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ECONOMIC EVALUATION OF ROBOTIZED INTERIOR FINISHING WORKS BASED ON FULL-SCALE EXPERIMENTS

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ABSTRACT

The paper examines the economic implications of performing interior building tasks with the aid of specially adapted robots.

The analysis is based on full-scale experiments with TAMIR - Technion Autonomous Multi-purpose Interior Robot - in recent years.

Three interior finishing tasks are included in the economic evaluation: (a) painting or plastering of walls and ceilings, (b) tile-setting on walls, and (c) building of interior walls and partitions. All three applications were performed and perfected in full-scale within fairly controlled laboratory conditions, which can be extrapolated to real-life site conditions.

The paper presents, in economic terms, various aspects of the robotic execution (e.g. travelling, calibration, productive work, etc.) of these tasks with necessary complementary manual works, based on actual measurements of performance rates, and rigorous estimates of all cost items. The economic comparison of robotic versus manual performance is presented, pertaining to typical residential and office buildings. Due to space limitations, the first application, painting, is analyzed in great detail, while the other three - plastering, tile setting and wall building - are analyzed in a concise manner.

FIG. 1: TAMIR - Technion Autonomous Multipurpose Interior Robot

INTRODUCTION

Robotized application of construction tasks has been developed at the Technion - Israel Institute of Technology, as a systematic multi-phase project. The advances have been regularly presented in ISARC symposia and other publications from conception [4] through feasibility studies [1,7], determination of parameters with the aid of graphic simulation [8] and scaled models [6] to full-scale applications with TAMIR - Technion Autonomous Multipurpose Interior Robot [2,3], which is presented in Fig. 1.

This paper focuses on the latest stage in this series - a detailed economic evaluation of robotized interior finishing works. The methodology for the evaluation follows the guidelines layed in [5], substituting actual numbers into the various formulae based on real experience with TAMIR.

COST ANALYSIS OF THE PAINTING TASK

Robotized painting was performed by an electrical spray-gun, which was adapted to the robot as an end-effector, with computer-controlled flow of the material. A conservative assessment of its economy assumes the following interventions of a human operator and/or human workers during the task:

1. Covering edges of openings such as doors and windows, as well as other surfaces which must not be sprayed, e.g. areas covered with tiles. These preparations, with adhesive tapes, should be done at the robot's entry.

2. Conveying the robot between different floors of the building by crane or elevator.

3. Leading the robot manually by the operator between adjacent workstations and between different locations on the same floor.

4. Stabilizing, levelling and calibrating the robot at each workstation semi-automatically by the operator.

Once the robot is calibrated at its temporary workstation, it performs the spraying task fully automatically, including avoidance or omission of openings and/or other predesignated areas. The robot covers, from each workstation, up to 5 sq.m. of wall plus 4 sq.m. of celing with a small overlap between adjacent sections.

Additional data that were used for the economic evaluation are listed in Table 1. Most of them were measured directly during full-scale experiments, while others are either calculations or best estimates, conservatively assessed.

Table 2 presents a breakdown of the operations that should be done for painting a typical segment of the building along with their duration and cost. This segment constitutes a 4 m long by 2.5 m high surface of wall, sprayed from two adjacent workstations, plus approximately 4 sq.m. of ceiling painted from each workstation, namely a total area of 18 sq.m. The numbers in the table stem from the aforementioned assumptions and data, combined with other realistic assessments based on typical layouts of building floor plans. (A subtask of this project, which is not described herein, dealt with examination and determination of typical travel distances between work areas, total floor areas at each level, typical quantities of relevant tasks per floor, etc. These examinations were done for both residential and office buildings.)

Table 1: Basic data for initial cost estimate: painting of walls and ceilings.

#	Item	Value and Units
1	Preparing the area for painting	4 sq.m/min.
2	Speed of travel between work areas	10 m/min.
3	Location and calibration at the workstation	1 minute per workstation
4	Covering the surface with a final layer of paint	0.33 sq.m.
5	Width of the area covered from one workstation	2.0 m
6	Average estimated surface to be painted on each floor	1000 sq.m.
7	Average utilization of the robot	6 hrs./day
8	Gross cost of the robot	74 NIS*/hr.
9	Gross cost of the robot's operator	30 NIS*/hr.
10	Gross cost of the crane	80 NIS*/hr
11	Gross cost of an unskilled worker	18.75 NIS*/hr
12	Gross cost of a painter	25 NIS*/hr
13	Equipment cost for one relocation of the robot from floor to floor	20 NIS*/hr

(*) 1 NIS (New Israeli Sheqel) ≈ US$0.45.

