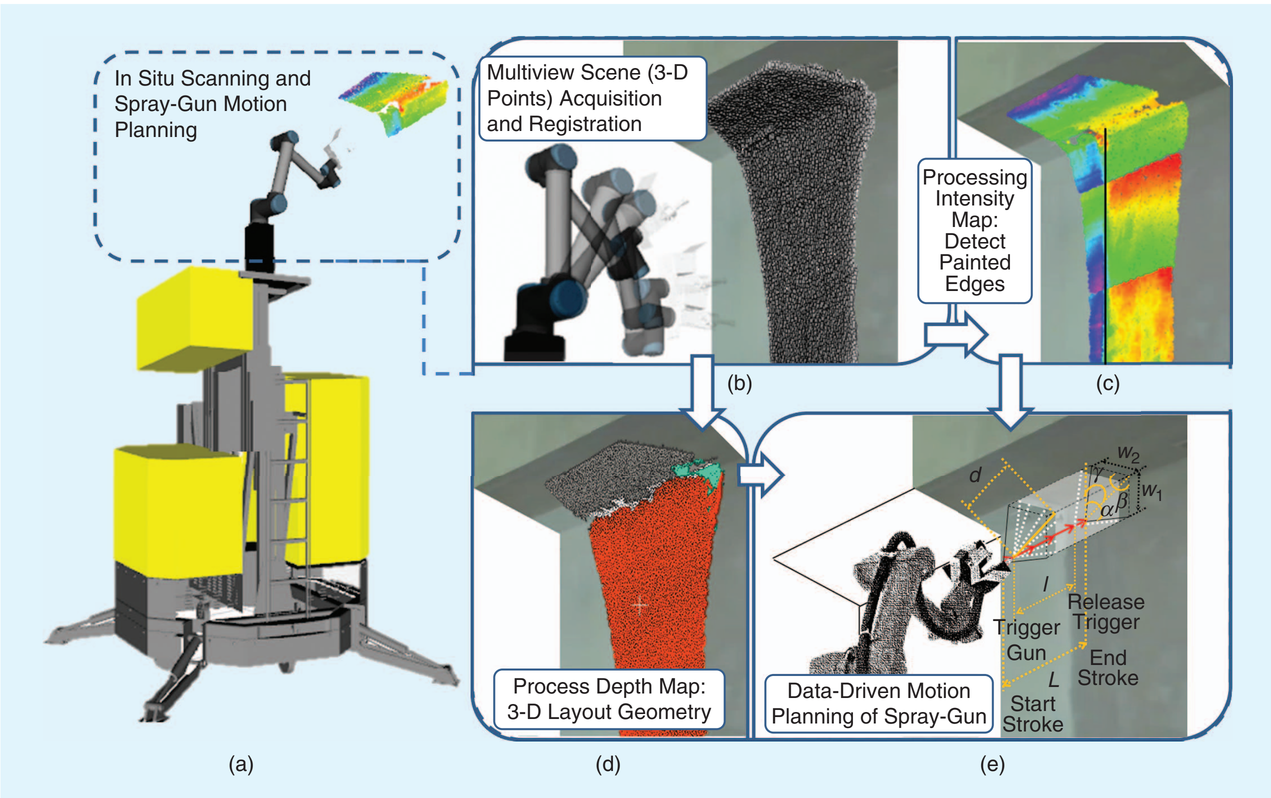


Figure 5. A schematic workflow of (a) sensor-driven interior finishing: (b) a multiview 3-D scene reconstruction, (c) a processing intensity map, (d) 3-D depth processing and 3-D layout estimation, and (e) data-driven spray-gun motion planning.

motions. By incorporating the manipulator motion, a relatively larger area is scanned from close ranges, considering that the robot must be placed in the proximity of the structure to benefit from the maximum workspace of the manipulator for spraying. Moreover, this arrangement is provided for a platform-free solution to integrate the painting head setup to the system quickly.

By actively moving the camera to several positions, the local point clouds are captured and merged to enlarge the scanning window, as shown in Figure 5. Point clouds in camera frame-of-reference (FoR) are transformed in real time to the arm FoR before merging them. This is done by utilizing forward kinematics that allows expressing the pose of the eye-in-hand camera according to the angle of all joints at each instance of scene acquisition. Scan registration methods that are 3-D, such as the iterative closest point, do not fit this application since the scene only includes the wall and frame; these methods do not perform well in scenes with few details or with many coplanar surfaces.

