Economic Analysis of a Robotic Construction Sandblasting Process

Miroslaw J. Skibniewski and Chris T. Hendrickson

Department of Civil Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213, USA

KEYWORDS

Robotics, Sandblasting, Surface Cleaning, Economic Analysis.

ABSTRACT

This paper introduces a methodology for evaluating the application of industrial robots to specific tasks performed currently by human construction laborers. A case study of robotized sandblasting is introduced. A routine for determining robot required capabilities and the technical feasibility of robotized work process with respect to the example application is presented.

The ultimately decisive factor for each successful robot application will be economic. The determination of the economic viability of each particular application requires a comprehensive analysis of resulting technical changes, their costs and benefits, and must reach in several dimensions. This paper summarizes the estimation of some of the projected robot costs and benefits. The costs are divided into robot hardware, software, control and system engineering. The benefits, with respect to the sandblasting application, are represented by the reduction in the health hazard of silicosis, labor savings, and work quality improvements.

As a method for determining the economic feasibility of the example application, a *Net Present Value* of the investment in robot is derived, based on the estimated costs and benefits.

Analyse Economique du Sablage dans la Construction, Utilisant des Robots

Miroslaw J. Skibniewski et Chris T. Hendrickson

Département de Génie Civil
Carnegie-Mellon University
Pittsburgh, PA 15213, USA

MOTS-CLES

Robotique, Sablage, Nettoyage des Surfaces, Analyse Economique.

SOMMAIRE

Cet article présente une méthodologie pour l'évaluation de l'impact de l'utilisation des robots industriels sur les travaux dans la construction relevant jusqu'ici des hommes. Une étude relative au sablage, est presentée. L'article présente une méthode systématique pour la spécification des fonctions du robot de même que pour l'étude de la faisabilité technique du processus de travail robotisé. On examine également les points communs ainsi que les différences relatifs aux fonctions requises du robot, inhérents au sablage.

Le facteur économique est déterminant pour aboutir à une utilisation à bon escient d'un robot. La détermination de la viabilité économique pour une tâche particulière se fera selon une approche multidimensionelle et recourra à une analyse synthétique des changements techniques qui résulteront ainsi que les coûts et profits qui découlent de ces changements. Certains des résultats concernant l'estimation des coûts et profits escomptés sont donnés. Les coûts se répartissent entre le matériel (robot), le logiciel, le système de contrôle et la planification globale du projet. Les avantages du sablage tiennent à la reduction du risque lié au silicose, l'économie réalisée sur le coût de la main d'oeuvre et à l'amélioration de la qualité du travail.

Une méthode pour la détermination de la faisabilité économique est presentée pour les cas d'utilisation nous concernant. Cette méthode s'appuie sur la *valeur nette actuelle* de l'investissement basée sur l'estimation des coûts et des profits.

Introduction

Sandblasting work in construction and in maintenance of buildings and other structures is a commonly applied surface restoration process worldwide. Sandblasting is a several million dollar a year business in a typical large U.S. or European city [1]. In addition to decorative applications, the largest volume of sandblasting works is the abrasive treatment of surfaces for corrosion removal and paint preparation. On-site sand blasting is possible because energy in the form of compressed air may be made available at any point on a surface. Sandblasting has some similarities to processes successfully automated in plants. In particular, sandblasting has the characteristic that an effector (nozzle) need only be positioned properly while the applied force (expansion of compressed air) operates. However, the dynamic and unstructured environment of construction sites makes robotic sandblasting challenging.

The productivity and work quality of existing sandblasting is largely affected by human factors. For example, existing U.S. work rules require one worker to watch the sand hopper while another operates the blast nozzle. 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 up to 70% of a 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 23 deg C. As can be appreciated from contractors' experience, operating conditions are often arduous, and with 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. Finally, there is enough medical and statistical evidence to support a claim that the sandblasting processes pose a substantial health hazard to human equipment operators in the form of life-threatening silicosis. Operators are require to wear cumbersome safety equipment, which effectively reduces their work productivity.

A few corporate and research organizations have gathered experience with system design efforts in regard to robotic sandblasting in construction-like environments. Several organizations have attempted to develop preliminary concepts for the necessary hardware, or have slightly advanced design work in the area, including *Ingolt Ship Building* of Pascaguola, Mississippi; *Hockett Systems of Florida*, located in Tampa, Florida; *R.T. Nelson*, a painting contractor from Oklahoma City, OK; *Wheelabrator Fry* of Indiana; and *Laser Technologies* of Dearborn, Michigan.

Sandblasting Robot System Design

A variety of system designs could be adopted for robotic sandblasting. One possible design is illustrated in figure 1, with the following features:

- Mobility and Maneuverability: Device movement will be provided by a tether or LED-guided mobile platform constituting a base for the robot sandblaster mounted on top of it, with a positioning accuracy of + /- 2.5 cm.

- 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.

