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FEASIBILITY ANALYSIS OF ROBOTIZED VS MANUAL PERFORMANCE OF INTERIOR FINISHING TASKS

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Abstract
The paper presents results of a feasibility analysis of a robot developed for performance of interior finishing tasks. Productivity and cost of robotized construction is compared with manual construction of the same tasks.

INTRODUCTION

The TAMIR - a construction robot shown in Fig.1, has been developed at the Technion, Israel Institute of Technology following a multistage process, described in [Warszawski, Navon 1991]. Its pre-prototype version adapted to performance of full scale construction work is based on the S-700 model of an industrial robot made by GMF. The arm of the robot has 6 degrees of freedom, a nominal reach of 1.62 m and a payload of 30kgf.

The robot travels between static work stations and executes at each station the work assigned to it. For this purpose it was mounted on a three wheel mobile carriage measuring 0.85 by 0.85 m and had effectors, sensors , feeding and control systems adapted to performance of various building tasks. At present the robot can be guided by a remote control box or follow a preprogrammed path. At a later stage it will be equipped with sensory devices and a control mechanism which will enable it to interact with environment, map it, and even plan and monitor its own work [Warszawski, Rosenfeld, Shohet 1992].

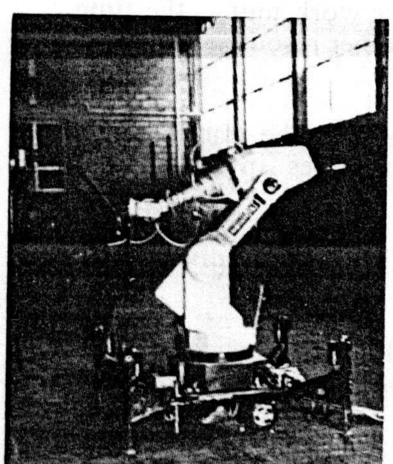

Figure 1 - The interior finishing robot

The robot is designated to perform eventually any type of interior finishing work in residential, commercial and similar buildings with single or multiple floor levels and an interior height of 2.60 - 2.70m . It has been adapted so far, and tested, to execute the following tasks:

a. Painting walls and ceilings.
b. Plastering walls and ceilings.
c. Tiling on walls.
d. Building walls and partitions.

The adaptation of the robot to performance of these tasks has been described in [Rosenfeld, Warszawski, Zajicek 1991].

Preliminary results of the economic performance of the robot were presented in [Rosenfeld, Warszwski 1992]. This paper brings revised and updated results, in a general context of robotized construction .

THE COST OF ROBOTIZED WORK

The feasibility of the robot must be examined by comparing the cost of its work with the cost of performance of similar tasks with conventional manual method. The cost per unit of robotized work includes all pertinent components which are affected by the employment of the robot technology namely:

a. the direct cost of the robotized system - the robot, its operator and other auxiliary labor.

b. the differential cost of materials , whenever materials used in robotized construction are more expensive than those used in conventional work for the same task.

c. the cost of the robot's movement between work stations. This cost depends upon the length of robot movement per work unit , its speed of movement , and the cost of robotized system.

d. the cost of the robot's positioning at work station. This cost depends upon the time of setup per work unit, and the cost of robotized system per time unit.

e. the cost of the robot's transfers between different work areas on site (on the same building or in different buildings). This cost depends on number of transfers per work unit , the time required per transfer , the cost of the robotized system , and the cost of other resources involved in the transfer.

f. the cost of installation of the robot on the building site. This cost depends on the transportation time to site, the setup time , the system cost , and the cost of other resources involved in the transfer.

The major parameters determining the cost of the robotized work can be therefore divided into three main groups:

a. parameters dependent on the robotic system - its cost, its work envelope (and hence the work area it can cover from a work station) , its speed of movement and mode of operation (extent of human control).

b. parameters dependent on the nature of the building site. These include the nature of the tasks to be performed, their quantity, the number of transfers necessary between work sections, and the location/distribution of work in each section.

c. parameters dependent on tasks to be performed by the robot - the output per hour for each task, the materials, and the auxiliary works needed.

PARAMETERS DEPENDING ON THE ROBOTIZED SYSTEM

The most important parameters of the robotic system are its cost and output.