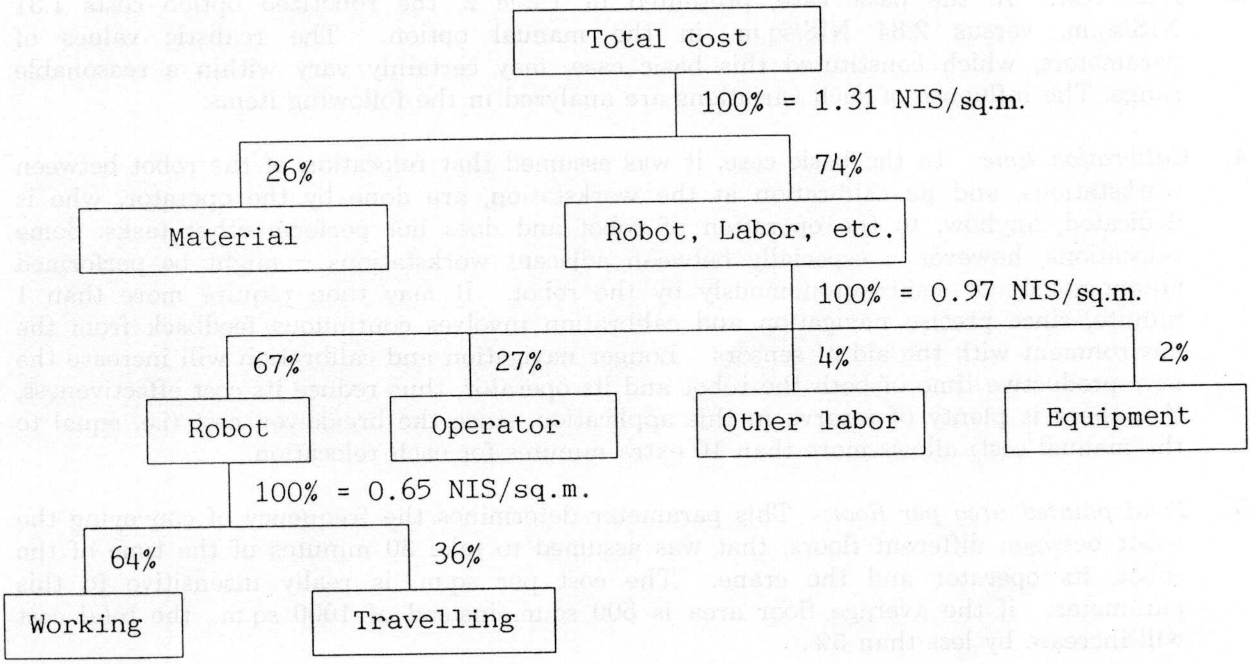
Table 2: Cost estimate [in NIS*] for robotized painting of a typical surface (wall plus ceiling) of 18 sq.m.

#	Item description	Unit	Qnt.	Min. per unit	Cost per unit	Min. per item	Cost per item
1	ROBOT						
1.1	Movement between areas	m.	4.0	0.1	0.12	0.4	0.49
1.2	Movement between workstations	m.	2.0	0.25	0.31	0.5	0.62
1.3	Stablization and calibration	unit	2.0	1.0	1.23	2.0	2.47
1.4	Relocation between different floors	unit	0.18	30.0	37.00	0.5	0.67
1.5	Painting by spraying	sq.m.	18.0	0.33	0.41	6.0	7.40
						9.4	11.70
2	OPERATOR						
2.1	Dedicated operator: works with the robot only	Sect.	1.0	9.4	4.70	9.4	4.70
3	OTHER LABOR						
3.1	Before and after the robot	sq.m.	10.0	0.25	0.08	2.5	0.78
4	EQUIPMENT						
4.1	Conveying the robot between floors	Unit	.018	30.0	20.00	0.5	0.36
4.2	Conveying of painting material	Unit	.005	2.0	2.67	0.0	0.01
						0.5	0.37
5	MATERIALS						
5.1	Painting material	Gallon	.29	--	21.30	--	6.13
6	TOTAL						
6.1	Cost per typical section of 18 sq.m.						23.16
6.2	Cost per sq.m.						1.31

(*) NIS ≈ US$0.45

Fig. 2 presents the distribution of the total cost in the robotized alternative between material and labor, etc. This can be compared to human performance of the same task that requires identical input of material, while the labor input (according to industry-wide accepted standards) adds up to 0.10 manhours/sq.m. which costs 2.50 NIS/sq.m., thus totalling 2.84 NIS/sq.m. versus 1.31 NIS/sq.m. in the robotized option.