This method segments the generated 3-D point cloud into horizontal and vertical planar surfaces using the random sample consensus method and subsequently extracts the 3-D layout and geometry of planes and intersections. These pieces of information are then processed to plan for sequences of painting different architectural features, e.g., surfaces, corners or edges, and to adjust the distance and orientation between the gun and surface for every single stroke. We cope with the variations in the evenness of a large wall by decomposing its surface into several smaller painting patches and taking into account changes in the normal vectors of each planar patch. Accordingly, the distance, $D(i)$, and orientation $\omega_n(i)$ between the arm FoR and each surface patch are calculated without the need for localizing the robot in a global coordinate frame. The value ω_n is the orientation vector between the normal vector to the surface and a ray connecting the origin of arm FoR and the measuring point. In this way, the modeling precision is acceptable at an affordable computation time, knowing that the coat quality standard is less strict in construction than other industries (e.g., automotive). Also, by analyzing the ToF intensity map, the edge of the latest vertical paint strip is extracted for planning a precise overlap between two consecutive vertical strips.

Task-Oriented Manipulator Motion Planning

When a single spray injection is applied on a surface, it results in a deposition pattern that is in the form of paint thickness distribution. The spray area with a flat fan nozzle can be geometrically expressed as an ellipse with a large major axis. By neglecting the loss of spray, the dry film thickness [18] could be calculated by

$$T_{DFT} = k \times \frac{m \times \cos\theta}{\rho_{\text{cm}} \times \pi \times d^2 \times \tan\alpha \times \tan\beta}, \qquad (2)$$

where d, θ, α, and β are the gun-target distance, the inclination angle of the spray-gun, and the span angles, with respect to the major–minor axis, respectively. M, ρ_{cm}, and k are the weight of coat material, density, and coefficient of spray, respectively. The problem of loss of spray will be studied in the "Field Experiments and Results" section by evaluating the TE.

According to (2), all of the aspects of the applicator, e.g., gun distance to the target, the angle of application, and traveling speed could affect the finish quality. The film thickness is inversely proportional to the square of the distance between the spray-gun and surface. Therefore, variation in paint thickness is a common problem in conventional spraying, particularly in high-rise spraying due to the difficulties of precisely controlling paint distribution by a human painter. Inconsistent film thickness contributes to various defects such as runs, drips, sagging, mottling, and striping.

The thickness variations in interior finishing could be substantially avoided by automated spraying if certain task constraints are satisfied by accurate and repeatable control of paint distribution across the surface. Thus, coverage paint planning is performed to generate the trajectory of the spray-gun by considering the 3-D layout of the as-built structure, characteristics of spray nozzle (i.e., spray angle, α, and spray pattern, w), arm workspace, and geometric constraints [Figure 6(a)]. The following constraints are considered and applied to provide an even paint distribution by using a flat fan nozzle.

- The spray-gun, coupled to the arm, is held and moved at an optimal and constant spray distance to the surface, $d = 30$ cm. Otherwise, a portion of the paint droplets become nearly dry before striking the surface, resulting in significant paint dust.
- The nozzle is pointed straight and perpendicular to the planar surfaces, $\theta = 0$. A small orientation between the gun head and the target surface will cause an uneven finish.
- The end effector is moved across the surface with constant speed while the wrist is fixed to align the gun perpendicularly.
- The gun is triggered after beginning the end effector movement (called the *lead stroke*) and released before ending the stroke (called the *lag stroke*), with no spraying during the acceleration or deceleration phases. This technique prevents inconsistent coating thickness at the beginning and end of each stroke: $L > l$, where L is the arm stroke length, and l is the coverage length.
- Horizontal paint strips, extended from left-to-right with a specific spray width, w, and 50% overlap, P_h, between two strips are applied to achieve the coating thickness.
- A spraying sequence starts from top-to-bottom: multiple, horizontal paint strips generate one patch, and multiple patches at different heights result in a vertical paint strip, as shown in Figure 6(a).
- A small overlap, P_v, between two vertical paint sections is considered to ensure complete paint coverage, as shown in Figure 6(b).

Utilizing these techniques in the task and motion planning stage will generate a unique deposition pattern and allow Pictobot to control the film thickness by the spray parameters, e.g., pressure, speed, and spray nozzle size.