The cost of the robotic system depends on the nature of the robot to be used , and the mode of its operation. It was assumed that at the present stage of development the robot will need a continuous supervision by a human operator . Consequently, the cost of a robotic system includes at present the cost of the robot and the (full or partial) wages of the operator.

The cost of the robot includes depreciation, interest on investment, maintenance, and operating expenses. In the particular case examined here the initial cost of the robot GMF S-700 was $100,000, and together with additional features - carriage, effectors, sensors, and adaptations - $130,000. In order to calculate the annual cost a rate of interest of 7% , and an economic life of the robot - 5 years without salvage value - were assumed. The cost of repairs and high level maintenance was assumed as 10% of the initial investment per year, and its other operating cost (including replacement of some wear affected parts) as $2 per hour. A routine - low level maintenance has been also taken into account (in the context of site activities).

The total cost per hour depends very much on the number of hours the robot will be employed per year. Since the robot will in fact replace skilled human labor which is continuously needed in building , under satisfactory environmental conditions (which can and should be provided on the building site) 1,500 - 2,000 hours of employment per year for a multipurpose robot can be reasonably provided.

Assuming $1,500 hours of employment per year, initial investment of $130,000 (based on the cost of the developed robot), 5 years of economic life, 7% interest and maintenance expenses , the cost of robot per hour amounts to $ 32. For 2,000 hours per year it amounts to $24 per hour . Assuming that an operator will continuously supervise the robot's work, his wages , examined at two levels - of $12.50 and $25 per hour, must be added to obtain the total cost of the system per hour.

The output of the robot for each task depends on the nature of the task, and the amount of time which the robot has to spend on indirect activities, which will be discussed later.

TASK DEPENDENT PARAMETERS

Task dependent parameters determine the direct time input of the robotized system for a particular task execution , the manual input of the human auxiliary activities necessary for the task performance, the cost of materials, and other resources. The performance of selected tasks by the robot was described in [Rosenfeld, Warszawski, Zajicek 1991].

Activities auxiliary to robotic system include the support which the system has to receive with human labor for performance of the designated tasks. These activities are preparations before the work execution - hoisting of materials or adjustment of the work area, and the assistance to the system by human labor, during or after the work execution.

PARAMETERS DEPENDING ON THE BUILDING SITE

Parameters dependent on the building site are the quantity of building work on the site and its distribution. They determine the time which the robot has to spend on activities not directly related to its work, and therefore the efficiency of its utilization.

The indirect time as explained earlier includes the time of installation, movement, transfers, positioning at the work stations, and routine maintenance. The higher is the ratio between this time and the actual task execution time, the less efficient the robotic system becomes, when compared to manual labor.

The installation time includes the transfer of the robot to the site, and its preparation for work. It is assumed that this should take somewhere between 4 and 8 hours, depending on the transfer distance and the efficiency of the user and operator organizations. The share of this cost in the total depends on the total amount of work on the site. The other cost - the truck, the loading and unloading, were not considered here, since they are incurred also in transfer of various types of equipment needed for manual work.

The time of positioning at work station depends on the characteristics of the system, and its contribution to total indirect time - depends on the amount of work to be done from the work station.

The positioning time includes self support of the robot, its self levelling, and the search for the task starting point. The measured time for these activities with the particular robot employed was estimated, based on the performance of the experimental robot, as 3 minutes per station. The amount of work per station depends on the wall (or ceiling) area covered by the robot from the work station.

The effective work envelope of the robot's arm sufficed to cover - for painting, plastering, tiling, building etc., from a minimal distance - of 0.60 m (considering the width of the carriage), an area of 2.70m height and a length of 1.70m (4.60 sqm), or an area of 2.60m height and a length of 1.90m (4.95 sqm) . The effective area covered will be generally less than the maximum, considering the layout of the wall and the openings . The full work area from a station will be utilized in a very well structured spaces like for example long, straight walls. In general it may be assumed that the work covered from a station will be somewhere between 0.75 and 0.90 of the maximum . In special cases , the work area from a station can be more than the maximum stated before. One such case may occur if the robot can perform the work from a station on two opposite surfaces - as in a corridor. Another, when the robot performs a task on the wall and the ceiling above it, as may be in painting or plastering.