ROBOTIZED PAINTING



MANUAL PAINTING

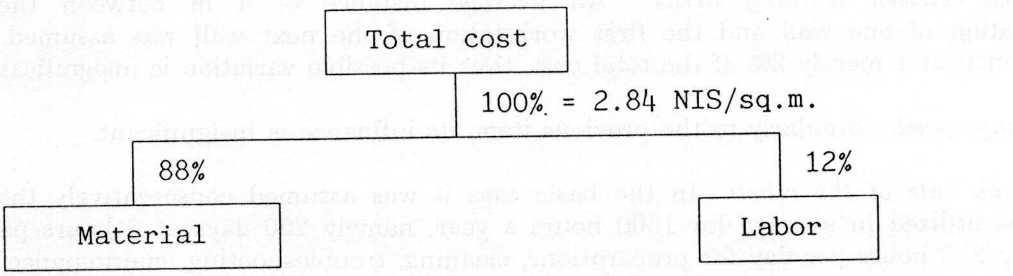


Fig. 2: Cost comparison of robotized versus manual painting

COMPARISON AND SENSITIVITY ANALYSIS

1. *Manpower requirement*: In the robotized option, labor requirements are merely 0.52 min/sq.m. of the operator plus 0.14 min/sq.m. of a laborer, versus 6 min/sq.m. in the manual option.

2. *Task duration*: One robot plus one operator complete 18 sq.m. in 9.4 min (including travelling, etc.), thus requiring 0.52 min/sq.m. on the project schedule. This is equivalent to the work rate of a dozen painters in parallel.

3. *Total cost*: In the basic case, presented in Table 2, the robotized option costs 1.31 NIS/sq.m. versus 2.84 NIS/sq.m. in the manual option. The realistic values of parameters, which constituted this basic case, may certainly vary within a reasonable range. The influence of such variations are analyzed in the following items:

4. *Calibration time*: In the basic case, it was assumed that relocation of the robot between workstations, and its calibration at the workstation, are done by the operator, who is dedicated, anyhow, to the operation of robot and does not perform other tasks. Some relocations, however – especially between adjacent workstations – might be performed autonomously or semi-autonomously by the robot. It may then require more than 1 minute, since precise navigation and calibration involves continuous feedback from the environment with the aid of sensors. Longer navigation and calibration will increase the non-productive time of both the robot and its operator, thus reduce its cost effectiveness. Yet, there is plenty of reserve in this application, since the breakeven cost (i.e. equal to the manual cost) allows more than 10 extra minutes for each relocation.

5. *Total painted area per floor*: This parameter determines the frequency of conveying the robot between different floors, that was assumed to take 30 minutes of the time of the robot, its operator and the crane. The cost per sq.m. is really insensitive to this parameter: if the average floor area is 500 sq.m. instead of 1000 sq.m., the total cost will increase by less than 5%.

6. *Conveying times between floors*: Similarly to the previous item, if the conveying time increases from 30 to 60 minutes, the cost will increase by less than 5%.

7. *Distances between working areas*: An average distance of 4 m between the last workstation of one wall and the first workstation of the next wall was assumed. This item constitutes merely 2% of the total cost, thus its possible variation is insignificant.

8. *Travelling speed*: Similarly to the previous item, its influence is insignificant.

9. *Utilization rate of the robot*: In the basic case it was assumed conservatively that the robot is utilized in average for 1500 hours a year, namely 250 days at 6 hours per day (leaving 2–3 hours per day for preparations, cleaning, troubleshooting, maintenance, etc.). In this application even 2 hours per day suffice to compete with the manual alternative (provided that the operator will not stay idle with the robot, but do something productive). If the robot is utilized for 2000 or 2500 hours a year, the total cost may decrease by 12% and 20% respectively.

