Analysis of Robotic Surface Finishing Work on Construction Site

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Abstract: The robotization of on-site surface finishing work, particularly sandblasting, is considered. A possible system design is presented with a cost estimate. Costs and benefits of applying the proposed robot system to on-site sandblasting are outlined and estimated. Net present value of the contractor's investment in the robot equipment is analyzed. Conclusions regarding the purchase price of the robot based on its economic feasibility are drawn.

Introduction

The purpose of this paper is to introduce the application potential of robotics in the field of construction, surface-finishing works, both to existing practice and with the possibility of altered designs. Surface-finishing work includes cleaning, scrubbing, shotcreting, derusting, descaling, coating, painting, sandblasting, and other surface applications. The basic surface operations include the following:

1. Cleaning and shaping: applying mechanical treatment to a raw structural surface to obtain better quality or utility. This is a repetitive and often hazardous task requiring protective equipment, continuous control, and high accuracy.
2. Coating and spraying: spreading a liquid substance on a structural surface. These are also repetitive and health hazardous tasks requiring protective clothes, high control, and accuracy.
3. Covering: placing sheets of materials over an existing surface to enhance its quality. This task requires high accuracy in manipulating the work material.

Judging from the ergonomic characteristics of these work processes, most of the surface treatment activities can be performed with similar robotic control strategies. Although the robot effectors in each application will differ, the approach to the operation logic and to the robot system design can be systematic.

Apart from hazardous environments, surface-finishing works may offer the most promising construction domain for rapid economic payoff, since this work closely resembles some of the arduous, repetitive work tasks already automated or roboticized in the manufacturing industries. Existing and foreseeable robotic capability in this domain are reviewed including

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generic system designs. In this paper, potential cost savings and quality improvements from the introduction of robot automation are summarized with respect to existing work in the case of sandblasting.

This paper introduces a preliminary design of a robotic surface-finishing system that can be implemented on the construction site, and analyzes the costs and benefits associated with the system implementation. A comprehensive engineering economic analysis of the robotic process should include the following items:

1. Extent of robotics impact on the work process:
   (a) direct substitution of human labor by a robot;
   (b) possible extension of the work process to other environments;
   (c) redesign of the traditional work process due to robot capability.
2. Extent of the robotic impact on various process levels:
   (a) impact on the work procedures on the construction site.
3. Impact of technological change over time on robotized work performance.

However, only a subset of these dimensions will be treated in this paper, due to the nature of the problem and the difficulty in obtaining relevant data at the present time. Other treatments of robotic potential for construction include Paulson (1985), Warszawski and Sangrey (1985), and Skibniewski (1986).

Justification for Introducing Robots

Surface applications are marked by the need for surface tracking, for avoidance of nonapplication areas, for accurate positioning of effectors with respect to the treated surface, and for quality assurance. Apart from hazardous environments, surface finishing is one of the most promising fields for a relatively quick economic payoff from robotics investment. The primary reason for such a judgment is that surface finishing operations (e.g., on building walls and slabs) involve small forces at the effector location and repetitive operations that can closely resemble some of the arduous, repetitive work tasks already automated or roboticized in the manufacturing industries. A second reason for believing that surface finishing offers considerable economic potential is the large amount of existing construction activity in the area.

As can be appreciated from experience with existing industrial robotics, surface finishing involves only a few relatively simple tasks, lending themselves to partial or full performance by an automated machine. As an example, tasks involved in sandblasting from the viewpoint of machine performance include: (1) Determining and following the work range path; (2) determining and following the work surface; (3) applying a uniform jet stream onto the surface; (4) control of work parameters (e.g., flow of abrasive, air pressure); (5) parallel control of blasting effect. Each of these tasks can be performed with currently available robotic technology and have been attempted with success for other applications in the manufacturing industries [Hunt 1983]. Thus, robotic sandblasting should be technically feasible. It also provides the following significant benefits.

