Improved Tools for Robotic Interior Painting

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Abstract

This paper presents new ideas for executing interior painting tasks by a robot. A unique end-effector was developed utilizing the advantages of the robotic system by an appropriate work-method. An analysis of the painting task, accompanied by full-scale experiments, was conducted in order to examine the integration between humans and the robot in their work. Two schemes of robotic systems, that differ from each other by their level of autonomy, are introduced. An economic analysis is conducted to examine the profitability of each system. The implications are presented in a way that allows drawing specific conclusions adjusted to any local-market circumstances.

1. Introduction

This paper is an outcome of a research that examined variations of human-robot integration in executing interior finishing tasks. Another paper by the authors in this symposium describes a robotic system for block laying tasks [1]. It is recommended for the reader to become familiar with the issue by reading that paper first.

Previous research conducted at Technion examined appropriate configurations for interior finishing robots. Primer technical feasibility was examined in full-scale experiments, in which a multipurpose robot executed several interior finishing tasks (e.g. wall painting, tiling, partition building) [2]. Subsequent research dealt with autonomous robotic mapping of the work area [3] and optimization of the robot's moves on a floor [4].

Initial results about the feasibility of robotizing the task of wall painting were achieved in earlier research [2]. The experiments conducted in that research relied on a robotic system that paints a wall by spraying. That system included a single sprayer mounted as an end-tool on the robot's arm (figure 1). Painting by spraying was examined in a much larger scale by a system for exterior painting robot [5]. That system also demonstrated technical ability to automatically adjust the trajectory of the end-tool to surface conditions.

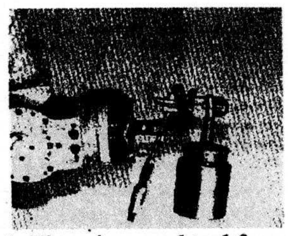

Figure 1: The primer end-tool for painting.

The aim of this paper is to present important aspects of human-robot integration in executing interior finishing tasks. The process of painting a wall with the robot's aid was examined in full scale. New ideas for better utilization of the robot's advantages are suggested. Two possible robotic systems are proposed for the painting task. Each system is analyzed, considering the requirements for executing the task completely, as a whole. The best output of each system was calculated, and the performance features are presented. An economic analysis was conducted in order to compare between the systems and draw some generalized conclusions.

2. A robot for the painting task

The common manual method of interior painting at construction sites is brushing, in which direct contact with the elements to be painted and continuous adjustments to the surface are required. Painting by a spraying, however, is less demanding in terms of accuracy, and therefore more appropriate for robotization.

2.1 End-effector (end-tool)

The robot's ability to carry heavy loads allows designing an end-effector that combines several sprayers, which can spray simultaneously and improve the robot's output. This was done by mounting the sprayers on a metal-bar fixed to the manipulator. Although the end of the manipulator can move only within the nominal work envelope of

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the robot, the metal-bar with the sprayers can cover surfaces much beyond the work envelope.

The length of the metal-bar is subjected to the desired width of a painted stripe. Painting with that kind of end-effector creates a rectangular coating sector (figure 2). The height of the sector (H) is to be as the height of the wall, that was reasonably taken as 2.70 m. The width of the sector (W, for a robot with a given work envelope), depends on the length of the end-effctor, that actually determines the width of a stripe (S) painted in a single tool-movement. Figure 2 presents the limits of the manipulator movements in front of a wall 2.70 m high. Covering this wall requires several painting movements. A tool with S=0.68 m can cover the sector within 4 horizontal movements. The width of such a sector is determined by the critical stripe, that is to say – the stripe in which the manipulator gets to the limits of its work envelope. In the presented case, the upper stripe is the critical one, and it dictates a sector 1.95 m wide. Figure 3 shows the coverage achieved by a tool with S=0.90 m that results in a sector 2.35 m wide. This case has an advantage over the previous one, because a wider sector can be covered from a single work station in less manipulator movements. A longer tool, with S=1.35m, will result in a sector 2.80 m wide covered by only two manipulator movements (figure 4). However, manipulating a tool this long might be awkward and even dangerous. Considering these, the second tool (with S=0.90 m) was chosen to be examined.

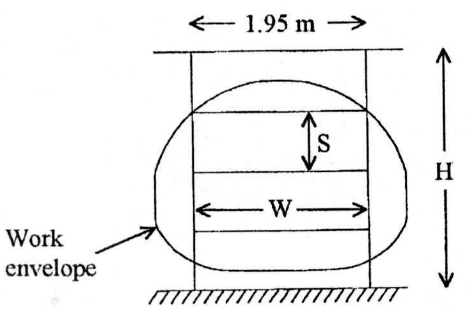


Figure 2: The surface covered by 4 painting stripes.

