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Cost and Design Impact of Robotic Construction Finishing Work

Abstract

The purpose of this paper is to explore the application potential of robotics in the field of construction finishing works, both to existing practice and with the possibility of altered designs. Finishing work includes cleaning, scrubbing, shot-creting, de-rusting, de-scaling, coating, painting, sand-blasting and other surface applications. Apart from hazardous environments, surface finishing works may offer the most promising construction domain for rapid economic payoff, since surface finishing 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 generic system designs. Potential cost savings and quality improvements from introduction of robot automation is summarized with respect to existing work. In addition, implications for the design of buildings, particularly large-scale, complex architectural projects, are explored.

1 Introduction

Surface finishing is one area in which many robot system components developed for a single application such as sandblasting can be readily transferred to applications such as insulation spraying. Surface finishing work as defined here can involve a variety of covering, inspection and removal operations, including cleaning, scrubbing, shotcreting, painting, sandblasting and others. These applications are marked by the need for surface tracking, for avoidance of non-application areas, 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 judgement is that surface finishing operations (e.g. on building walls and slabs) can closely resemble some of the ardouous, 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 amount of activity in the area.

The basic surface operations include the following:

1. **Finishing**: 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.

Besides the surface treatment operations, other operations applicable to construction would require a similar amount of control if performed by a robotic machine:

1. **Sealing**: applying a sealant to the joint edges of structural elements to obtain uninterrupted and isolating surface.

2. **Concreting**: pouring concrete mix into previously prepared formwork to create structural volume. This requires strength and endurance on the part of laborers.

3. **Backfilling**: replacing empty space between foundation walls and the ground with soil. Requires transfering large volumes of soil with mechanical pushers and backhoes.

Judging from the ergonomic characteristics of the above work processes, the authors believe that 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 some degree to the robot system design, can be systematic. The design of modular construction robotic equipment will be an involved and costly task. Therefore, careful economic justification and a thorough system design effort will be necessary.

Examples of benefits accrued from the robotization of surface finishing can be as following:

1. Labor Savings: are expected to be significant, due to the often arduous, repetitive work, and worker productivity decreasing with time due to tiredness.

2. Work Safety Savings: since work is often performed at heights, there is a strong potential for eliminating the danger of falls. At present, falls of persons are the major type of death-causing accidents in construction.[5] Due to the same reason, significant savings on scaffolding purchase/leasing and erection can be accrued.

3. Worker Health Savings: many surface finishing operations (e.g. sandblasting, polishing, painting, etc.) poses a significant health hazard to workers exposed to dust, toxic vapors, and noise. Additional savings on safety equipment can be experienced.

[5]M. Skibniewski: Methods to Improve the Safety Performance of the U.S. Construction Industry, M.S. Thesis (unpublished), Carnegie-Mellon University, 1983.

4. Design Improvements: with lower costs or different capabilities, architects and engineers can alter designs to produce more cost effective or aesthetic finished surfaces.

2 Relevant Prototypes

A number of existing single purpose prototypes of robot surface finishing exist,[6] including:

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.[7]

Slab Finishing Robot: Finishing the rough surface of a cast-in-place concrete slab after pouring usually requires laborious human hand work, 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.[8] By means of a gyro-compass and a linear distance sensor, the machine navigates itself and automatically corrects any deviation from its pre-scheduled 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.[9] The first version, the SSR-1, was built to use the same materials as in conventional 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

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[6] I. Oppenheim, M. Skibniewski: Robotics in Construction, *Encyclopaedia of Robotics*, John Wiley & Sons; to be published in 1986.

[7] Y. Sagawa, Y. Nakahara: Robots for the Japanese Construction Industry, *IABSE Periodica 2/1985, May 1985, IABSE Proceedings P-86/85*

[8] M. Saito et al.: The Development of a Mobile Robot for Concrete Slab Finishing, Technical Report (unpublished), Mechanical Engineering Development Dept., *Kajima Co.*, Tokyo, Japan.

[9] T. Yoshida, T. Ueno: Development of a Spray Robot for Fireproof Treatment, *Shimizu Technical Research Bulletin* No. 4, March 1985, *Shimizu Construction Co.*, Tokyo, Japan.

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 minutes for one work unit while a human worker takes about 51 minutes. The SSR-2 does not require much manpower for the spraying preparation, only some 2.08 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.[10] The RM3 weighs 206 lbs 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 8.2 ft/min. (150 m/hr). RM3 has a cleaning rate of 53,800 sq.ft./day (5,000 m^2 per day) and a 320 foot range. *Nordmed* entered into a joint venture with *Renault* to use a version of RM3 to paint chemical storage tanks.