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Reduction in Health Hazards

There is enough medical and statistical evidence to support a claim that sandblasting processes pose a substantial health hazard associated with lung silicosis to human equipment operators. Some construction sandblasting contractors interviewed on this issue estimated that the elimination of this hazard by replacement of human labor with an autonomous robotic machine would provide them with a monetary benefit in the amount of up to 40% of the traditional human labor cost. Medical and statistical evidence of this danger is presented in Skibniewski (1986).

Expected Increase in Work Productivity

According to information obtained from sandblasting contractors in the Pittsburgh area, sandblasting is a several million dollar per year business in a typical large city in the U.S. (Skibniewski 1986). The productivity and work quality of sandblasting is largely affected by human factors. Eliminating some of the human limitations and drawbacks could decrease the labor cost and possibly increase the quality of work considerably. For example, the existing work rules require one worker to watch the sand hopper while two other are operating the blast nozzles. Every three hours a rotation is mandatory. Each sandblaster is also entitled to four hours of rest after performing four hours of work at the nozzle. Experience indicates that on a typical job site up to 70% of the day's production is normally completed between 8 and 12 a.m., due to workers' partial exhaustion. Also, the overall day's productivity is down by about 20% if the air temperature is over 30°C (Skibniewski 1986).

Sandblasting operating conditions are often arduous, and if the operator works on scaffolding or in tanks, his productivity will decline without rest. Apart from wearing cumbersome clothing and wearing a compressed air-fed helmet, his vision will gradually be impaired as the visor becomes dimmed with abrasive action and dust. This often precludes satisfactory control of the blast outcome on the surface during the work itself, and later corrections of previous work are costly and cumbersome.

Labor Cost Savings

Expected cost savings on labor are partially a direct result of eliminating the same factors that affect productivity. Reorganization of the sandblasting crew to meet the needs of the robotic sandblaster will require the elimination of the operator and assistant work tasks. Instead, technical supervision of robotized equipment will be necessary.

TABLE 1. Construction Sandblasting Labor and Tooling Cost Data, 1985 (I) (Mahoney 1985)

	Bare Costs		Including Subs O&P		Cost/Man-H	
Item (1)	Hr ($) (2)	Daily ($) (3)	Hr ($) (4)	Daily ($) (5)	Bare cost ($) (6)	Including O&P ($) (7)
One Labor foreman (outside)	17.50	140.00	25.25	202.00	—	—
Four building laborers	15.50	496.00	22.40	716.80	15.90	22.97
One Air Compressor (6.75m^3/min)	—	106.20	—	116.80	—	—
Air tools and accessories	—	23.70	—	26.05	—	—
2-15 m Air Hoses 0.04m Φ	—	11.60	—	12.75	3.53	3.89
Totals	—	777.50	—	1,074.40	19.43	26.86

TABLE 2. Construction Sandblasting Labor and Tooling Cost Data, 1985 (II) (Mahoney 1985)

Daily output, S_d (m²) (1)	Bare Costs Material ($) (2)	Installation ($) (3)	Total ($) (4)	Total including O&P ($) (5)
Wet system min. 63	$0.08	$0.46	0.54	0.72
max 153	0.12	1.11	1.23	1.67
Dry system min. 135	0.08	0.26	0.34	0.45
max. 270	0.12	0.52	0.64	0.85

The current labor and tooling costs of performing sandblasting work on a building face are listed in Tables 1 and 2. Current productivities are also listed in this table. As can be seen from these data, because of the relatively high labor costs, the potential savings to the contractor due to the elimination of human labor through a robotic replacement can be substantial. Their magnitude will depend upon to what extent the cost of human work performance can be eliminated by employing the cheaper work of the sandblasting robot.

Relevant Prototypes

A number of existing single-purpose prototypes of robot surface finishing exist.

Shotcrete Robot

In the new Austrian tunneling method, shotcrete application takes as much as 30% of the total time; improving the efficiency of this one task can bring about significant benefits. Normally, a skilled operator is needed to regulate the amount of concrete to be sprayed and the quality of hardening agent to be added, both of which depend on the consistency of the concrete. Kajima Co. has developed and implemented a computer-controlled applicator by which high quality shotcrete placement can be achieved (Sagawa and Nakahara 1985).