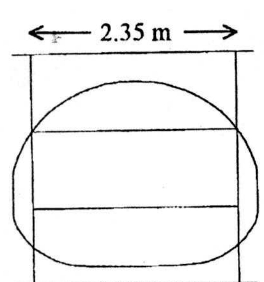


Figure 3: The surface covered by 3 painting stripes.

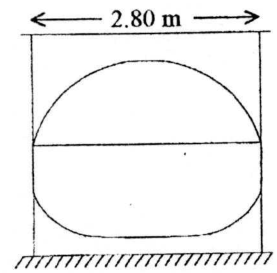
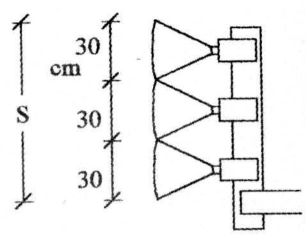


Figure 4: The surface covered by 2 painting stripes.

In order to cover a stripe in the required width, numerous sprayers should be mounted in a row on the metal-bar. On the one hand, mounting many sprayers will allow a more accurate painting process, but, on the other hand, it might be subjected to increasing number of technical failures. The tool that was used for the experiments is composed of three sprayers, each one covers a stripe of 0.30 m in width (figure 5).



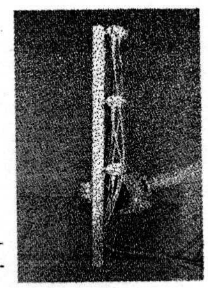


Figure 5: The end-effector for a painting task.

2.2 The painting method

Using the presented equipment, the robot can paint a surface of 2.7 x 2.35 m from any side of the robot's platform. The trajectory of the end-effector is composed of three kinds of movements (figure 6):

1. Moving the tool in three linear horizontal movements in which the paint is being sprayed. During the movement, each sprayer is activated or de-activated according to the presence of openings (doors, windows) in front of them.
2. Moving the tool between the painting stripes. As presented in figure 6, the transition of the tool from the upper stripe to the middle stripe is done in a linear vertical movement, while the transition from the middle stripe to the bottom stripe is done by an inward rotational movement.
3. Painting a corner. The tool stays in its position in space but changes its orientation by rotating around a vertical axis.

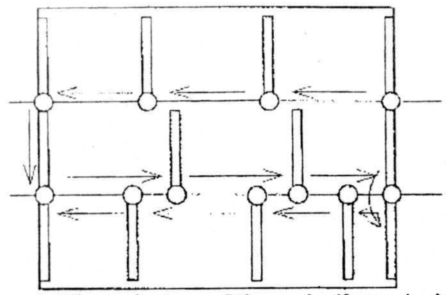


Figure 6: The trajectory of the end-effector in front of a wall.

Each sprayer is controlled by electrical signals sent from the robot's controller or from the tool sensors. The actuation of each sprayer is determined in a strict manner, i.e. a sprayer will be activated even if it partially "paints" an opening. A sprayer will be de-activated only when the whole width of the sprayed-beam falls on an opening (figure 7). In this way, an opening might be partially "painted" but no part of the wall surface will be neglected (e.g. the top of the door and the bottom of the window).

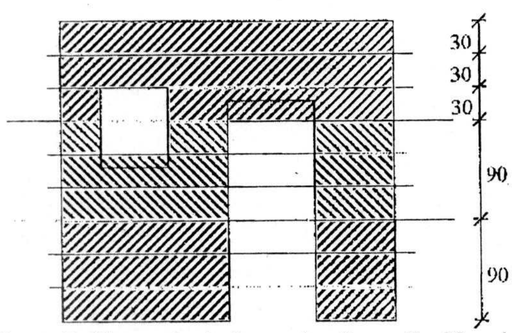


Figure 7: The method of covering the wall with paint.

3. The robotic painting process

The robotic painting process comprises of the following sub-tasks: preparing the system at the beginning of the day, marking the robot's work stations, travelling between the work stations, maneuvering at the work station, inputting the data that is relevant to the work station, replacing the paint tank, painting, cleaning the system at the end of the day, and transporting the robot between floors. Some sub-tasks might be changed according to the features of the system.

The experiments that were conducted examined the functionality of the system (figure 8). Each step of the painting process was examined carefully and its duration was either measured or estimated.

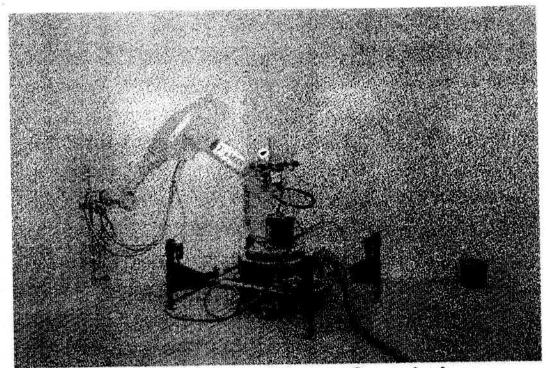


Figure 8: Robotic system for painting.