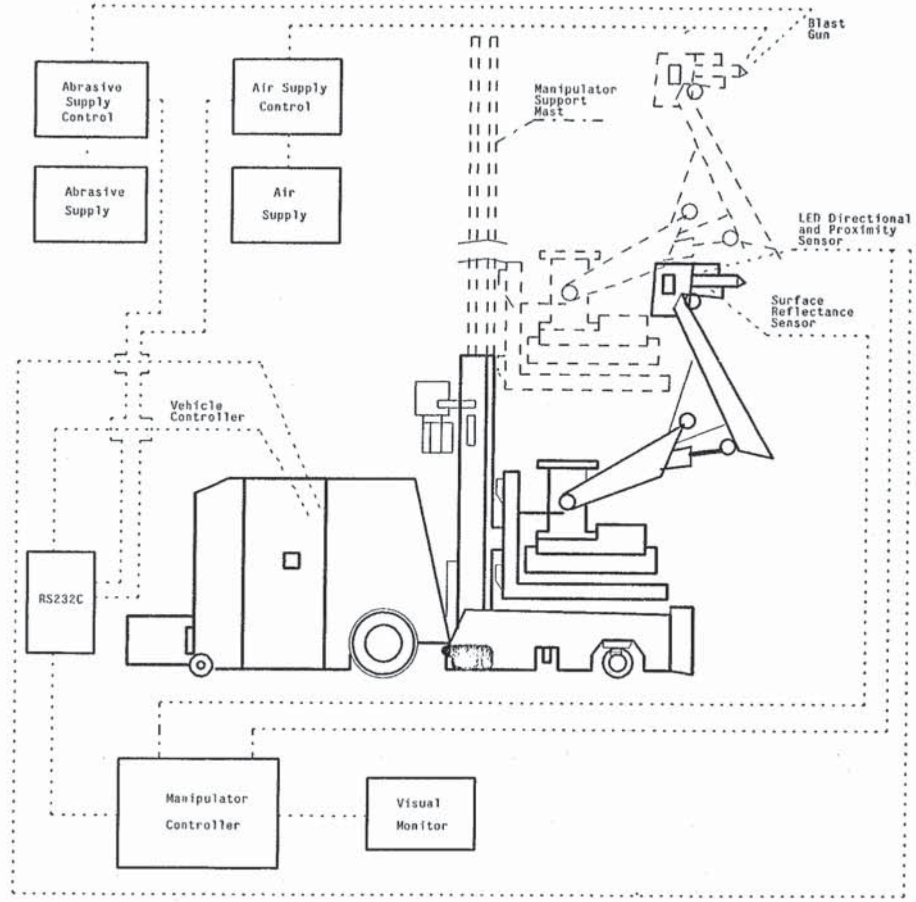

Figure 1: General Setup of a Proposed Sandblasting System.

- 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.

- 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; 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; and a surface reflectivity meter will inspect the effect of the blasting process continuously.

- 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 dampness meter, an air flow sensor, and blast air pressure sensor will be used.

These system features will allow general application of the robotic sandblaster to regular surfaces with good access. Additional design details appear in [1]. 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. Literature available from vendors contains an overview of selected commercially available components applicable to the subsystems of the considered sandblasting robot.

Capital Cost Estimation

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. The capital cost items can be divided into two major groups:

Robot component costs. These costs include purchase of the AGV, the stationary robot, the necessary control hardware, and other miscellaneous items [1]. These costs are characterized by a fairly high level of prediction accuracy. System components are either commercially available, or could be 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 1.

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. The cost estimation of the system engineering effort to introduce roboticized sandblasting work is a multi-stage process determined by the level of work system design. Each of these levels is characterized by a different estimation accuracy factor. The quantification of these factors goes beyond the scope of this paper. These factors can be determined either by the experience of previous robotic systems designs, or by a consensus of experts in system design strategies.

An extensive inquiry effort aimed at similar robot system developers has been undertaken [1]. The obtained results were only partially conclusive with regard to specific items on the system construction process schedule. The numerical data were obtained from several U.S. sandblasting contractors, as well as from a few Japanese construction companies, which have had relatively broad experience with the development of their own construction robotic systems for specific applications. As a general figure, an amount of $5,000,000 might be required for system design to be amortized over total sales of the sandblasting robot, which could double the purchase price.

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 1: Estimated Cost of Sandblasting Robot Components.

Operating Savings

For the purpose of estimating the operating savings 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 of the tank to be blast cleaned is approximately 1360 m^2 (14620 s.f.).

Blast Operator Labor Savings: Labor savings accrued from the elimination of human operators can be calculated as follows. First, work time for a standard crew is 1360 m^2 / 140 m^2/days = 10 days, where the standard productivity rate is reported in [2]. Thus, labor cost (C_L) for the required crew of 4 laborers is $496 * 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.