Field Experiments and Results

The Pictobot has been successfully test-bedded and evaluated under actual conditions at two industrial developments with high walls. The results of two separate experiments are given here to demonstrate the painting sequence, the improvement in spraying efficiency, and the robot performance in collaboration with workers.

The first test focused on the robot deployment for the painting of a large wall with a height of 4.6 m and the corner between the wall and a horizontal beam. The painting sequences and the finishing results are depicted in Figure 7. First, the operator filled the reservoir with a water-based emulsion paint, turned the pump on, and set the desired painting pressure and nozzle coverage width, *w*, which were 2,000 lb/in^2 and 40 cm, respectively. Second, the operator teleoperated the mobile base to the left side of the wall and parked it at approximately 60–80 cm from the structure, while the end effector faced the wall surface. Next, the operator sent a control command to the robot to autonomously scan and paint one vertical strip from ceiling corner to the bottom height, which was 2.6 m. The operator can concurrently adjust the pressure, if necessary, to optimize the spray pattern or activate the safety button, in the event of a malfunction. Figure 7(a)–(d) illustrates multiple sequences of horizontal spray strokes for painting the ceiling corner and the wall surface at different heights. Figure 7(e)–(h) show the robot actions for the third and fourth vertical strips where the operation was achieved by painting each vertical strip in two patches. For painting the top patches, the jack-up mechanism was moved up approximately 30 cm [e.g., Figure 7(e) and (g)] to reach the ceiling corner. For performing sensor-driven spray painting, the actual trajectory and speed of the end effector for the top patch with the corner are depicted in Figure 8(a) and (b), respectively. The arm motion started with