Slab-Finishing Robot

Finishing the rough surface of a cast-in-place concrete slab after pouring usually requires laborious human handwork, often performed at night and in adverse weather. The robot designed for this task by Kajima Co. is mounted on a computer-controlled mobile platform and equipped with mechanical trowels that produce a smooth, flat surface (Saito 1985). By means of a gyrocompass and a linear distance sensor, the machine navigates itself and automatically corrects any deviation from its prescheduled path. This mobile floor-finishing robot is able to work to within one meter of walls. It is designed to replace at least six skilled workers.

Fireproofing Spray Robot

Shimizu Co. has developed two robot systems for spraying fireproofing material onto structural steel (Yoshida and Ueno 1985). The first version, the SSR-1, was built to use the same materials as in conventional

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fireproofing, to work sequentially and continuously with human help, to travel and position itself, and to have sufficient safety functions for the protection of human workers and of building components. A second robot system, the SSR-2, was developed to improve some of the job-site functions of the first prototype. From an economic viewpoint, the SSR-2 can spray faster than a human worker, but requires time for transportation and setup. The SSR-2 takes about 22 min for one work unit while a human worker takes about 51 min. The SSR-2 does not require much manpower for the spraying preparation, only some 2.1 man-days compared to 11.5 for the SSR-1. This shortening of preparation time contributes considerably to the improvement of robot-system economic efficiency. As the positional precision of the robot and supply of the rock wool feeder were improved, the irregular dispersion of the sprayed thickness decreased and became nearly equal to that applied by a human worker.

Wall-Climbing Robot

Nordmed Shipyards of Dunkerque, France, developed the RM3 robot for marine applications, including video inspections of ship hulls, γ-ray inspections of structural welds, and high-pressure washing, deburring, painting, shotblasting, and barnacle removal (Robotix News 1985). The RM3 weighs 94 kg and has three legs, one arm, and two bodies. Magnetic cups on its hydraulic actuated legs allow the RM3 to ascend a vertical steel plate, such as a ship's hull, at a speed of 150 m/hr. RM3 has a cleaning rate of 5,000 m^2 day and a 96-m range. Nordmed entered into a joint venture with Renault to use a version of RM3 to paint chemical storage tanks.

Robotic Sandblasting

Ingolt Ship Building of Pascaguola, Mississippi, has developed a preliminary design and a prototype of a robotic sandblaster for the application in shipyards. The machine is to be used for blasting of side surfaces of tankers. A robotic arm is supported on a steel truss vertical tower and has a reach of 16.5 m in vertical and 9 m in horizontal direction. The truss tower is mounted on a self-navigating platform which moves itself through a preprogrammed path. The vehicle is able to accept input from a human operator when necessary and work in a playback mode. This mode is equipped with optical collision-avoidance capability for a quick recovery from obstacle-troubled paths in the robot's evolving work envelope.

Design Specifications for Sandblasting Robot

In this section, a preliminary system design for a robotic sandblasting system is presented. This system is outlined in some detail since it could share numerous features with other surface treatment robots. The sandblasting robot will also serve as the prototype for cost and benefit estimation of robot potential in the following sections.

The following robot features are necessary for successful performance of the sandblasting task:

1. Mobility and maneuverability can be provided by a tether of light emitting diode (LED)-guided mobile platform constituting a base for a robot sandblaster mounted on top of it, with a positioning accuracy of ±2.5

cm. It is expected that a commercially available automatically guided vehicle (AGV) platform can be used.

2. Robot arm characteristics: The robot arm should be extendable up to 2.5 m. There could be one end effector and three sensors mounted on the arm: a blast gun, a sonar for surface proximity measurement, LED-direction sensor, and a surface-reflectivity meter. The arm will have four degrees-of-freedom: one at the base, one at the elbow, and pitch and yaw.

3. End effector: The only end effector applicable to the surface sandblasting will be the blast gun. Its basic design and function remains similar to the gun used in manual sandblasting operation.

4. Motion control system: The control system will be provided by a set of microprocessors mounted next to the arm sensors and an on-board computer managing all the individual functions of the robot. The control of the following motion functions are considered: (1) Sensory information processing (from LED, sonar, and reflectometer) for the motion command initiation; (2) speed and direction of platform travel; and (3) speed and direction of the robot arm move.