Ingolt Ship Building of Pascaguola, MS, has developed a preliminary design and a prototype of a robotic sandblaster for the application in ship yards. 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 55 feet in vertical and 30 feet in horizontal direction. The truss tower is mounted on a self-navigating platform which moves itself through a pre-programmed path. The vehicle is able to accept input from 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.

3 Concept of Multi-Purpose Surface Application Robot

The example prototypes described above are machines built for a single-purpose application. However, may similarities in design approaches to the total robot work system can be discovered and systemized for the benefit of similar design efforts.

Modular robot system design effort to fulfill the needs of many types of surface finishing operations will involve several stages of activities (see figure 1). These activities invlove the following:

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[10] Technical information compiled by Robotix News. July/August 1985.

1. Robot Purpose Analysis:

   a. Definition of robot work [illegible] individual robot system functions, such as surface polishing, painting, spray[illegible] [illegible], etc. must be pre-specified for the subsequent design of robot capabilities;

   b. Identification of individu[illegible] tasks [illegible] with respect to the general function of the robot): these tasks must be dete[illegible] [illegible] work function; then groups of tasks accross all functions are compared [illegible] for distinctive characteristics;

   c. Identification of various [illegible]: these diversified locations provide different constraints for the same [illegible] the robotic system. The set of components satisfying the requireme[illegible] [illegible] work sites is one of the goals of the system design, although there w[illegible] [illegible] variations for the scale or orientation of the workplace.

   d. Establishment of environ[illegible] and performance parameters: the knowledge of these parameters is necessary for adequate selection of robot subsystems, their characteristics, and their [illegible] under varying environmental conditions;

   e. Identification of field hardening requirements: a second iteration on those components and subsystems which can significantly increase the total system reliability in specific work environments;

2. Robot System Development:

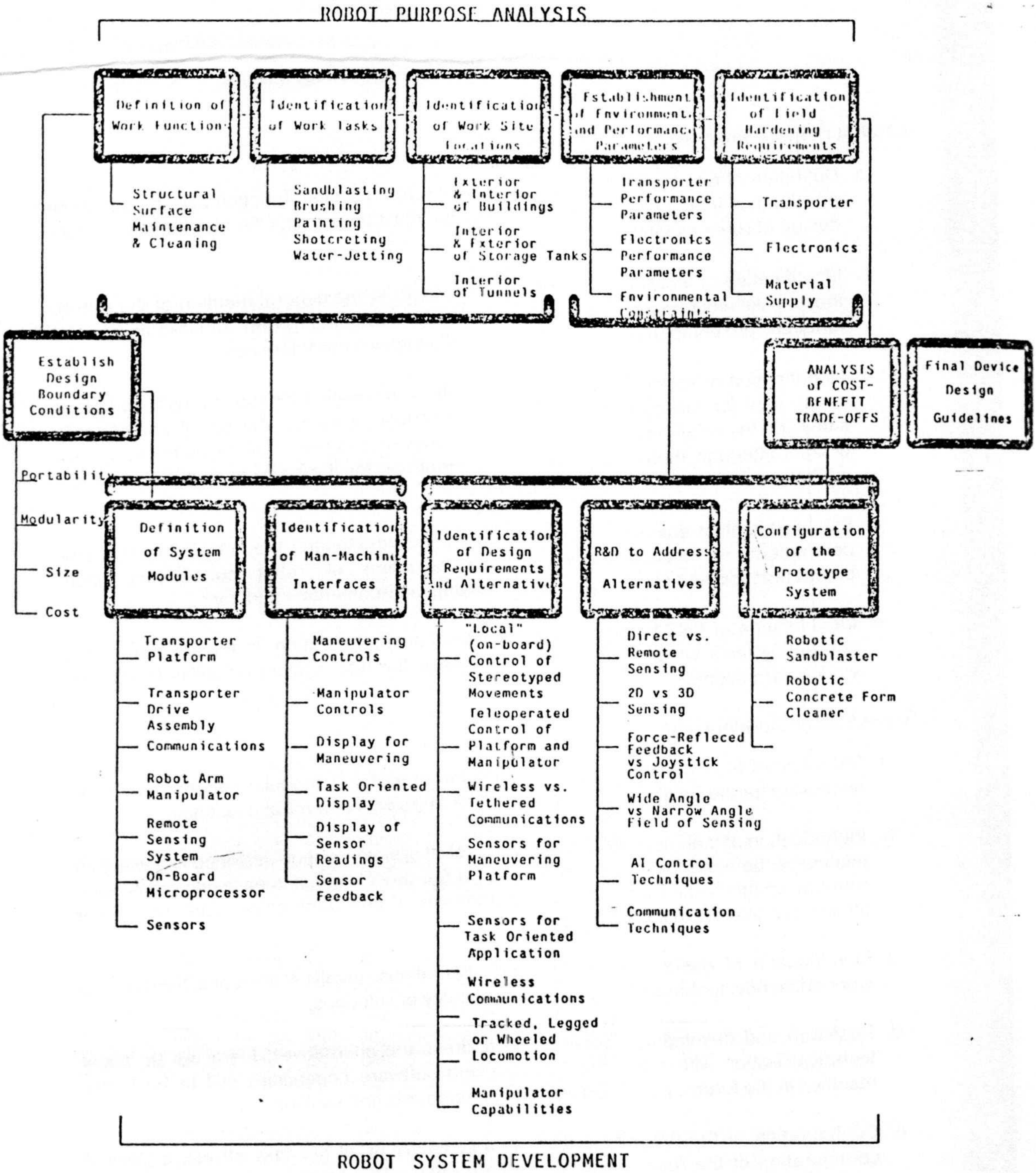
   a. Definition of the system [illegible]: determination of system's modular subcomponents is necessary for the fulfillme[illegible] [illegible] work tasks with one robotic machine;

