DESIGN OF AN INTERIOR FINISHING ROBOT WITH A SIMULATION MODEL

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Introduction

Four generic types of construction robots have been suggested in [4]. They were an assembling robot, an interior finishing robot, an exterior wall finishing robot, and a horizontal floor finishing robot. The interior finishing robot, as explained there, was designated to execute various interior finishing operations, such as partition erection, painting, plastering, jointing, taping, etc., from static work stations. The performance specifications for this robot, and its preliminary design, were described in [3]. The preliminary design assumed a jointed configuration of the robot and dimensions which allowed the robot to perform its task from a single work station in a typical space of residential building. A more rigorous analysis of the desired configuration of a general purpose interior finishing robot was necessary in order to evaluate also alternative configurations of the robot's arm, its reach and performance of its joints. Such analysis was performed with the aid of graphic simulation and is described in the following paper.

The method of study

The purpose of the study, as stated above, was to determine the desired configuration of an interior finishing robot. The decision involves a very large number of variables and must be based on the knowledge of many parameters that cannot be assessed a priori with a sufficient degree of certainty. The procedure adopted for this purpose was, therefore, not an optimization, but rather a consistent multistage evaluation process.

Three types of decision variables were considered: the general configuration of the arm, its reach, and the performance - velocity and acceleration, of its joints.

The configuration assumed 6 degrees of freedom - 3 at the wrist and 3 at the arm - a reasonable minimum for execution of the various construction tasks from a static work station. Two tasks, which were explicitly examined in the

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study, were "dry method" building of partitions, and painting of walls and ceiling. Robotic performance of both tasks was described in [2].

The evaluation procedure consisted of 4 stages. In the first stage 64 different configurations of the arm were considered for their feasibility, in view of the determined tasks. 6 configurations were then identified as generally feasible, and specifically examined in the second stage for their efficiency in the performance of the prescribed tasks. The search was then narrowed down to two alternatives, which were clearly superior to others. These were examined in the third stage, with the aid of a graphic simulation system for their performance in a representative dwelling model. The model included two large rooms, two smaller spaces (kitchen and bathroom) and a corridor between them. The simulation program, ROBCAD, selected for this purpose, runs on a SILICON GRAPHICS work station.

The program enabled a follow-up, in a three-dimensional environment after the performance of the tested robot configurations. It also indicated the time required for a real performance of each task. As a result of this simulation, an arm configuration, including 3 rotational joints, was found as more advantageous for the intended tasks.

In the final stage the preferred alternative was examined for its optimal reach and joints performance. This was again attained with the aid of a graphic simulation model by examining the various dimensions and joint velocity alternatives. Three criteria were used throughout the research: The general efficiency of operation, as reflected by several performance features, the productivity, as measured by the time it takes the robot to complete its task in the model environment, and the economy of its employment expressed in terms of the cost per work unit.

Each of these stages will now be described.

Evaluation of the configuration alternatives

As explained earlier, an arm with three degrees of freedom (DOF) was examined for its configuration. 4 types of joints were considered in this context:

a. a prismatic joint in the direction of the former link (in the vertical direction for the first joint).

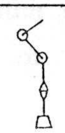
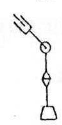
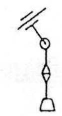
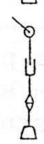
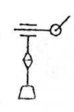
b. a prismatic joint perpendicular to the former link (in the horizontal direction for the first joint).

c. a rotational joint around the axis of the former link (around a vertical axis for the first joint).

d. a rotational joint around an axis perpendicular to the former link (around a horizontal axis for the first link).

The 4^3=64 possible combinations of these types for the joints were tested, in the first stage, for their ability to complete, from a static work station, the building of a basic element - vertical wall with a height of 2.60m (an interior height of a residential building). The six alternatives, which were found feasible for the performance of this task, are shown in Table No. 1.

Table No. 1 - The feasible configuration alternatives

No.	Scheme	Joints sequence[1)]
1		RRR - RRR
2		RRP - RRR
3		RRP - RRR
4		RPR - RRR
5		RPR - RRR
6		PRR - RRR

1) R - Rotational P - Prismatic

The others were found inadequate for the following main reasons:

a. an ineffective horizontal projection of the robot's work envelope. This is typical for all alternatives without a joint of type c, and for most alternatives in which this joint is not at the base.

b. an ineffective vertical projection of the robot work envelope. This is typical for all alternatives without a joint of type d.

c. a redundant degree of freedom. This happens, in all configurations which contain 2 joints of the type a or c in direct continuation of each other, or three joints of the types a and c only.

Second stage elimination

The second stage elimination procedure involved evaluation of the operation efficiency of all 6 feasible alternatives identified in the first stage.

Several criteria were employed for this purpose:

a. The efficiency in building. This was measured through the length of a partition (of 2.60m height) which could be built from a single work station.

b. The efficiency in ceiling painting. It was evaluated through shape and area of ceiling which could be painted from a single work station.

c. The maneuverability. It was assessed through the minimum width of a corridor required for transfer of robot from one room to another in the dwelling model, described earlier.

All alternatives were assumed to have the same horizontal reach of 2.50m.

The results of this analysis are shown in Table 2.