5. Environment sensing can be performed by three types of sensors:

(a) The light beams generated by the light emitting diodes (LED) mounted on the corners of the work surface will be sensed by a light sensor capable of detecting the distance and the direction from which the light beam is emitted. Data obtained from these sensors will serve to determine the spacial position of the robot with respect to the work surface.

(b) A sonar mounted on the robot arm will provide for a short-range proximity sensing, to enable the arm to position itself closely to the work surface.

(c) A surface reflectivity meter will inspect the effect of the blasting process continuously and provide the information through its microprocessor to the on-board computer.

6. Material feed and flow control: A continuous, uninterrupted feed of sand and compressed air will be assured by microprocessors mounted in critical locations of the feeding system.

(a) A dampness meter to measure the dampness of sand stored in the hopper. Dampness above a critical value will be reported by microprocessor to the host computer for decision making and appropriate action.

(b) An air-flow sensor to measure the flow of air from the compressor to the blast nozzle. Any deviation from the regular flow quantity will be signaled to the on-board computer by the flow sensor and considered for appropriate action.

(c) A pressure sensor will be mounted near the blast nozzle to monitor the air pressure in the air/sand mixture. Any deviations detected by sensor's microprocessor will be reported to the computer.

The sandblasting robot will perform a continuous task of applying a stream of pressurized sand onto the cleaned surface. To accomplish this objective, the following steps are to be taken:

1. Light-emitting diodes (LED) are mounted on the characteristic corners and other locations of the work area. Their signals are received by directional light sensors placed on the robotic vehicle carrying the sandblasting arm. The on-board computer uses this information to determine the relative location between the work surface and the robotic vehicle.

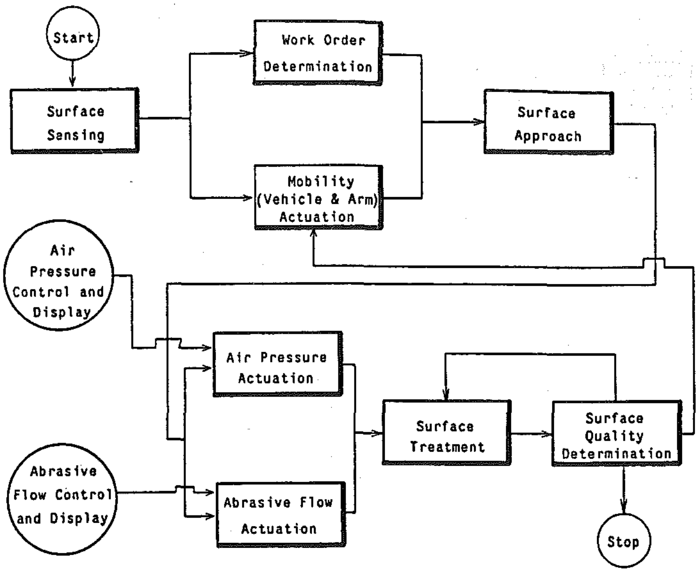

FIG. 1. Flow Chart of Sandblasting System

2. The vehicle approaches the work surface and stops at its initial work position. The sonar sensor mounted on the robot arm determines the relative position of the nozzle with respect to the work surface. The arm moves to its initial work location.

3. The air and sand flow is activated at a given "ready" signal. After applying the jet stream to the given location, surface cleanliness measurement is assessed by means of a reflectivity meter and a microprocessor. The assessment signal is sent to the on-board computer for the decision making. The decision is sent back to the blast nozzle actuator and the blast action is repeated at the same location or the arm is moved to the next area. The blast areas will slightly overlap to ensure proper blasting effect on the area between the nozzle moves.

4. The blasting process repeats, and after a positive surface assessment, the nozzle moves to the next location. At the completion of blasting the last location, the stop signal is issued and the vehicle is removed from the work area.

Fig. 1 shows the flow chart of the sandblasting system.