   b. Identification of man-machine interfaces: the robot system must be designed in a way that minimizes the need for human interaction. On the other hand, it is necessary to provide routines enabling the human operator to intervene at any stage of the work process or alter its parameters in a flexible manner

   c. Identification of design requirements and alternatives: involves the considerations of work efficiency, technical feasibility, and availability of solutions;

   d. Research and development necessary to address the alternatives: there will be many technical issues with respect to hardware and software capabilities still to be better resolved in the future, when more powerful components are available;

   e. Configuration of the prototype system: as a summary of all previous efforts, a general configuration of the robot system will be performed. This configuration is expected to meet the basic requirements of all surface finishing tasks as performed by an autonomous device.


ROBOT PURPOSE ANALYSIS
Definition of Work Functions
Identification of Work Tasks
Identification of Work Site Locations
Establishment of Environmental and Performance Parameters
Identification of Field Hardening Requirements
Structural Surface Maintenance & Cleaning
Sandblasting
Brushing
Painting
Shotcreting
Water-Jetting
Exterior & Interior of Buildings
Interior & Exterior of Storage Tanks
Interior of Tunnels
Transporter Performance Parameters
Electronics Performance Parameters
Environmental Constraints
Transporter
Electronics
Material Supply
Establish Design Boundary Conditions
ANALYSIS of COST-BENEFIT TRADE-OFFS
Final Device Design Guidelines
Portability
Modularity
Size
Cost
Definition of System Modules
Identification of Man-Machine Interfaces
Identification of Design Requirements and Alternatives
R&D to Address Alternatives
Configuration of the Prototype System
Transporter Platform
Transporter Drive Assembly
Communications
Robot Arm Manipulator
Remote Sensing System
On-Board Microprocessor
Sensors
Maneuvering Controls
Manipulator Controls
Display for Maneuvering
Task Oriented Display
Display of Sensor Readings
Sensor Feedback
"Local" (on-board) Control of Stereotyped Movements
Teleoperated Control of Platform and Manipulator
Wireless vs. Tethered Communications
Sensors for Maneuvering Platform
Sensors for Task Oriented Application
Wireless Communications
Tracked, Legged or Wheeled Locomotion
Manipulator Capabilities
Direct vs. Remote Sensing
2D vs 3D Sensing
Force-Refleced Feedback vs Joystick Control
Wide Angle vs Narrow Angle Field of Sensing
AI Control Techniques
Communication Techniques
Robotic Sandblaster
Robotic Concrete Form Cleaner
ROBOT SYSTEM DEVELOPMENT

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4 Sandblasting Example

With the above prototype implementation framework, a concept of a multi-task, surface-application-oriented machine applicable to a variety of cleaning, scrubbing, coating, and washing tasks can be exemplified on a specific task of concrete wall sandblasting. It has been selected as an example of possible significant benefit for its extremely high health hazard of silicosis to human operators.

The various types of sandblasting work on structures are usually performed by highly specialized and small or medium-sized contracting firms. For example, a firm specialized in masonry restoration sandblasting would not be prepared to perform rust removal from the bearing elements of a highway steel bridge, and a steel container sandblasting contractor would usually not perform blasting of concrete or brick walls. The work styles, due to somewhat different occurrencies and intensities of health and safety hazards, are also different, since the surfaces and environment in which laborers work differ considerably.

The sandblasting process involves only a few relatively very simple work tasks, lending themselves to partial or full performance by an automated machine. These tasks are as following:

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.