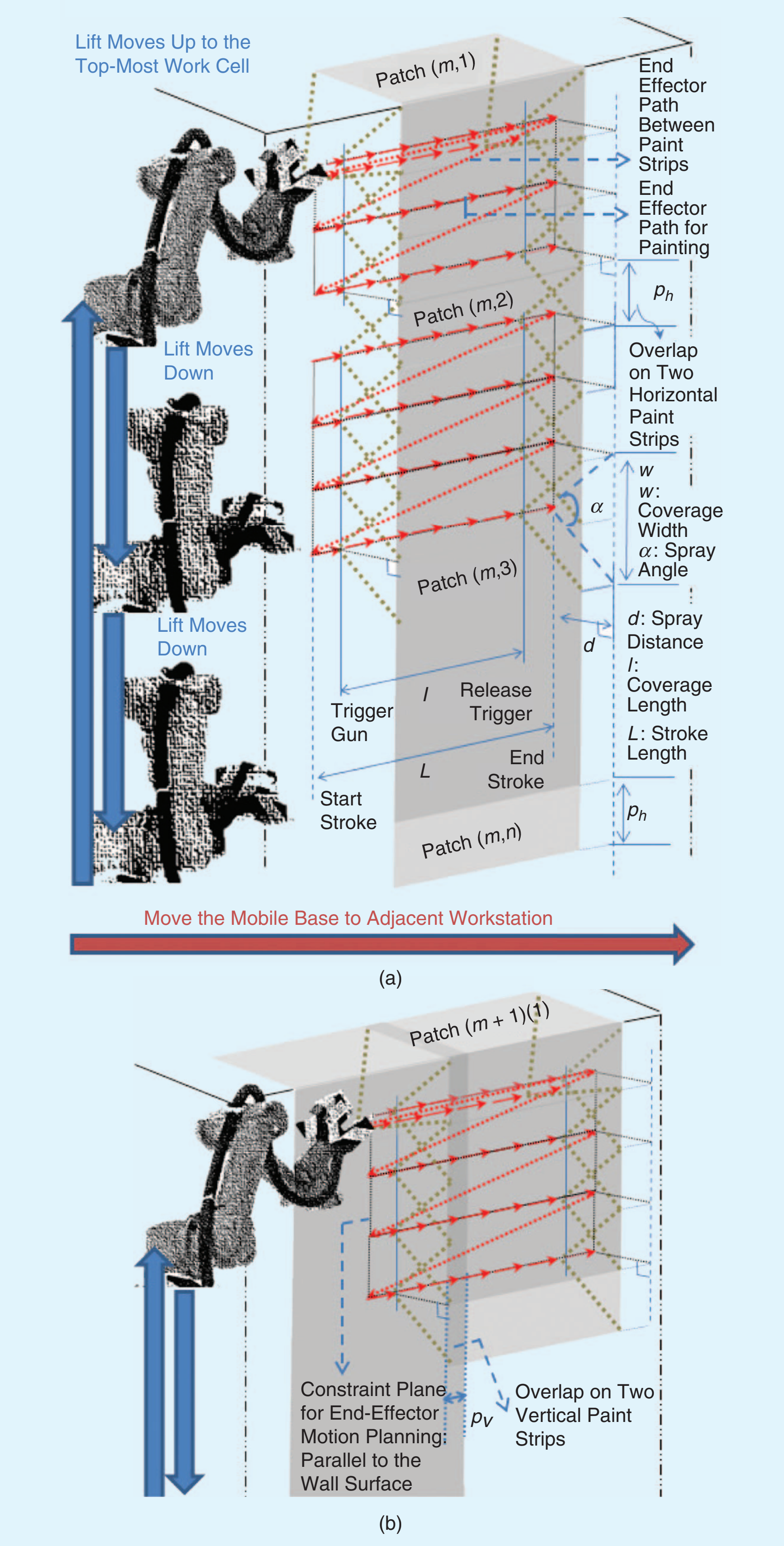


Figure 6. The spraying sequence and spray-gun trajectory planning for (a) a single vertical paint strip; the spraying sequence and geometry model of constrained path planning and (b) multiple vertical paint strips; the spraying sequence and geometry model of constrained path planning.

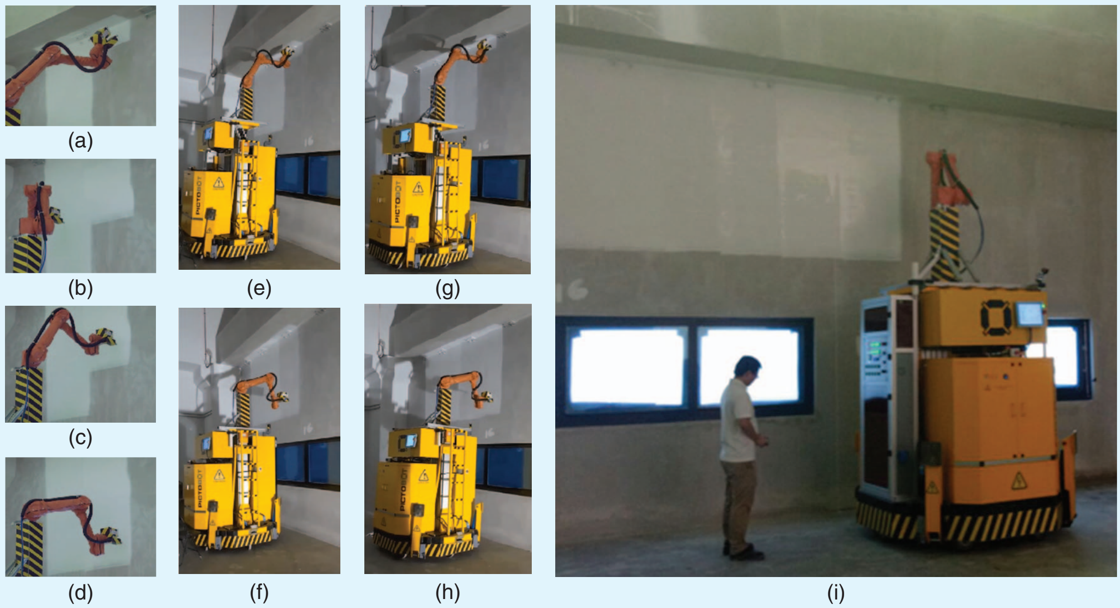


Figure 7. An actual field performance in industrial development. Pictobot autonomously performs painting of several vertical strips side by side, while the operator teleoperates the mobile base in stepped courses: (a)–(d) Pictobot painting horizontal paint strips, (e) and (f) painting a third vertical section, (g) and (h) painting a fourth vertical section, and (i) Pictobot's painting of eight vertical strips from the corner of the ceiling measured 4.6 m.

alignment and scanning actions and continued with moving the end effector to the painting start point. The painting section comprised four linear movements for painting four line strips. Subsequently, the jack-up platform move down and the second paint patch was realized Figure 7(f) and (h)]. Once the paint operation was finished, the operator drove the robot [Figure 7(e) and (f)] to the adjacent working station and executed the robot again. Figure 7(i) presents the result of painting eight vertical strips side-by-side by deploying the mobile base from various positions.