The robotic components necessary for the construction of the autonomous sandblasting machine are available on the commercial market in the United States and/or other industrialized countries. Most of them already constitute elements or segments of existing industrial robotics. With respect to the components specified, there are in most cases several options from which to select the desired hardware and controls. Skibniewski (1986) contains an overview of selected commercially available components applicable to the subsystems of the considered sandblasting robot.

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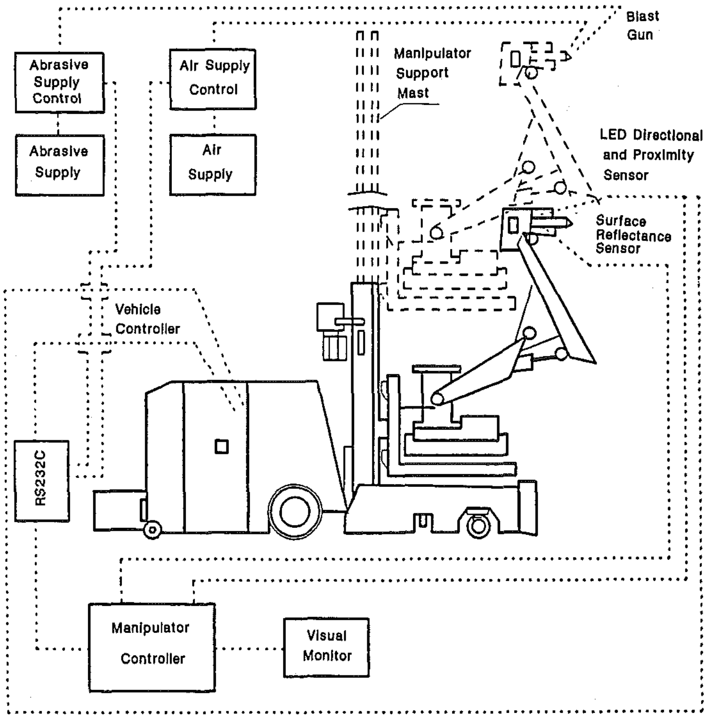

FIG. 2. General Setup of Sandblasting System

The robot system mechanical setup must be particularly rugged to withstand typical and unforeseen work-site conditions. However, no large external forces exerted on the machine are anticipated. It is expected that the manipulator arm frame can be made of lightweight metal material.

The sandblasting robot shall consist of the following components (see Fig. 2):

1. Mobile robotic platform. An autonomously guided vehicle available on the commercial market and subjected to slight modifications will be implemented. A sample selection of available vehicles is presented in Skibniewski (1986).

2. Robot manipulator. A stationary industrial robot should prove suitable for the sandblasting task. The robot will be mounted on an extendable steel frame mast fixed on the mobile platform. The manipulator will consist of a blasting gun as the end effector, a light sensor as a surface shape orientation and proximity sensing device, and a surface reflectometer as the work quality control device.

3. Power supply. A standard AC/DC power supply of approximately one kW should be sufficient to drive the manipulator mechanisms and the mobile platform. It is assumed that in most cases an on-site power supply connection will be available. In other cases, a 48-V, 6-hr battery for the operation of the electric engine should be feasible.

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4. Sand and air pressure supply. A standard air compressor used in the manual sandblasting process will be implemented. Sand will be supplied by means of a traditional hopper into the pressure vessel.

5. Electronic controls. Four types of controls, supplied with microprocessors, will be used: (1) Sand dampness meter and control; (2) sand supply control; (3) air pressure control; (4) vehicle position control; (5) manipulator position control; and (6) surface condition control.

6. System state displays. The displays will inform the operator about the parameters of the work process underway. They will include display of the vehicle position with respect to the work-site layout, manipulator position with respect to work surface, air pressure, sand supply, and electric power supply values.

Estimated Cost of Sandblasting Robot

Estimating the cost of roboticized sandblasting involves several levels of estimation. Each level is associated with different accuracy and uncertainty factors, due to the current lack of relevant system design experience and prototypes. These factors will considerably affect the reliability of the final cost estimate and must therefore be assessed on an individual basis.