The time of movement between work stations depends on the speed of robot movement and the distance between stations. The speed of the present robot - 4 m/minute, has been determined by the capacity of the carriage motors. The speed can be easily increased to 10 m/minute. The distance between work stations is determined by the length of area covered from a station. In a case of continuous work - this will amount, as explained earlier, to 0.75 - 0.90 of the maximum width (in this case 1.9 m). However, in cases where the work to be done is scattered between separate locations , the distance to be traveled between these locations has to be added.

The transfer of the robot between adjacent floors or other locations on the building site should not exceed 20-30 minutes of the robot time. This includes the travelling of the robot to the transfer point from the last, and to the first, work area on the floor. The time of the crane or extra labor needed for transfer is negligible.

The routine maintenance time is probably somewhat different for each particular task. It has been arbitrarily determined here as 0.5 hour per working day of 8 hours, or approximately as 6% of the total working time.

The "burden" of the indirect activities i.e. the ratio between the duration of the indirect and the direct activities for a particular building task on site depends therefore on the following parameters: the total amount of work on site (for the task), the amount of work on each floor, and the amount of work per work station, when related to the direct robot input in the task.

THE ECONOMIC COMPARISON

The feasibility of robot employment for each particular task depends on the building site parameters. The results presented here pertain to a typical office building of eight stories with a story area of 1,000 sqm, and an interior height of 2.6 m. Such building may typically include (see for exmple Means 1990) approximately 600 sqm of partitions and 1,500 sqm of wall cover per floor.

The "burden" of robot movement, with its associated unproductive cost of the robot and the operator will depend on the extent of the robot utilization at a work station. It will be assumed here that the configuration of the work to be done allows the robot utilization of 75% of its maximum reach from an average work station. It is presented for each of the examined tasks in figure 2.

The feasibility of robotic vs manual work in view of these site parameters has been examined for each task. by comparing it to a conventional, manual execution of the same work. The direct labor of the robotic system for each task has been determined from experiments with the robot . The input of auxiliary labor has been determined from the analysis of each task. The labor necessary for performance of similar task with a conventional, manual, method was determined from accepted productivity rates (Means 1990, Israeli Institute of Productivity 1980).

The indirect labor input - for movement, positioning, transfer, and maintenance has been determined as explained before in the section dealing with parameters of the building site.

The comparisons between total labor input in robotized vs. conventional execution of the various tasks are presented in figure 3 .

The cost of the robotized system - of the robot and the operator was determined considering the direct and the indirect time input and the cost of the system per hour as was explained before. The full cost analysis has been performed in [Warszawski, Rosenfeld, Zajicek 1993] for different wage rates and different annual utilization times (in terms of hours per year). The sensitivity analysis with respect to various cost parameters was also performed.

The result of cost comparison between robotized and manual construction for two wage levels one low of $12.50 per hour for skilled labor (including operator's wages) and $9.40 per hour for unskilled labor per year and the other high - of $25 for skilled labor and $18.80 for unskilled labor are shown in figure 4. The cost comparison assumes 1,500 work hours of the robot per year, and only those materials which differ between the two construction methods.

FINDINGS AND CONCLUSIONS

The following general conclusions can be drawn from the economic analysis of performance of the multipurpose interior finishing robot:

1. Most of the interior finishing tasks in building can be effectively executed by a mobile robot of jointed configuration with six degrees of freedom and 1.60 - 2.00 m reach. The robot can be adapted to each task by appropriate adjustment of the end effector and of control program.

2. Although it is possible to program the robot to move between its work stations, identify its tasks and execute them almost autonomously it will be more advantageous under the present conditions to have it acting under a continuous supervision of a human operator. The operator will guide it to work stations, identify the work initiation points and deal with various problems which may occur during the operation. Although the operator may be employed during his idle time to perform various auxiliary tasks needed to complement the robot's work this seems undesirable considering his qualifications and the continuous attention required by the robot . The cost of the operator may be reduced by assigning, in the more time consuming tasks such as building or tiling, two robots to one operator.