The second experiment demonstrates the robot operation at various high elevations while working safely in close proximity to a worker painting the low wall. Figure 9 shows the results of the automated spray painting of multiple vertical strips starting at different heights, and the manual painting of multiple vertical strips [Figure 9(f)] using a roller brush. The robot is painting one vertical strip starting from 7.2 m up to a minimum height, and the operator is finishing the rest of the wall down to the floor.

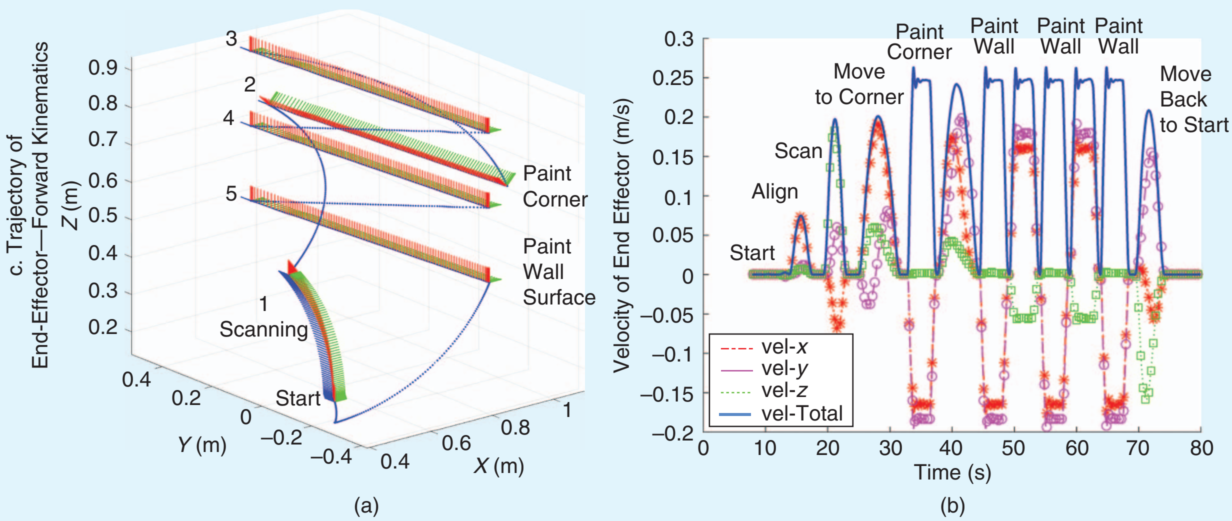


Figure 8. The actual trajectory and velocity of an end effector for one patch (a) the trajectory of an end effector: the arm motion includes three main parts including scanning, painting, and connectors (indicated by blue dotted lines) and (b) the actual velocity of an end effector.

Performance Discussion

Table 1 shows the comparison and analysis of the manual spray painting and the robotic method through human–Pictobot collaboration. Pictobot enables the existing workforce to achieve more by ensuring consistency in the quality of paint coat that meets industry standards and significantly minimizes paint dust. The risk of falling from great heights during manual spray painting is also eliminated. Moreover, physical activities such as climbing, bending, kneeling, and reaching are minimized. Pictobot can also operate for long hours in darkness.

Working Time and Manpower

The overall working time is computed from the timing statistics of deploying the robot in 30 vertical sections. The operator and Pictobot could finish an area of 100 m^2, 8 m in height and 12.5 m in length, in roughly 2 h. The automatic spraying operation comprises ≈70% of the total area, from 8 m to 2.4 m, which takes 105.9 min for the spraying of 17 vertical strips in an average time of 374 s/high-vertical-strip $(5.6\ m \times 0.8\ m)$. It also requires 15.5 min for the operator to drive the robot between 17 workstations in an average time of 55 s/move. Each tall vertical strip was painted in 5.5 surface patches (Np = 5.5) in an average time of 66.5 s/patch $(1.2\ m \times 0.8\ m)$, with $w = 0.4$ m and $P_h = 0.2$ m: approximately 16.5 s for vertical movement of the lift, scanning, and processing, as well as 50 s for spraying each patch. During the automatic spraying of walls at the top, the other ≈30% of the total area located at the low height from 2.4 m to the ground is manually painted using a roller brush in an average time of 250 s/low-vertical-strip $(2.4\ m \times 0.8\ m)$. Roller painting is slower but with high-TE compared to any spraying solution. According to construction experts, it would take more than 3 h for two or three painters using a scissor lift and sprayer to finish the whole area with comparable coat quality and TE. The resulting comparison of working time and manpower in Table 1 could be subject to change due to the construction environment, working conditions, and the skills of the painter or the human operator.