In general, the following robot system cost items will be considered:

1. Mobile robot platform (adopted from an automatically guided vehicle, AGV)
2. Robot manipulator (adopted from a commercially available stationary industrial robot)
3. Platform/manipulator setup
4. Platform/manipulator motion control system (custom-built from the commercially available components)
5. Utility and material supply control systems
   (a) sand supply control
   (b) sand dampness control
   (c) air pressure control
   (d) power supply control
6. Custom-built sensors
7. Microprocessors
8. Interfaces, communications, and displays
9. Job environment preparation
   (a) light emitting diodes (LEDs) in crucial locations on the work surface
   (b) guidepaths and guidewires for the mobile vehicle.
10. System operating cost
   (a) reprogramming to suit varying jobsite requirements
   (b) labor cost (technician)
   (c) electric energy
   (d) system re-setup and dismantling
   (e) transport to new work site

These cost items can be divided into two major groups:

1. Robot component costs. These costs include purchase of the AGV, the stationary robot, the necessary control hardware, and other miscella-

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TABLE 3. Estimated Cost of Sandblasting Robot Components

Component (1)	Cost ($) (2)
Automatically guided vehicle (AGV)	50,000
Robotic manipulator	40,000
Control systems:	
Sand hopper controller	1,000
Sand flow controller	900
Air pressure controller	1,200
Power supply controller	1,800
Guidewires and guidepaths	1,000
Custom-built sensors	2,000
Graphic displays and communication	5,000
Total (approximate)	100,000

neous items. These costs are characterized by a fairly high level of prediction accuracy.

2. Robot system engineering costs. These costs include the development effort to implement the system in the specific work environments. It can be broken down into system control engineering, software engineering, and hardware setup costs. The level of predictability for these costs is low, but for the sake of completeness of this cost analysis must be roughly quantified.

System components specified in this subsection are either commercially available or custom-built, according to specifications comparable with similar subsystems built by others for previous applications. Thus, some extrapolations of these costs can be performed and incorporated into the system's financial analysis. Estimates are contained in Table 3.

Projected operating cost figures for the sandblasting robot are based on the experience of relatively comparable equipment used either in construction or in the manufacturing industry. They include only those items that do not also represent the operating costs of the traditional, human-operated sandblasting equipment. The projected figures are contained in Table 4.

TABLE 4. Projected Operating Cost of Sandblasting Robot

Item (1)	Cost/project ($) (2)
Supervision cost (one technician)	1,250
On-site reprogramming and adaptations	300
System re-setup (three technicians, one day)	600
System dismantling (two technicians, one day)	400
Electric energy (battery and power line)	300
Transport to new work site	500
Maintenance and repair	400
Total (approximate)	3,500

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These costs consist of the following items:

1. On-site programming and software adaptation. User-level programming services will be required when the need for changing input parameters of the work environment or adopting the existing software to new conditions occurs. Based on experience of comparable system users, a contingency value for these services in the amount of $300 per project is assumed.
2. Labor cost. A full-time technician to service the robot during operation is required. Based on the current wages for this group of employees, the cost of $1,250 for one technician per project is assumed.
3. Electric energy. To operate the mobile platform, a standard 48-V, 6 hr, 1,080,000 A-s battery can be used. The lifetime of such battery is expected to be three working seasons, thus its average cost per project can be approximated to $300 (including the cost of reloading).
4. System re-setup and dismantling. Assuming full mobility and transferability of the sandblasting system, the cost of dismantling the equipment attributed to the robotic aspects of the system can be approximated at $400. This cost is based on the work of two technicians for one day. The amount of $600 is assumed for the re-setup of the robotic part of the system. This figure is based on the work of three technicians for one day.
5. Robot transporting cost. These costs will be part of the total transportation cost of the sandblasting system to a new job location. The increase in these costs due to the necessity of transporting sensitive and relatively fragile robot components must be considered; it is approximated at $500 per project.
6. Maintenance and repair. A contingency value, based on experience of manufacturing industries for comparable equipment and increased by an uncertainty factor of 0.5 is assumed and approximated at $400 per project.