3. The efficiency of the robot employment will affected to a great extent by the burden of indirect activities associated with its work. These activities include transfer to project site, transfers between various locations on site, traveling to work stations, positioning at the work station, and routine maintenance. The amount of time spent on these activities may exceed in certain tasks the time spent on direct work in station. The robot will be used most efficiently on sites with ample amount of work at each floor level (4-8 hours of employment on floor seem reasonable in this respect), and work distributed in a manner which allows for maximum utilization of the robot capacity at each work station. A utilization of less than 60% - 75% of the capacity , especially in the less time consuming tasks- painting and plastering, may adversely affect the economy of robot employment.

4. The cost of the robotized work will be much affected by the utilization of the robot in terms of its hours of employment per year. Since the robot will in fact replace skilled human labor which is continuously needed in building , under satisfactory environmental conditions (which can and should be provided on the building site) 1,500 - 2,000 hours of employment per year for a multipurpose robot can be reasonably provided.

5. The robot can bring considerable saving in the manual labor on site. The saving in skilled labor ranges between 60% and 90% for typical tasks. Even the remaining skilled labor will be employed in supervisory and technical rather than manual tasks.

6. The costwise feasibility of robotized vs. manual work depends upon the prevailing wages of labor. For wages of $25 per hour 1,500 - 2,000 robot employment hours per year, suitable site and proper organization of materials packaging and handling, savings of 20% - 50% in the cost of work , or roughly 10 - 15% in the total cost including material, can be realized in several examined tasks. The savings will be considerably smaller, and in some tasks nonexistent when considering lower rate - of $12.5 per hour for skilled labor.

7. Some special requirements of robotized performance are difficult to assess in economic terms but must nonetheless be taken into account in the comparison. One of them has to do with much stringer precision and quality control than the one which is customary today in traditional construction. Another has to do with precise packaging and positioning of building materials which have to be used by the robot. A third has to do with a superior planning and organization of work on site which will allow the robot to move unobstructed to its work stations, and operate there efficiently. Any permissiveness with respect to these requirements will most probably make the robotized system non-operable.

Summing up, it may be concluded from the study that employment of a robot for interior finishing works has considerable potential for productivity improvement on the building site. It appears that economic savings can be also realized from robots employment. Other non quantifiable benefits which can be also obtained include increased safety, reduction of strenuous and unpleasant tasks, and better quality of building. Realization of these benefits depends however on very high precision of the building shell and a very high level of materials packaging and handling, and work organization on site.

BIBLIOGRAPHY

Israeli Institute for Productivity of Labor "Catalog of Labor Input in Building", Tel Aviv, 1980

Mean's Estimating Handbook, R.S. Means Co, Kingston, MA, 1990

Rosenfeld, Y., Warszawski, A., and Zaijcek, U.," Interior Finishing Building Robot",The 8th International Symposium of Automation and Robotics in Construction, Stuttgart 1991

Rosenfeld, Y., Warszawski, A., and Zajicek, U., "Economic Evaluation of Robotized Interior Finishing Works based On Full Scale Experiments" The 9th International Symposium of Automation and Robotics in Construction, Tokyo 1992

Warszawski, A., "Industrialization and Robotics in Building", Harper and Collins, 1990

Warszawski, A., and Navon, R., "Development of A Robot for Interior Finishing Works", Journal of Construction Engineering and Management , Vol 107(2) , 1991

Warszawski, A., Rosenfeld, Y., and Zajicek, U., "Feasibility Analysis of Robotized Performance of Interior Finishing Works", National Building Research Institute, Haifa, 1993

Warszawski, A., Rosenfeld, Y., and Shohet, I., "Autonomous Control System in Interior Finishing Robot" The 9th International Symposium of Automation and Robotics in Construction, Tokyo 1992

APPENDIX (FIGURES)