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, existing work rules require one worker to watch the sand hopper while to other are operating the blast nozzles. Every three hours a rotation is mandatory. Each sandblaster is also entitled to 4 hrs of rest after performing four hours of work at the nozzle. Experience indicates that on a typical job site, due to workers' partial exhaustion, up to 70% of day's production is normally completed between 8 and 12 a.m. Also, the overall day's productivity is down by about 20% if the air temperature is over 75 deg F.

As can be appreciated from contractors' experience, operating conditions are often arduous, and in addition with the operator working on scaffolding or in tanks, his tiredness will grow rapidly if he works too long 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 often costly and cumbersome.

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.

The current U.S. labor and tooling costs of performing sandblasting work on a building face are listed in table 1.

	Bare Costs		Incl. Subs O&P		Cost per Man-Hour	
	Hr.	Daily	Hr.	Daily	Bare Cost	Incl.O&P
1 Labor Foreman (outside)	$17.50	$140.00	$25.25	$202.00		
4 Building Laborers	15.50	496.00	22.40	716.80	$15.90	$22.97
1 Air Compr. (250 c.f.m.)		106.20		116.80		
Air Tools & Accessories		23.70		26.05		
2-50ft Air Hoses 1.5"Φ		11.60		12.75	3.53	3.89
		$777.50		$1,074.40	$19.43	$26.86

Table 1: Construction Sandblasting *Means* Labor and Tooling Cost Data, 1985.

Current productivities are listed in table 2.

As can be seen from these data, the potential savings to contractor due to the elimination of human labor through a robotic replacement can be substantial. Their magnitude will depend upon the extent to which the cost of human work performance can be eliminated by employing the cheaper work of the sandblasting robot.

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

- <u>Mobility and Maneuverability</u>: It will be provided by a tether or LED-guided mobile platform

Daily Output S_d (Sq. Feet)		Bare Costs: Material	Installation	Total	Total (incl. O&P)
Wet System min.	700	$0.08	$0.46	$0.54	$0.72
max.	1,700	0.12	1.11	1.23	1.67
Dry System min.	1,500	0.08	0.26	0.34	0.45
max.	3,000	0.12	0.52	0.64	0.85

Table 2: Construction Sandblasting *Means* Productivities and Unit Cost Data, 1985.

constituting a base for robot sandblaster mounted on top of it, with a positioning accuracy of +/- 2.5 cm. It is expected that a commercially available AGV platform will be used.

- Robot Arm Characteristics: The robot arm should be extendable up to 2.5 m. There is 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 4 degrees of freedom: one at the base, one at the elbow, pitch and yaw.

- 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.

- 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:

  - Sensory information processing (from LED, sonar, and reflectometer) for the motion command initiation

  - Speed and direction of platform travel

  - Speed and direction of the robot arm move

- Environment Sensing: will be performed by three types of sensors.

  - The light beams generated by the Light Emitting Diods (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.

  - 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.

  - Surface reflectivity meter will inspect the effect of the blasting process continuously and provide the information through its microprocessor to the on-board computer.

- Material Feed and Flow Control: A continuous, uninterrupted feed of sand and compressed air will be assured by microprecessors mounted in critical locations of the feeding system. The following sensors and microprocessors are considered:

- 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.

- 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.

- 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.

A diagram of a possible design appears in figure 3. 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 Diods (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.

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 at 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 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 removed from the work area.

Figure 2 illustrates the work flow.

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 robotic components necessary for the construction of the autonomous sandblasting machine are available on the commercial market in the U.S. and/or other industrialized countries. Most of them already constitute elements or segments of existing industrial robotics. With respect to the components specified above, there are in most cases several options from which to select the desired hardware and controls. Manufacturers' catalogs contain an overview of selected commercially available components applicable to the subsystems of the considered sandblasting robot.

The sandblasting robot would consist of the following components:

1. Mobile robotic platform. An autonomously guided vehicle available on the commercial market and subjected to slight modifications will be implemented. A selection of available vehicles is available from the manufacturers-supplied technical information.

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 fiexed 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 surface reflectometer as the work quality control device.

3. Power supply. A standard AC/DC power supply of approx. 1 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 hour battery for the operation of the electric engine should be feasible.

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. Six types of controls, supplied with microprocessors, will be used: sand dampness meter and control, sand supply control, air pressure control, vehicle position control, manipulator position control, and 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.

5 Cost Estimation of a Sandblasting Robot

Estimating the cost of roboticized sandblasting involves several levels of estimation. Each level is associated with different accuracy and uncertainty factors. These factors will considerably affect the reliability of the final cost estimate and must therefore be assessed on an individual basis.

Capital Cost

System components are either commercially available, or custom-built according to specifications which are 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.