The cost estimation of the system engineering effort to introduce the roboticized sandblasting work is a multistage process determined by the level of work system design. Each of these levels is characterized by a different estimation accuracy factor. These factors can be determined either by the experience of previous robotic systems designs or by a consensus of experts in system design strategies. The writers draw on both of these approaches in their estimation effort.

An extensive inquiry effort aimed at similar robot system developers has been undertaken (Skibniewski 1986). The obtained results were only partially conclusive with regard to specific items on the system construction process schedule. The numerical data were obtained largely from several Japanese construction companies, which have had relatively broad experience with the development of their own construction robotic systems for specific applications.

A broad consensus among the interviewed parties has been found, that the minimum system engineering cost associated with the development of this type of equipment was approximately eight to ten times greater than the direct cost of robot hardware and application software combined (Skibniewski 1986). However, there were less consistent opinions among the interviewed companies as to how the future selling (or purchase) price for such robotic equipment is to be established. The most logical approach

TABLE 5. R&D Cost for Ship Sandblasting Robot

Item (1)	Cost ($) (2)
Base of robot	270,000
Horizontal linkage of manipulator	71,000
Vertical support	107,000
Surface prep. end effector	34,000
Applicator Effector	30,000
Surface prep. subsystem	400,000
Applicator subsystem	40,000
Control systems hardware:	
Computer servo-loops	40,000
Optical collision avoidance	40,000
Man-machine interface	14,000
Software (including control of system elements)	600,000
Total (approximate)	1,650,000

would be to base the selling price on either the equipment development cost, which would most likely fail in the market economy, or on the expected benefit to the contractor from the use of the robot on his job site. Current demand for the equipment will influence this value by a consid-

TABLE 6. Cost Breakdown of R&D on Japanese Construction Finishing Work Robot

Description (1)	Cost ($) (2)
(*a*) Prototype stage	
Manpower for R&D (engineering, system/machine design, planning, scheduling, coordination, etc.) 408 man-days	74,100
Product Testing:	
Work surface treatment	15,000
Teaching	1,000
Traveling	1,500
Navigation wiring	900
Purchase of industrial robot hardware	90,350
Purchase of tractor and traveler (for robot mobility)	25,000
Subtotal (approximate)	208,000
(*b*) "Mark 2" System	
Manpower for R&D (engineering, system/machine design, planning, scheduling, coordination, etc.) 254 man-days	45,550
Product testing:	
Position sensor	1,800
Surface treatment by robot	600
Material feeder	1,100
Conversion from prototype to "Mark 2" system (improved hardware, controller, software)	40,000
Subtotal (approximate)	89,000
Total (approximate)	300,000

erable factor, which will also depend on the equipment manufacturing cost and alternate equipment supplies.

As an example, financial data has been obtained from a robot design aimed at robotization of descaling ship surfaces in ship hulls (see Table 5). The figures, however, do not explain the distribution between hardware and engineering cost, since they merely allocate cost figures to individual parts of the robot system. The system developer indicated that the total expected cost for the system development can be anticipated at approximately $2,000,000. The cost reduction due to the application of the robotic machine is estimated by the company in the amount of $100,000 per ship (including sandblasting and painting).

More detailed data on the R and D costs have been obtained from Japanese system developers. For example, a major Japanese contracting firm involved in the development and production of a structural surface finishing system has experienced the development cost breakdown presented in Table 6.

The current human labor cost in Japan for the operation roboticized by the equipment described in Table 6 is $9.40 (including O and P) per man-hr. According to 1985 construction cost data (Mahoney 1985), the corresponding average cost of human labor for similar operations in the U.S. amounts to $18.60, approximately double that of Japan. This could indicate that with the assumption of identical worker's productivity, the U.S. labor savings accrued from the implementation of the robot would be 100% higher than in Japan.