The calculations were made for applying the method in a few typical rooms (e.g. figure 9). The total time input of the system was calculated for spraying one layer of paint. This value was doubled to find the time input of painting two layers, assuming that the second layer is painted on a different day and all of the steps must be re-done (strict assumption).

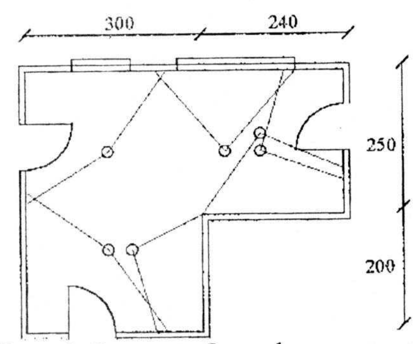


Figure 9: Coverage of a work area - example.

Two types of systems were examined. The use of each type was determined with the aim of employing the robot as much as possible. The analysis showed that in both systems, the task should be done by the robot and a single operator, and no additional worker is required.

3.1 A semi-autonomous robotic system

A semi autonomous robotic system paints autonomously at the work station, but it is led between work stations by the operator. After marking the robot's work stations, the operator drives the robot to its place. Precise leveling of the robot is not required, since the performance of the task is not very sensitive to accuracy. The operator inserts the data that concern the current work station (e.g. borders of the sector) and leaves the robot to do the painting autonomously. Towards completion of the job from the current work station, the operator gets a signal to come and transfer the robot to the next work station. Such a system can be easily adapted to work in unmapped work areas or in any area that its geometry dose not fit the plans.

The analysis showed that the time input of the system is 0.026 hr/sq.m..

In order to analyze the level of utilization of the robot and the operator, the required actions were categorized into three types:

1. Actions done autonomously by the robot.
2. Actions that employ both the robot and the operator together.
3. Actions done by the operator alone. While executing these actions, the robot is unemployed (idle).

The following results were attained:

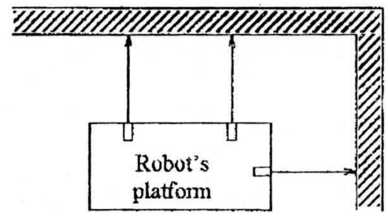
- The part of each category out of the total task duration: category no. 1= 41%;
  category no. 2= 41%; category no. 3= 18%.
- The robot is employed for 82% (=41+41) of the overall task processing time.
- The operator is employed for 60% (=41+18) of the overall task processing time.
- Apparently the operator can manage to do additional tasks while the robot is painting, however, in reality this is impossible because each cycle of the autonomous robotic work is very short (130 sec/work-station in average) so the operator can not be dismissed to do other tasks.

3.2 A highly autonomous robotic system

A highly autonomous robotic system not only paints autonomously, it also drives autonomously between work stations. The operator identifies and marks the position of the first work station in an area (e.g. room), and brings the robot to its start position to begin the painting process. Upon ending the work at the current station, the robot autonomously navigates and drives to the next one, to proceed with the painting there.

As defined, the robot needs a navigation system. A well-known method for finding the orientation is based on triangulation, using a laser beam and several reflectors. This method can obtain good results but has some disadvantages that make it less appropriate for an indoor mobile robot. Knowing the exact position of the reflectors relative to the laser origin is essential for the accuracy of the method, but these positions are hard to be determined while the reflectors and the robot are continuously transferred from one work area (e.g. room) to another. The method is also sensitive to the robot's inclination, that could differ from one work station to another. Moreover, navigation methods that require fixing of aid-equipment are not likely to be used within the painting task because this task deals with covering the surrounding. For example, using bar-code stickers for transferring position data is not suitable for the painting task.

The analysis in this section assumes the use of a navigation method suggested by Warszawski et al. [6] as well as by Pritschow et al. [7]. In this method, distance sensors measure the distance to two nearby non-parallel walls (figure 10), and the robot's position is being determined accordingly. In order to implement this method, the plans of the work area must be "known" to the robot's computer. The accuracy of the positioning of the robot is not high, though it is sufficient for getting the expected performance of the suggested painting method.



distance sensors:

Figure 10: Positioning system using distance sensors.

The analysis showed that the time input of the system is 0.019 hr/sq.m..

In order to analyze the level of utilization of the robot and the operator, the required actions were categorized into four types:

1. Actions done autonomously by the robot.
2. Actions that employ both the robot and the operator together.
3. Actions done by the operator alone. While executing these actions, the robot is unemployed (idle).
4. Actions done by the operator simultaneously with the working of the robot on other sub-tasks.