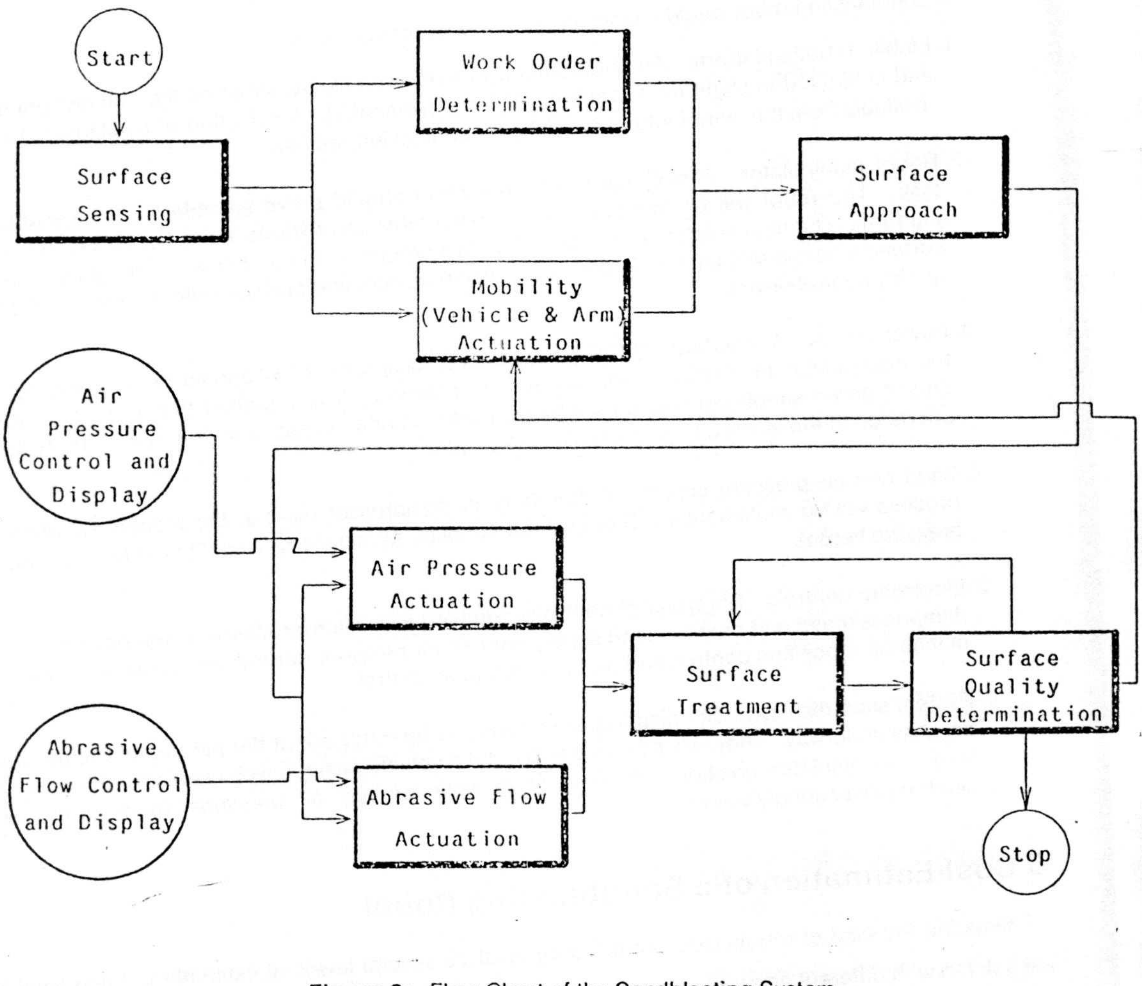

Figure 2: Flow Chart of the Sandblasting System.