BENEFIT ESTIMATION

For the purpose of estimating the benefit of the roboticized sandblaster, an example unit project involving a circular concrete fuel storage tank is assumed. The base diameter is 36 m and the height is 12 m. Thus, the side wall area of the tank to be blast-cleaned is approximately 1,360 m^2. The following benefits can be obtained from the use of the sandblasting robot: (1) Blast operator labor savings; (2) elimination of scaffolding; (3) eliminated risk of silicosis; (4) productivity gains; and (5) extension of work into difficult climatic conditions. A detailed analysis of these benefits is included in Skibniewski (1986). Their quantities for the example project are contained in Table 7.

TABLE 7. Estimated Benefits from Example Roboticized Sandblasting Project

Benefits/savings (1)	Value/project ($) (2)
Operator labor	7,500
Scaffolding elimination	3,000
Health and safety	3,000
Work quality	750
Productivity gain	0
Extension of activities	1,425
Total (approximate)	15,500

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Net Present Value Estimation

The estimation of the net present value of the sandblasting robot is performed for two reasons: (1) For the purpose of determining the attractiveness of the investment in its development and serial production (from the developer's viewpoint); and (2) for the purpose of determining the attractiveness of its purchase (from a contractor's viewpoint). Each of these viewpoints is characterized by a different philosophy and approach to estimating costs and benefits of undertaking the effort leading to robot application, as explained earlier in this paper.

The most relevant parameters to be determined for the net present value estimation are the following: (1) Economic life of the robot and the planning horizon; and (2) minimum attractive rate of return (MARR). The economic life of a robotic system has been discussed in Engelberger (1974). It will be assumed for the purpose of this analysis that the useful economic life of the robotic sandblaster is three years.

The determination of the most feasible value of the minimum attractive rate of return (MARR) is very complex for investment in new technologies and reaches out beyond the scope of this paper. Thus, four likely and typical values will be considered: 10%, 15%, 20%, and 25%.

Let us assume a typical number of ten projects per season, which has been the approximate number of projects for a medium-sized sandblasting contractor in the Pittsburgh, Pennsylvania area, between 1980–1985. The cash flows resulting from the previous analysis are presented in Table 8.

Different net present values (NPV) of the implementation of the sandblasting robot can be derived using various probable values of MARR with respect to the cash flow presented in Table 8. The approximate NPV values can be obtained (see Table 9).

Given the data in Table 9, break-even points of the robot value can be determined. In other words, there is a treshold value assigned to the robot, above which the machine would no longer be profitable under the given

TABLE 8. Cash Flow Projections for Sandblasting Robot

Season (1)	Costs ($) (2)	Benefits ($) (3)	Net cash flow ($) (4)
0	150,000	—	150,000
1	35,000	155,000	120,000
2	35,000	155,000	120,000
3	35,000	155,000	120,000

TABLE 9. Net Present Value of Sandblasting Robot

MARR (%) (1)	Net present value ($) (2)	Uniform seasonal value ($) (3)
10	148,500	59,500
15	124,000	54,500
20	103,000	49,000
25	84,000	43,000

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TABLE 10. Break-Even Value of Sandblasting Robot

MARR (%) (1)	Break-even value of robot to contractor (approximate $) (2)
10	300,000
15	275,000
20	250,000
25	235,000

operational assumptions. These values are contained in Table 10; values in Table 10 indicate that the predicted purchase price of the sandblasting system in the amount of $150,000 should prove attractive.

Conclusions

This paper presented the point that a multitask surface-finishing robot applicable in a variety of construction finishing tasks may be technically and economically feasible, and potentially offers greater variety and flexibility in the design of building surface finish. Based on the experience of developing previous robotic systems, the estimated cost of system components has been provided. Also, the benefits derived from the application of such a system are estimated on the example of roboticized sandblasting. Both system costs and benefits are only approximate estimates. The accuracy of these estimates must be measured against the future experience in implementing robotics to various specific work tasks. Therefore, in order to better estimate these quantities, several prototype robots capable of performing surface-finishing tasks in construction will be necessary. The surface quality implications of robot implementation to these tasks were outlined. In the writers' opinion, robotics have a potential for better workmanship quality and greater flexibility in surface finish. After a technical and economic analysis of the robotic alternative, it is concluded that the application of a robotic machine to a series of comparable, repetitive surface application tasks can be technically and economically viable.

Appendix. References

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