10. *The cost of the robotic system*: The 74 NIS hourly cost of the robotic system (in Table 1) was calculated by its estimated initial cost, economic life, interest rate, maintenance cost, working hours per year, etc. The influence of the last parameter was assessed in the previous item, while the influence of the former ones is even less significant.

11. *Coverage from each workstation*: This parameter is insignificant, since the robot spends merely 36% of its active time on non-productive activities (see Fig. 1), if the coverage from each workstation will decrease by 20% or 40%, the cost per square meter will increase by 3 % or 6 % respectively, and vice-versa (the material cost per sq.m. does not change).

12. *Multi-layer spraying*: The basic case assumed that the painting task is performed by the robot with one single layer of spray. If, for technological reasons, it would be necessary to spray two or three thinner layers, then the robot will have to perform two or three separate rounds on each floor (including one or two extra relocation and calibration for each workstation), which will increase the cost per square meter by 25% or 50% respectively.

To summarize, only two of the aforementioned parameters have significant effect on the cost per square meter within reasonable variations:

1. The utilization rate of the robot (item 9).

2. Multi-layer spraying (item 12).

The substantial difference in cost between the robotized and the manual options (1.31 NIS/sq.m. versus 2.84 NIS/sq.m.), allows significant flexibility even for these parameters, while for the other parameters it allows really great variations. Moreover, some of the parameters are likely to vary toward the "good side", namely they may decrease the cost of the robotized option, e.g. more than six hours of utilization per day, lower cost of the robotic system as the technology will become widespread and/or more autonomous and user-friendly robotic systems, which will not require a dedicated full-time skilled operator for each robot.

Another, most important factor, which is likely to foster the economy of robotic applications, is the increasing labor cost in the construction industry worldwide: as the labor cost increases, and the technology cost decreases - the robotic options are becoming more and more economical. As the scarcity of construction workers is becoming a severe problem - especially in developed countries and in certain unpleasant tasks - the utilization of robotic or semi-robotic alternatives will become a necessity rather than a pure economic choice.

These general remarks are mentioned at this early stage, in order to make the reader aware of them as we proceed to deal with other applications whose economic advantage is not so obvious as in this painting application.

CONCISE COST ANALYSIS OF THREE OTHER APPLICATIONS

Three additional applications: 1) interior plastering, 2) Tile-setting on walls, and 3) building of interior partition walls, were examined and analyzed in similar details and depth. However, due to space limitations in this conference article, they are presented only briefly. General descriptions and technical data about these applications were provided in the last two ISARC meetings [2,3], while Table 3 presents a concise summary of their cost items in robotic versus manual performances, in a breakdown similar to Table 2.

The respective cost items in conventional manual performances of these three applications are presented in Table 4, with a breakdown to Labor, Materials and Equipment:

Table 3: Cost estimations [in NIS*] for robotized application of three interior finishing tasks

No.	Item Description	Application and Typical Section Area		
		Plastering 10 sq.m.	Tile Setting 5 sq.m.	Wall Building 10 sq.m.
1	ROBOT			
1.1	Movement between areas	0.5	0.1	1.0
1.2	Movement between workstations	0.6	0.6	0.6
1.3	Stabilization and Calibration	2.5	7.4	7.4
1.4	Relocation between floors	0.4	1.2	1.2
1.5	Productive work	12.3	77.1	41.8
2	OPERATOR			
2.1	Dedicated operator: works with the robot only	6.6	35.4	21.1
3	OTHER LABOR			
3.1	Before and after the robot	0.8	--	15.2
4	EQUIPMENT			
4.1	Conveying the robot between floors	0.2	0.7	13.3
4.2	Material supply	--	--	0.7
5	MATERIALS			
5.1	Major material	73.0	225.0	284.0
5.2	Support material	--	5.0	9.0
6	TOTAL			
6.1	Cost per typical section	97.-	353.-	395.-
6.2	Cost per sq.m.	9.7	70.6	39.5

(*) 1 NIS (New Israeli Sheqel) ≈ US$0.45

Table 4: Cost estimates [in NIS*] for conventional manual application of three interior finishing tasks

No.	Item Description	Application and Typical Section Area		
		Plastering 10 sq.m.	Tile Setting 5 sq.m.	Wall Building 10 sq.m.
1	LABOR	94	139	163
2	MATERIALS	73	240	157
3	EQUIPMENT	--	--	35
4	TOTAL			
4.1	Cost per typical section	167	379	355
4.2	Cost per sq.m.	17	76	36

(*) 1 NIS (New Israeli Sheqel) ≈ US$0.45

DISCUSSION

1. The data presented in Tables 3 and 4 encourage robotic applicaton of plastering which is very similar to painting; however, they do not encourage immediate application of robotic alternatives for tile-setting and wall building at the examined conditions. The differences in total cost per sq.m. of robotic versus manual application of these two tasks are not significant. Small variations in the conditions or in values of the assumed parameters may cause "flip-flops" between the choices from purely economic considerations.