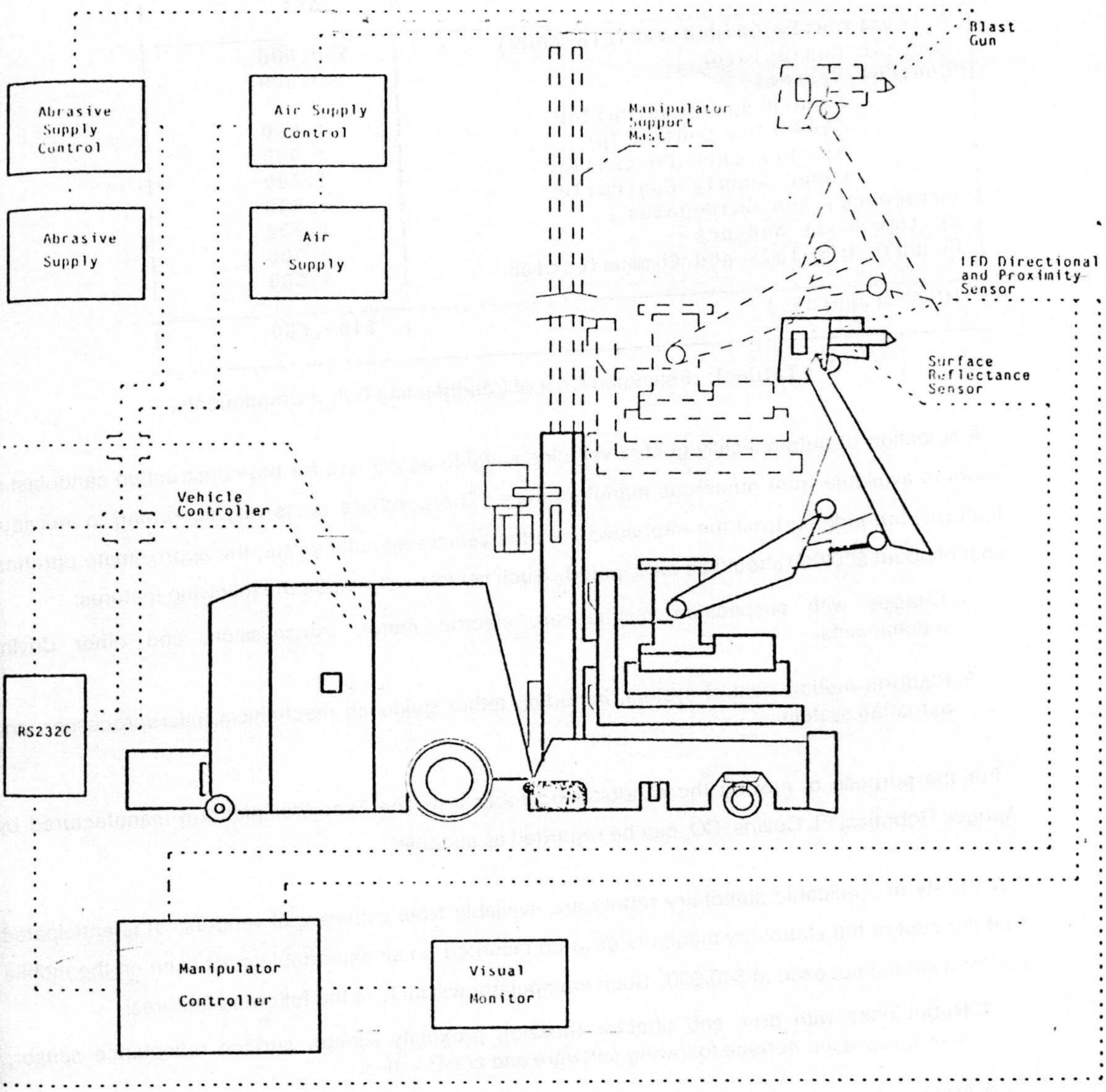

Figure 3: General Setup of the Sandblasting System.

Component	Cost
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 (approx.)	$100,000

Table 3: Estimated Cost of Sandblasting Robot Components.

A selection of automatically guided vehicles suitable as carriers for the construction sandblasting robot is available from numerous manufacturers. The purchase costs vary according to individual features, but judging from the interviews with the vehicle manufacturers, the approximate purchase cost of about $50,000 should be anticipated. Such vehicle will include the following features:

1. Chassis with suspension mechanism, electric motor, transmission, and other driving mechanisms.

2. Platform motion control system, including tether guidance mechanism, microprocessor, and actuating system.

For the purpose of moving the sandblasting robot arm, the *Expeditor* platform manufactured by Apogee Robotics, Ft. Collins, CO, can be regarded as suitable.

A variety of applicable stationary robots are available from commercial vendors. It is anticipated that the cost of the stationary manipulator to be mounted on an extendable mast fixed on the mobile platform should not exceed $40,000. Such manipulator will include the following features:

1. Robot base with arm, end effector (nozzle), proximity sensor, surface reflectance sensor, microprocessor, surface following software and accessories.

2. Motion control hardware and software for the manipulator.

The material supply solution will remain traditional, i.e. with the similar supply and distribution equipment as in the manual work method. The cost of this hardware can only partially be counted as part of robot hardware system, since most of the equipment should be adopted directly from the traditional, manual method. Certain additional hardware and control features will be, however, necessary for the incorporation into the robot system:

1. Hopper control: microprocessor based device to inform the main system control computer about the status of sand supply level, its dampness, consistency, and other physical properties. Such device can be set up from the commercially available hardware with the necessary accessories for approximately $1,000.

2. Abrasive flow control: microprocessor based device to detect the value of the abrasive (sand) flow in the hoses and at valve locations. Flow sensors and suitable microprocessors can be purchased for this system for approximately $900.