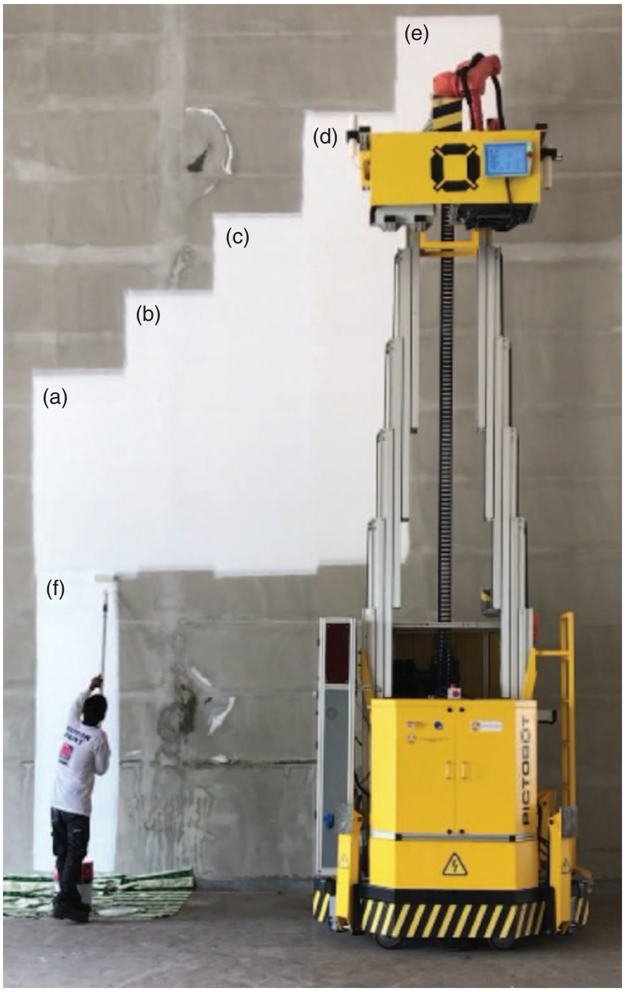


Figure 9. Pictobot in an actual industrial setting working safely in close proximity to a human worker. The results of automated spray painting of multiple vertical strips, starting from a height of (a) 4.5 m, (b) 5.2 m, (c) 5.9 m, (d) 6.4 m, (e) 7.2 m, and manual roller-based painting from a height of (f) 2.4 m.

Objective Fluency of Human–Pictobot Collaboration

In [19], four objective measures regarding the fluency of the interaction are introduced relative to the periods of action that are used here to evaluate the fluency in human–Pictobot collaboration. Due to the repetitiveness of the painting process, one part of the task is to paint one vertical section from the top to the ground is assessed, with the result shown in Figure 10.

According to the data given previously, the total time for painting each vertical section, with respect to the number of patches, is computed by $T_{\text{total}} = 55 + \lceil N_p \rceil \times 16.5 + N_p \times 50$, and it is approximated as $T_{\text{total}}(N_p = 5.5) = 429$ s, considering five-and-a-half patches. The first measure, the rate of robot idleness corresponds to the percentage of time that the robot did not perform spraying. The ineffective time of Pictobot operation, $T_{R-\text{idle}} = (55 + \lceil N_p \rceil \times 16.5)/T_{\text{total}}$, $T_{R-\text{idle}}(N_p = 5.5) = 35.8\%$, occurs when the mobile base is teleoperated or the robot performs other actions, including vertical movement of the lift, in situ scanning, and arm motion planning. Reducing ineffective time will increase productivity by cutting the duration of the operation. The rate of human idle time, $T_{H-\text{idle}} = (T_{\text{total}} - (55 + 250))/T_{\text{total}}$, $T_{H-\text{idle}}(N_p = 5.5) = 28.9\%$, corresponds to the percentage of the time that the human was not involved in teleoperation of Pictobot or manual painting. A positive human idle time can be perceived as wasted time of the operator or boredom. On the other side, a negative idle time suggests the lack of enough time for the operator to paint each section at low height concurrently with the Pictobot. Accordingly, this happens if the wall is shorter than 6.25 m in height to be painted at the top in less than four patches. The rate of concurrent activity, $T_{\text{concurrent}}(N_p = 5.5) = 42.8\%$, corresponds to the percentage of time in which both Pictobot and the operator perform painting at the same time. The fourth measure is the rate of delay experienced between the completion of human teleoperation, and the beginning of automated spray painting, or vice versa.