2. The main reason for this rests with the high portion of material cost in the last two applications. It varies from 65% in tile-setting to 74% in wall-building. The remaining 25-35% of robot cost plus labor cost must be outstandingly efficient in order to make the robotic option significantly less expensive than the manual, and this is not yet the case.

3. Another major obstacle to the "economy" of robotic alternatives for these tasks stems from the conservative assumption that the operator is dedicated to the robot and does not perform other tasks even though the robot is supposed to work smoothly and autonomously for long periods of 24-35 minutes at each workstation without any operator intervention. The authors preferred to adopt, for the basic case, a rigorous attitude based on full scale monitored experiments, rather than speculating about possible future improvements which are very likely to reduce the cost of the robotic options. In addition to possible savings in operator cost, the next three items point at some promising improvements for future development in each application.

4. In robotic plastering - significant savings can be achieved by using a more powerful, yet accurate, spraygun. The measured rate of 60 seconds per sq.m. was caused by limitations of the spraygun, not the robot. It is quite realistic to count on 20 sec/sq.m. instead of 60, and a thinner, yet uniform layer of plaster - 10 milimeters instead of 15. These technological perfections of the application can save 37% in the robotic application, thus confronting 6.1 NIS/sq.m. in the robotic option versus 16.7 NIS/sq.m. in conventional manual plastering.

5. In robotic tile-setting the most promising technological development seems to be modification of the typical cycle to achieve a rate of merely 10 seconds per tile instead of 30. It seems to be achievable though it was not yet tested. The faster rate can be combined with the use of a much lighter robot than TAMIR and only half as expensive (TAMIR's initial cost was assumed at US $130,000. These foreseen immediate technological improvements can save 18 NIS/sq.m. in the robotic option, thus confronting a total 52.6 NIS/sq.m. versus 75.9 NIS/sq.m. in the manual alternative. Due to the very high portion of material cost, which is identical in both robotic and manual tile-setting, it is worthwhile mentioning that with these suggested technological improvements - the "labor" cost (i.e. labor + robot) can be reduced from 28 NIS/sq.m. in conventional tile setting to merely 6.7 NIS/sq.m. in the improved robotic application - a reduction of 76% (!) in "labor" cost.

6. In the wall-building application, the major technological promise can be found in the material component rather than in the robotic technology: The robotic application, as performed in our experiments was quite efficient; however, it required the use of fairly expensive interlocking lightweight gypsum blocks with smooth surfaces for reliable handling with vacuum grippers. The present cost of these blocks is 28.4 NIS/sq.m. out of the total 39.5 NIS/sq.m. cost of the entire robotic option. Due to improvements in the production technology, combined with larger markets for the product, it is conceivable that the future cost of these, or of similarly performing other blocks will become closer to the current cost of conventional blocks (15.7 NIS/sq.m.). As this happens, the robotic option will become much more economical than now.

CONCLUSION

This paper presented economic results of full-scale experiments with robotic application of interior finishing tasks. The economic analyses of the 'basic cases' are rigorously rooted in real measurements without speculations on future developments. They show that robotic painting and plastering of building interiors are already substantially less expensive than conventional manual alternatives. As to tile-setting and wall-building, the differences are insignificant at the present mode of the robotic application. It is foreseen, however, that with additional research and development efforts these applications can be substantially improved and successfully compete with conventional methods. The most promising directions for further development were also outlined.

Two additional magatrends will certainly foster, in the future, any kind of automation and robotics in construction: These are, on one hand, shortage in and cost escalation of construction labor and, on the other hand - fascinating developments in machine intelligence and their sensory capabilities combined with affordable costs of high technology.

These two megatrends are bound to accelerate the penetration of robotic and other advanced technologies into the Construction Industry.

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