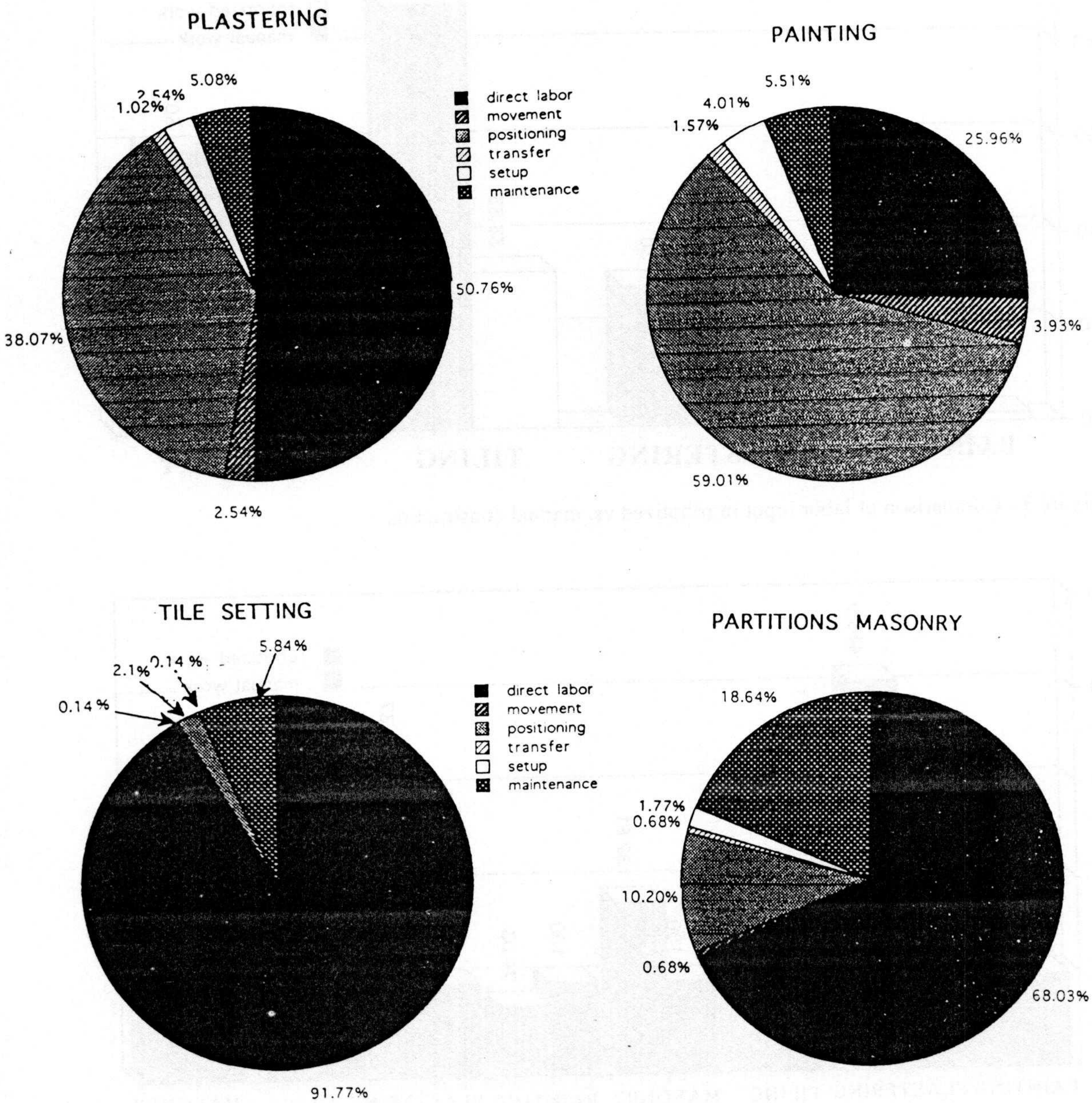

Figure 2 - Breakdown of work time of the interior finishing robot

INPUT OF TOTAL LABOR (min/sqm)