TE and Quality

Painter technique has a more substantial influence on spraying efficiency than any of the other variables. TE and coat thickness, known as *build efficiency* (*BE*), are two measures of spraying efficiency and quality. TE is expressed as the fraction of paint sprayed that adheres to the surface, and it is crucial to productivity, paint saving, and cost. The maximum TE, $A_{\max}$, is defined by spraying at an optimal distance, d_{opt}, when applying a spray-gun normally to the surface. For most spraying cases, the dependence of the TE, A, on the inclination angle θ, and distance, d, can be expressed [20] by

$$A(\theta, d) = \gamma \times A_{\max} = A_{\max}\left[1 - q\frac{d - d_{\text{opt}}}{d}\right]\cos^{m}\theta,$$

where θ is an angle between the normal vector to the surface and the ray connecting the gun tip and the target point. Accordingly, the efficiency decreases with the increase in θ and d, while the rate of efficiency decrease is dependent on two experimental parameters, $m = 0.5$ and $q = 0.5$. The influence of Pictobot deployment on spraying efficiency is as follows.

- The experiments demonstrate that Pictobot ensures low error in the gun-to-target distance, $d_{\text{avg}} = 31.5$ cm, in which another rangefinder was attached in close proximity to the spray-gun and implemented for directly measuring the distance along 50 strokes without performing a spraying operation, while the robot was deployed from various positions. The inclination angle is also approximated as the mean slope of the distance changes $\theta_{\text{avg}} = 2$ deg along the strokes. Accordingly, (3) implies an average TE rate $A_{\text{Pictobot}} = 0.975A_{\max}$ close to the maximum TE achievable by that sprayer. However, it is nearly impossible to maintain a fixed distance in the manual spraying of tall walls. Although measuring the applied distance by a human painter, along with spraying operation is not feasible, our observations and evaluations provided by expert feedback suggest an average distance of 60 cm, while the maximum distance varies up to more than 1 m depending on working condition, human skill, and fatigue. Thus, approximating the average distance, d_{avg}, as 55, 60, or 65 cm, and $\theta_{\text{avg}} = 15^{\circ}$, the corresponding average TE, A_{MS}, will be $0.766A_{\max}$, $0.737A_{\max}$ and $0.708A_{\max}$, respectively.
- Based on (2), constant gun-to-target distance and spray angle lead to even film thickness. Moreover, for each spray stroke, a consistent travel speed, 0.25 m/s, is achieved after acceleration, as indicated in Figure 8(b). The paint distribution is kept consistent by the controlled triggering of the spray-gun immediately after acceleration and before deceleration. Keeping the BE constant across whole surfaces is as important as ensuring a good TE rate. TE is not affected significantly by the changes in speed.
- The automatic spraying process greatly reduces worker fatigue caused by holding the spray-gun in the desired position. The operator's attitude and skill in teleoperation have some effects on the overall working time of the system, but the visual and range data feedbacks could reduce the reliance on the operator skill.

Current Challenges, Future Works

The current configuration of using passive caster wheels prevents the operator from teleoperating the mobile base to the desired workplaces effortlessly. Deploying an omnidirectional mobile base could reduce the time and effort associated with teleoperated robot movements between workstations. Implementing a robotic arm with a larger workspace will increase the size of each painted patch, which leads to fewer base movements and higher productivity. More data and alarm feedbacks representing the various status of subsystems could be provided to the on-screen display for assisting the operator as well as additional autonomy features, e.g., wall following. Furthermore, we are planning more field experiments through collaborations with construction contractors to schedule and deploy the robot at industrial developments, and to collect more data on its operation and performance.