3. Air pressure control: a set of air pressure meters distributed in the crosspoints of the air delivery system and connected to the on-board microprocessor will constitute the air pressure control system. The set of air pressure meters with suitable electronics can be obtained for approximately $1,200.

4. Robot power supply: a standard power supply unit of approx. 1 kW should be suitable for driving the robot mechanisms. The power supply unit approximate cost can be regarded as $1,800.

5. Guidewires and guidepaths: a tether guidepath of the total length of approx. 200 m will be required for the site operation of the sandblasting robot. The hardware cost of the tether line can be regarded as $1,000.

6. Custom built sensors: surface shape and proximity sensors are required for the operation of the mobile vehicle. Also, for the quality of blasting control, a surface reflectance sensor is required. According to author's communications with sensor manufacturers, the total cost of these sensors should not exceed $2,000.

7. Graphic display and communication package: This is a feature necessary to provide easy human-machine interaction and current information about system parameters and states. A commercially available package suitable for this application is priced at approx. $5,000.

In addition to component costs, system engineering costs are also incurred. However, with modular development of a variety of surface finishing works, these engineering costs can be spread over several robotic applications. For example, surface tracking, positioning, and communications would be common to virtually all surface finishing applications. As a rough approximation, system engineering costs for a sandblasting robot would likely double the costs shown in table 3, depending on the extent of cost sharing among different systems and the extent of the robot market.[11]

Robot Operating Cost

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

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[11] M. Skibniewski: A Strategy for Engineering and Economic Evaluation of Robotics to Selected Construction Work Operations, unpublished Ph.D. Thesis (1986), Carnegie-Mellon Univ., Pittsburgh, PA 15213.

only those items which do not also represent the operating costs of the traditional, human-operated sandblasting equipment. The projected figures are contained in table 4.

ITEM	COST (per project)
Supervision Cost (1 Technician)	$1,250
On-Site Re-Programming and Adaptations	300
System Re-Setup (3 Technicians, 1 Day)	600
System Dismantling (2 Techn., 1 Day)	400
Electric energy (battery & power line)	300
Transport to New Work Site	500
Maintenance and Repair	400
TOTAL (approx.)	$3,500

Table 4: Projected Operating Cost of Sandblasting Robot.

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 hour, 300 A-h battery can be used. The life-time of such battery is expected to be 3 working seasons, thus its average cost per project can be approximated to $300 (incl. cost of re-loading).

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, and 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 uncertainty factor of 0.5 is assumed and approximated at $400 per project.

6 Benefit Estimation

Labor and Equipment Savings 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 d = 36 m and the height is h = 12 m. Thus, the side wall area S of the tank to be blast cleaned is approximately 1360 m² (14620 s.f.).

Labor savings accrued from the elimination of human operators can be calculated as follows:

Required max. work time (t_{max}) for a standard crew (see table 2)

$$t_{max} = \frac{S}{S_d} = \frac{1360\,m^2}{140\,m^2/day} = 10\ days$$

Bare labor costs (C_L) for the required crew of 4 laborers (see table 1)

$$C_L\ (minimum) = c_l \times t_{max} = \$496 \times 10\ days = \$4{,}960$$

This standard cost should be verified if the work is performed in extreme temperature, humidity, lighting, etc. Judging from the interviews with sandblasting contractors in the U.S. and W. Germany, the standard productivities used in establishing the norms on which the above calculation is based are usually lower than the actual ones experienced on difficult job sites such as the interiors of concrete storage tanks by approximately 50%. This implies a higher labor cost required to perform the example project in the amount of

$$C_L\ (corrected) = \$7{,}500$$

The implementation of the robotic sandblaster results in the elimination of the necessity to construct a substantial amount of scaffolding. Savings accrued due to its elimination depend on the height of the cleaned wall, the area to be covered with scaffolding, and the duration of its use. For the example project in question, a contractor-owned set of scaffoldings in the form of circular steel tubings and steel decks is assumed.[12] According to *1985 Means Cost Data, Masonry and Conrete Work*, the current cost of implementing own scaffolding for the performance of a site blast cleaning varies from approx. $136 to $272 per 1000 s.f. These costs imply that the average cost of building and maintaining a suitable scaffolding for the example project can be assumed as approximately $3,000.

Two additional major benefits can be derived from the elimination of human labor of blast nozzle operators: savings on the protective equipment (pressurized helmets with accessories, separate air compressor, suits, gloves, protective shields, etc.), and the elimination of the danger of exposure to silica sand abrasive. This danger is documented in OSHA literature. However, no consistent

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[12] For elevations over 16 m from the ground level, a swing suspended from the top of the structure is more suitable.

information enabling to estimate the monetary amount of this hazard is available.[13] Judging from conversations with sandblasting contractors, a consensus was reached that it is reasonable to assume that the total benefit of eliminating human exposure to silica abrasives can be regarded as 40% of current human labor cost. This implies the amount of monetary savings as approximately $3,000 per project.