The following results were attained:

- The part of each category out of total task duration: category no. 1= 62%;
  category no. 2= 32%; category no. 3= 6%; category no. 4= 2%.
- The robot is employed for 94% (=62+32) of the overall task processing time.
- The operator is employed for 40% (=32+6+2) of the overall task processing time.
- The operator has no work to do when the robot moves from one work station to another. The duration of the robot's work in painting and driving is 62% of the overall task duration and it leaves enough time for the operator to do different tasks. In that way, the operator may simultaneously operate another robotic system or paint the spots that the robot can not reach.

4. Economic analysis

An economic analysis was conducted in order to examine and compare the profitability of the system types that were described in the previous section. The economic analysis is based on a method presented by Warszawski and Rosenfeld [8]. This method, with appropriate changes, allows to calculate the cost of painting one work unit, i.e. one sq.m. of a wall.

The principles and assumptions that led the economic analysis are further described in another paper of the authors in this symposium [1].

The analysis is based on the assumptions that the common input of human work in manual painting of walls is 0.27 work hours/sq.m. [9].

The transition from painting by humans to working with either of the robotic systems requires buying the robot, and employing an operator instead of simple workers. The wage of the operator is likely to be higher than the wage of simple workers.

4.1 Results of the analysis

Figures 11 and 12 present the profitable maximum cost of a robotic system dependent on the workers costs per hour.

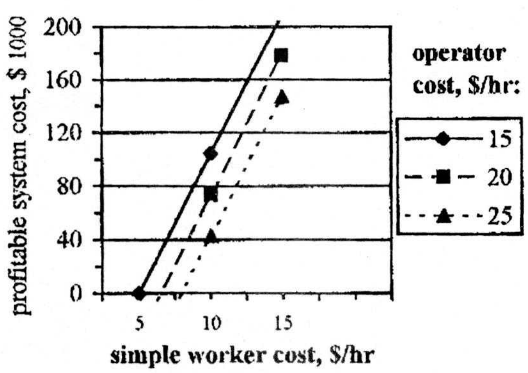


Figure 11: Profitability of transition from the present state to working with a semi-autonomous robotic system.

From figure 11 it can be seen, for example, that a semi-autonomous robotic assistant system which will cost $ 60,000 will be profitable in the following circumstances:

- If a simple worker costs 9.5 $/hr then the operator should cost no more than 20 $/hr.
- If a simple worker costs 11 $/hr then the operator should cost no more than 25 $/hr.

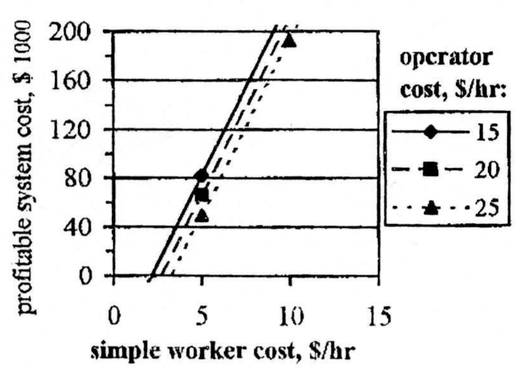


Figure 12: Profitability of transition from the present state to working with a highly autonomous robotic system.

From figure 12 it can be seen that, with a highly autonomous robotic system, the requirements for getting a profitable price of the robotic system are easier to achieve. This was attained because the operator was found to be free to do different tasks for about 60% of the total task duration (see previous section). Therefore, the analysis was conducted as if the operator is employed directly with the painting task done by one system only for 50% of the total task duration.

It can be noticed from figure 12 that a highly autonomous robotic system which will cost $60,000 will be profitable even if a simple worker costs only 4-5.5 $/hr while the operator costs 15-25 $/hr.

5. Conclusions

This paper examined two types of robotic systems for interior wall painting. These systems differ from each other by their level of autonomy and by the task-allocation between humans and robots. Each type was determined in the best possible way for its category and an economic analysis was conducted.

The following conclusions can be drawn:

1. Implementing human-robot integration in the painting task reduces the task duration by 70%-80%.
2. Using the unique painting tool presented in this paper utilizes the robot's advantage of high physical strength and, at the same time, it contributes to lowering of the total time input.
3. The wage level in a certain construction market is a crucial factor in determining the profitability of a robotic system. The ratio between the profitability and the wage level is visually presented, and conclusions can be drawn according to the local circumstances in any market.
4. Finally, it was found that assigning the robotic system to paint also the ceiling may reduce even further the total time input per sq.m. of the task. An empirical analysis showed that in painting a regular dwelling room the task duration may be reduced by another 15-20%.

6. References

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