While autonomous navigation in a changing environment, such as a building under construction, is limited by many practical constraints, it will open other research opportunities in combined task and motion planning. Thus, future work would focus on study of a coordinated motion planning of the mobile base and the articulated manipulator for a painting task. If extra information, such as a building information model is available, it could also be used for preplanning purposes.

Table 1. A comparison of manual spray painting and human–Pictobot cooperative task operation.

Items	Manual Spraying	Human–Pictobot
Working time	3 h/100 m^2	2 h/100 m^2
Transfer efficiency	$\gamma = \left[1 - 0.5\frac{55-30}{55}\right]\cos^{0.5}15$	$\gamma = \left[1 - 0.5\frac{31.5-30}{31.5}\right]\cos^{0.5}2$
	$A = \gamma \times A_{\max} = 0.766 \times A_{\max}$	$A = \gamma \times A_{\max} = 0.975 \times A_{\max}$
Quality (thickness)	Hard to get consistent thickness	Very even and consistent thickness
Convenience	Profoundly difficult task	Less climbing; bending and reaching
Safety	Highly dangerous: working at heights; hazardous chemicals	Low safety concerns: eradicate fall risks; low paint dust
Manpower	Labor intensive, two-to-three workmen	Low labor intensity, one operator
Other features		Long hours of operation even in dark

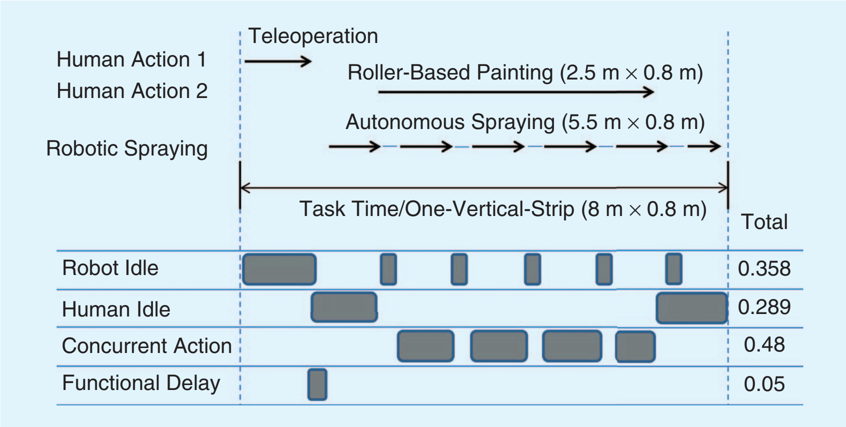


Figure 10. The objective fluency of a human–Pictobot collaboration.

Conclusions

A robotic painter is presented in this article for interior finishing of industrial buildings, which provides a way to combine the benefits of human ingenuity with those of automation in construction. The Pictobot and human work collaboratively, wherein the worker's judgment and perception becomes the upper robot planner, and the robot will adjust the painting plans autonomously from various deployed positions. The Pictobot works safely in close proximity to a worker performing the repetitive painting process at high elevations. Unlike the conventional paint robots that implement CAD model-based planning approaches, the Pictobot is outfitted with a sensor-driven painting system via in situ scanning and spray-gun motion planning, which adapt to the uncertainties of the construction environment. The robot is tested in actual industrial developments successfully, and the results demonstrate the advantages of the proposed solution in leveraging the TE, due to the precise positioning of the spray-gun and even paint distribution. The human–Pictobot collaboration enables the existing workforce to achieve more with less effort. Further improvements could be considered to address the limitations in the current design and reduce the duration of the operation.

The full deployment of human–Pictobot could meet the real-life challenges of improving sustainability, productivity, quality, and safety of interior finishing services, as well as the fostering a robotics industry and an ecosystem that will transform construction into a modern production system. Pictobot could provide the following impacts: First, the robotic spray painting will reduce the reliance on skilled workers in the repetitive painting process and relieve human workmen of the tiresome task. Second, it will improve productivity and ensure high transfer and BE by streamlining and optimizing the painting process for the entire building. Finally, it will reduce the human exposure to harmful paint chemicals and eradicate the risk of falling from elevated heights. The extent of the impact will be driven by forthcoming air pollution and environmental regulations behind the adoption of technologies to limit the emissions of paints with VOCs.

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