Work Quality: There is a strong expectation that the application of robotics to the performance of construction sandblasting will ultimately result in a substantial improvement in the overall quality of work. It is difficult at the present time, however, to quantify the benefits derived from this improvement in monetary figures. These data will be available as soon as the field application of sandblasting robots is introduced. A methodology for estimating the increased work quality benefits after the introduction of robotics to the field work is presented in [1]. For this example estimation, the benefit derived form work quality improvement will be neglected.

Savings Due to Elimination of Scaffolding: The implementation of the robotic sandblaster results in the elimination of the necessity to construct a substantial amount of scaffolding. Savings depend on the height of the cleaned wall, the area to be covered with scaffolding, and the duration of use. For the example project, contractor-owned scaffoldings in the form of circular steel tubings and steel decks is assumed; for elevations over 16 m from the ground level, a swing suspended from the top of the structure is more suitable. The average cost of building and maintaining a suitable scaffolding for the example project is approximately $3,000.

Eliminated Risk of Silicosis: Two 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 publications collected by OSHA [3][4]. However, no consistent information enabling to estimate the monetary amount of this hazard is available. Only scattered data on compensation claims involving loss of workers' health due to silicosis incurred during the performance of site sandblasting work were found. Judging from interviews with sandblasting contractors, 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, including special equipment and health effects. This implies the amount of monetary savings as approximately $3,000 per project.

Productivity Gains: 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 [5][6]. 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. 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.

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. Of course, 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. However, some 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 was established through verbal communications with contracting firms that the extension of work into extreme temperature periods can generate a 10% increase in the business activity for each year, and thus a 10% increase in the monetary benefits incurred. Table 2 summarizes the estimated benefits for the example project. Against these costs are set the extra robot operating costs. 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 [1]. Relevant data has been obtained by the authors from the robotic application experience of *Sperry-New Holland Co.* The projected cost data for the sandblasting robot presented here include only those items which do not also represent the operating costs of the traditional, human-operated sandblasting equipment. The projected figures, based on the interviews with robot application practitioners in the manufacturing industries who are also familiar with the construction work environment are contained in table 3.

Benefits / Savings	Value (per proj.)
Operator Labor	$7,500
Scaffolding Elimination	3,000
Health and Safety	3,000
Work Quality	750
Productivity Gain	0
TOTAL (approx.)	$14,000

Table 2: Estimated Benefits from the Example Roboticized Sandblasting Project.

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 3: Projected Operating Cost of Sandblasting Robot.

Net Present Value Estimation

A robotic sandblaster is only advantageous if benefits to a user outweigh costs. In this section, we develop a net present value calculation for purchase of a robotic sandblaster. Let us assume a typical number of 10 projects per season; this is the approximate number of projects for a medium-sized sandblasting contractor in the Philadelphia, Pa. area, between 1980-1985. The cash flow resulting from the previous analysis would be a net benefit of $120,000 in each year of operation. Based on three years of operation, the *'Break Even'* points of the robot value can be determined, representing a treshold value above which the machine would no longer be profitable under the given operational assumptions. For an interest rate (minimum attractive rate of return) of 10%, the value of operating savings is $300,000; at a 25% MARR, the value is $235,000. These values indicate that the predicted purchase price of the sandblasting system in the amount of $200,000 should prove attractive. This implies that the market performance for a robot developer should be favorable, as long as several hundred units can be sold per year.

Conclusion

In this paper, we have described a general system design for a sandblasting robot, developed system costs, and estimated operational benefits. Our conclusion is that a roboticized sandblaster can be both technically and commercially viable.

References

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

[2] Means Construction Cost Data, 1985 issue.

[3] F. Blaizot: Workplaces Exposed to Silicosis in Building and Civil Engineering in the Paris Region, *Cahiers des Comites de Prevention du Batiment et des Travaux Publics*, April 1975, No. 2, pp. 85-88.

[4] B. Samimi, M. Ziskind, H. Weill: Relation of Silica Dust to Accelerated Silicosis, Ecotoxicology and Environmental Safety, March 1978, Vol. 1, No. 4, pp. 429-436.

[5] S. Suzuki, Construction Robotics in Japan, *Third International Conference on Tall Buildings*, Chicago, 1986.

[6] T. Yoshida and T. Ueno: Development of a Spray Robot for Fireproof Treatment, *Shimizu Technical Research Bulletin*, March 4, 1985.

A Comprehensive CAD-CAM Prefabrication System

A. Warszawski
Head, Building Research Station
Technion - Israel Institute of Technology
Haifa 32 000, Israel

KEYWORDS

Computer-aided-design, Computer-aided-manufacturing, Construction, Robotics.

ABSTRACT

The full benefits of prefabrication has not been realized to date due to communication problems between a designer and a contractor/precaster with a specific prefabrication system. A considerable portion of building construction works, even with prefabrication systems, is performed usually on site at low productivity.

These problems can be alleviated by an introduction of a comprehensive CAD-CAM system. The objective of the system will be to allow a maximum design freedom to an architect, even in relatively small building projects with minimum extra design and resources adjustment cost at the prefabrication plant.