Table 2 - Performance of the evaluated configuration alternatives

No. of configuration alternative	Length of wall(m) built from a single work station	Ceiling painted from a single work station		Minimum width of a corridor for maneuverability
		Area(m^2)	Shape	
1	3.60	9.0	Solid	1.10
2	3.00	5.4	Hollow	1.10
3	2.20	0	Hollow	2.10
4	1.00	0	Hollow	2.10
5	0.60	3.0	Hollow	2.00
6	1.00	0	Hollow	2.10

It is clear from Table 2 that alternatives 1 and 2 are superior to all others with respect to wall building, ceiling painting and maneuverability. Alternative 1 was the only one which could yield a solid surface of painted ceiling from a static station, while others could not be efficiently used for this purpose. Despite this disadvantage, it was decided to test both alternatives 1 and 2 with respect to a complete simulation model in the next stage.

The selection between remaining alternatives

The two preferred alternatives from stage two – 1 and 2 were fully tested with the computer simulation with respect to the building model described earlier.

The following parameters were tested in the simulation runs: the productivity (in m^2 per hour), the minimum number of work stations necessary for work execution, and the percentage of work in the model which could be performed by the robot, considering the space constraints. The results are presented in Table 3.

Table 3 - The simulation results of the tested alternatives

Configuration alternative	Work productivity (m^2/hr)[1]		Extent of utilization (% of total area)		Number of work stations[1]	
	Building	Painting	Building	Painting	Building	Painting
1 (Jointed)	7.9	21.3	100	100	6	6
2 (Spherical)	7.6	19.5	100	46	8	8

1) The productivity and number of work stations pertain to the area covered both by painting and building tasks (46% of the total).

The calculations in Table 3 assumed a transfer time of 5 minutes of the robot from one work station to the next one, including movement, installation and placement of the tool at the initial work point. They also assumed a reach of 2.50m as noted earlier, and the joints velocity of 80° per second for the first 3 DOF, and 110° per second for the last 3 DOF (at the wrist). A range of additional values for each parameter was tested separately.

The results of simulation show a distinctive advantage of alternative 1 with respect to alternative 2: a higher productivity, a smaller number of work stations for the same work volume, and a significantly higher utilization of the robot. Consequently, alternative 1 – the jointed configuration, was preferred and evaluated in the last stage for specific determination of the arm dimensions.

The determination of the robot reach

The final stage analysis involved an evaluation of the optimal reach of the selected robot alternative. The robot reach was examined for increments of 0.20m−0.30m starting with the shortest reach of 1.60m, which still enabled an execution of the designated tasks, and ending with the largest reach of 2.90m, which allowed the performance of a complete task in the largest room of the model, from a single work station.

The effect of the reach variation was evaluated with respect to the robot productivity, number of work stations, and the general efficiency of operations (expressed by the extent of the robot's utilization in the examined model). The results were presented in Table 4.

The cost of the robot arm, for the various arm dimensions, was also calculated, and so was the cost per work unit in the two tasks.

The cost of arm for the reach alternatives was calculated on the basis of the required section found from a structural analysis of stress and deflection. Subsequently, the cost per hour for the various reach alternatives was calculated as in [1], assuming an economic life of 5 years, interest rate of 10%, and 1,500 hours of employment per year.

The cost per unit of work under these assumptions, for the two tasks, is also given in Table 4.

Table 4 - The robot performance parameters for different reach values

No.	Reach (m)	Productivity[1] (m^2/hr)		No. of work[1] stations		% of coverage		Cost of arm per work hour($)	Cost of arm per Work unit($/$m^2$)	
		Building	Painting	Building	Painting	Building	Painting		Building	Painting
1	1.60	7.1	--	21	--	100	--	5.37	0.76	--
2	1.80	7.9	19.3	11	17	100	100	5.42	0.69	0.28
3	2.00	8.1	20.0	9	14	100	100	5.52	0.68	0.28
4	2.30	8.4	21.0	6	10	100	100	5.68	0.68	0.27
5	2.50	8.4	(22.3)	7	(3)	100	62	6.00	0.72	(0.27)
6	2.70	8.2	(21.7)	7	(4)	100	62	6.17	0.75	(0.28)
7	2.90	7.9	(21.7)	6	(4)	100	62	6.68	0.85	(0.31)

1) Robot of 1.60m reach can be used for building only. The productivity, number of work stations and cost per work unit for 2.50−2.90m reach in painting (in brackets) pertain to covered area only.

It follows, from Table 4, that the optimal reach, both for building and painting activities is between 1.80m and 2.30m. The productivity is highest for the two tasks at the reach of 2.30m. Also, the number of work stations at this reach is the smallest. This does not only contribute directly to the productivity, but also has other intangible beneficial effects, such as less operator's time involved in the robot's transfer, less orientation problems at each station, and others. On the other hand, a shorter arm - that of 1.80 is not only associated with the lower cost , but also improves the maneuverability of the robot, and its accuracy and repeatability. A reach of this range deserves, therefore, preferential consideration.

The sensitivity analysis

The sensitivity of the results, presented in Table 4, was examined with respect to the changes in the following parameters:

a. The transfer time between work stations. Three transfer times were examined - 2, 5 and 10 minutes.

b. The rotational velocity at the joints. A range of velocities between 30 and 500° per second, and accelerations - between 60 and 1,000° per second^2 were examined.

c. The cost per 1 kg. of arm weight - $100-$300.

d. The economic life of the robot was assumed as 5 years and 3 years.

e. The interest on investment was assumed as 7 and 10%.

The general conclusions were not significantly affected by these changes.

Conclusions

A graphic simulation model can be efficiently used for evaluation of new robot configurations adapted to unstructured construction tasks. The criteria for evaluation are the productivity of the examined alternatives, their cost and efficiency of operations. In the case of an interior finishing robot, an evaluation process of the many possible alternatives indicated as the preferred one - a jointed configuration with 6 degrees of freedom and an arm reach of between 1.80 and 2.30m.

Bibliography

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