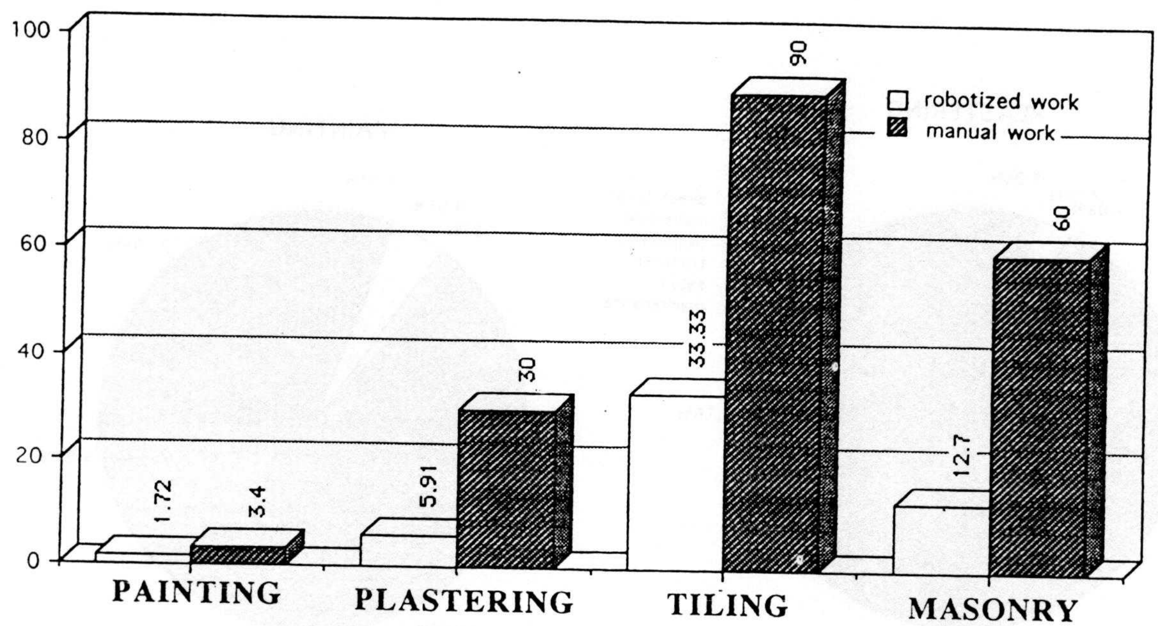

Figure 3 - Comparison of labor input in robotized vs. manual construction

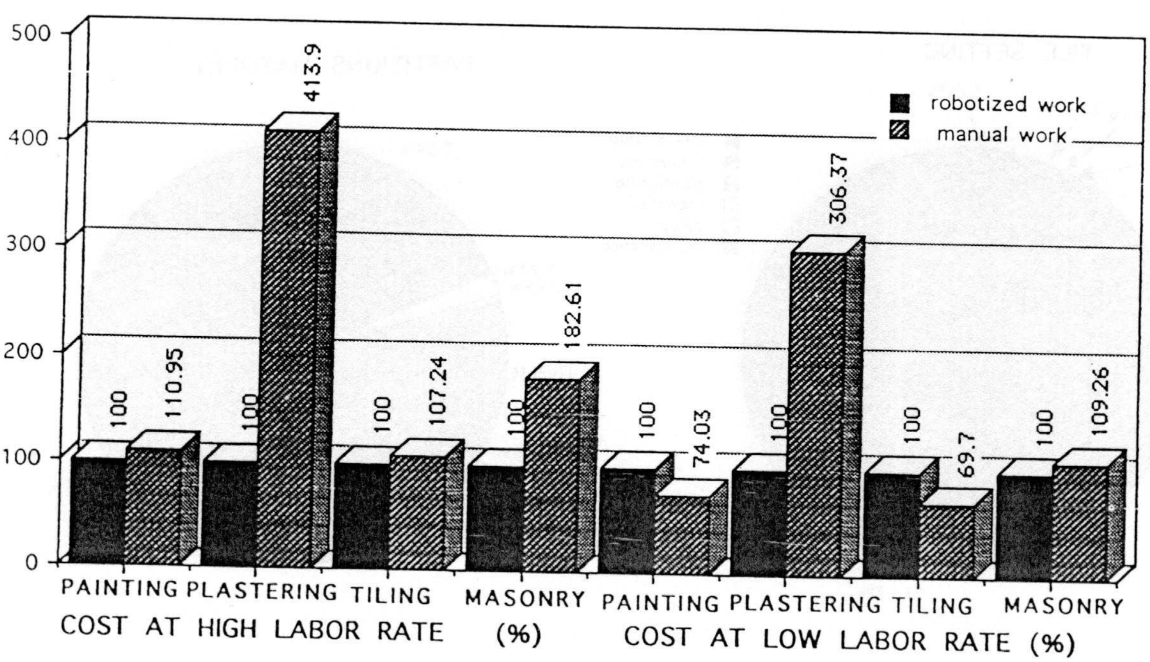

Figure 4 - Comparison of cost in robotized vs manual construction