Productivity Gains

A robotic machine is better equipped to perform ardous, repetitive work tasks, without lowering its output due to tiredness, temperature, humidity, dust, noise, and other relevant factors significantly affecting human work performance. It has been determined by Japanese system developers that the application of robotics to construction finishing tasks can lead to increased productivity. Examples of such improvements are *Kajima*'s Slab Finishing Robot and *Shimizu*'s Fireproof Spraying Robot SSR-2. Although this productivity advantage could be extrapolated onto the sandblasting robot, this benefit will not be regarded in this example analysis as a monetary gain, due to difficulties in predicting the correct estimate. In such case, it will serve as an additional argument for the attractiveness of the robotic alternative.

Extension of Work into Difficult Climatic Conditions

The substitution of robot for human labor will make it possible to perform sandblasting tasks in extreme temperatures. This fact is important due to possible expansion of work activity into extremely warm (e.g. over 30 deg C) or cold periods of the year.[14] Such expansion can generate more work volume and thus the increase in the net benefit from robot implementation. The estimation of this benefit depends on the geographic location of the work market (whether local or regional) and the current demand for sandblasting services.

For the purpose of the benefit estimation, it is assumed that the extension of work into extreme temperature periods generates a 10% increase in the business activity for each year, and thus a 10% increase in the monetary benefits incurred.

Table 5 summarizes the estimated benefits for the example project.

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[13] Only scattered data on compensation claims involving loss of workers' health due to silicosis incurred during the performance of site sandblasting work were found.

[14] Extension of activity into cold periods can be limited by technological constraints on the efficiency of air compressors and on the physical properties of the abrasive material. Details of these constraints are addressed in technical literature.

Benefits / Savings	Value (per proj.)
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 (approx.)	$15,500

Table 5: Estimated Benefits from the Example Roboticized Sandblasting Project.

7 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 developer's viepoint);

2. For the purpose of determining the attractiveness of its purchase (from contractor's viewpoint).

Each of these viewpoints is characterized by different philosophy and approach to estimating costs and benefits of undertaking the effort leading to robot application.

Let us assume a typical number of 10 projects per season (approximate number of projects for a medium-sized sandblasting contractor in Philadelphia, Pa. area, between 1980-1985). The cash flows resulting from the previous analysis are presented in table 6:

Season	Costs	Benefits	Net Cash Flow
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 6: Cash Flow Projections For the Sandblasting Robot.

<u>Net Present Value Analysis</u>

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 6. The approximate NPV values can be obtained (see table 7): Given the above data, *'Break Even'* points of the robot value can be determined. In other words, there is a treshold value assigned to the robot,

MARR	Net Present Value	Uniform Seasonal Value
10%	$148,500	$59,500
15%	124,000	54,500
20%	103,000	49,000
25%	84,000	43,000

Table 7: Net Present Value of Sandblasting Robot.

above which the machine would no longer be profitable under the given operational assumptions. These values are contained in table 8:

MARR	'Break Even' Value of Robot to Contractor
10%	approx. $300,000
15%	275,000
20%	250,000
25%	235,000

Table 8: 'Break Even' Value of Sandblasting Robot.

Values in table 8 indicate that the predicted purchase price of the sandblasting system in the amount of $150,000 should prove attractive. This indicates that the market performance for robot developer should be favorable.

8 DESIGN IMPLICATIONS - To be Written by Patrice

As an example, considering the specific development of robotic sandblasting of concrete work, the benefits which could be realized in the design aspect include:

- Design Variety: A roboticized sandblasting process, in its ability to be easiliy programmed to perform differing tasks, will allow for a variety of architectural decoration on the concrete surface within a single project.

- Quality Control: A roboticized sandblasting process will afford stricter control of the quality of finish on the concrete surface. An acceptable quality and tolerance can be decided at the outset with the confidence that such quality will be maintained without exception throughout the project. Such a process will also relieve the engineer and architect of much inspection work.

- Design Flexibility: A roboticized process will be easily reprogrammed in the event of a desired or necessary change to the surface finishing specification.

Thus, the introduction of a roboticized finishing process into the construction of large-scale buildings offers many design options and quality safeguards. Such options and safeguards can only result in a more exciting, better quality exterior surface on the buildings of the future.

MORE

9 Conclusions

- A multi-task surface finishing robot technically feasible;
- System costs and benefits difficult to estimate;
- However, expected substantial economic payoff.

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