Development of a New Dimension and Computer-Aided Construction System for Shotcreting Robot

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ABSTRACT

This paper addresses the improvement of the semi-automated shotcreting robot. The arm of the robot has six degree of freedoms and is remotely controlled by the operator using a control box with six sticks and three buttons on the board. However, based on the results of utilization, the concurrent model has two major drawbacks for the job site practice: (1) the control board has too many joint sticks and buttons for the operator to control, (2) due to the poor visibility, the operator is hard to place the nozzle to the spraying position. According to the problems addressed, an improving plan is developed and classified in two stages: First, the control system of the semi-automated robot is improved by reducing the number of joint sticks from six to two. To reduce the development cost and risk, a real time computer simulation model is developed to identify the feasibility of the proposed model. In the second stage, the robot is improved from semi-automated to fully automated. An automated profile measuring instrument is used to measure the excavation surface. Based on the measurement, the simulation model calculates and identifies the path of nozzle for shotcreting. The automated shotcreting robot is achieved by integrating the graphical model with the robot control system.

1. INTRODUCTION

Shotcrete containing coarse aggregate has been successfully used for many years in mining and tunnel construction as primary support and finishing lining. Investigations showed that lining of rock tunnels with shotcrete combined with other measures such as rock bolts, reinforcement mesh, or light rebar trusses would be more economical and would also minimize the hazard of construction under adverse rock conditions. Thus, typical shotcrete designs were developed for the permanent support of rock tunnels. In construction, the concrete has to be placed immediately after mucking up, and before the next round could be drilled. To speed up the driving operations, collapsible steel forms are used and the concrete is placed using pumps.

Conventionally, shotcrete is manually operated by the nozzleman. The operators are subjected to high concentrations of noise, dust, rebound, causticity, poor visibility, and poor footing. The nozzleman experiences the worst conditions while handling the shotcreting nozzle. Hence, the replacement of the human handling with the semi-automated shotcrete machine can not only improve the construction progress and reduce professional harm, but also increase the construction efficiency and quality.

This paper addresses the improvement of the semi-automated shotcreting robot. The prototype of the robot is a hydraulic spraying arm model for placing shotcrete in tunneling and mining operations. The arm of the robot has six degree of freedoms and is remotely controlled by the operator using a control box with six sticks and three buttons on the board. The replacement of the manual spraying method with the robot shotcreting significantly improves the construction productivity and working place hygiene for the nozzle operator.

2. RESEARCH PURPOSES AND OBJECTIVES

The primary purpose of this paper is to improve the semi-automated shotcreting robot. The objectives required to achieve the primary purpose are the following: (1) apply the shotcreting robot to replace the manual spraying method, (2) improve the prototype shotcreting robot to increase construction efficiency, (3) use computer simulation to reduce the development cost and risk for the robot, and (4) employ graphical animation model for in-house training.

3. IMPROVING PLAN AND PROCEDURES

When an automated construction equipment developed from manufacturing, it may not be suitable for all job site conditions. For the needs of utilization, the prototype robot is required to make some adjustments and modifications. The plan and procedures to improve the prototype robot are described as follows: (1) investigate the drawbacks of the concurrent model, (2) propose an improving plan, (3) develop a real-time 3D computer model for graphical simulation and animation, (4) improve the prototype, (5) apply for field test, and (6) employ the animation model for in-house training.

3.1 CONCURRENT MODEL

The first generation of the model is a multi-joint arm robot with eight degree of freedoms (Figure 1). Due to the complexity of operation and control, the robot is modified to the concurrent model (Figure 2a). The second generation of the robot arm has six degree of freedoms and is remotely controlled by the operator using a control box with six joint sticks and three buttons on the board. A pivot drive with pedestal forms the connecting element between the spraying arm and the carrier vehicle. Figure 2b shows the control board of the concurrent model. The pivot drive controlled by Rod 6 can be rotated 360° in y axis while the solid arm system controlled by Rod 1 is made to rotate 270° around z axis (tunnel axis).

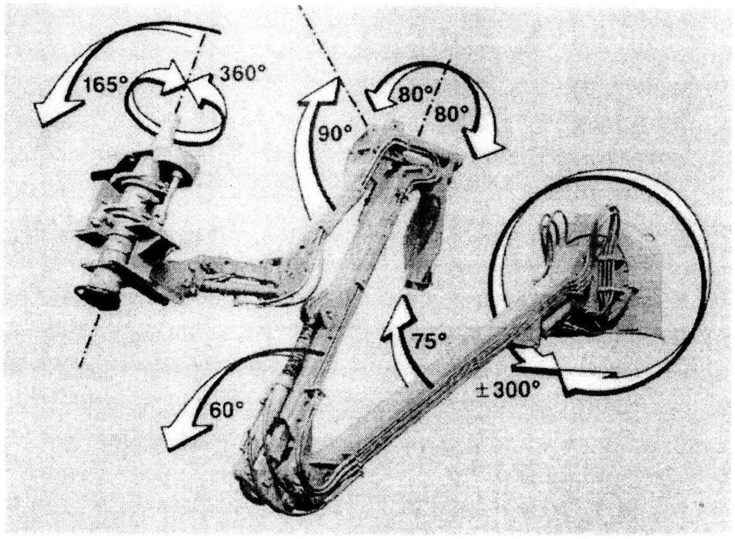


Figure 1 Shotcreting Robot Prototype

In Figure 2a, the solid arm system consists of three arms, four joints, and one spraying head. Based on z axis, Arm I is controlled by Rod 2 and can be rotated in x axis for downward 30° and upward 45°. Arm III controlled by Rod 3 is a telescopic lance for additional horizontal displacement of the nozzle to 1.7 meters maximum. Along vertical axis, Arm II controlled by Rod 5 can be rotated back and forth for 30° around x axis. Likewise, Rod 4 controlling the spraying head is made to rotate the spraying head up and down for 22.5° in x axis. The buttons are the switches of the control board and the spraying of shotcrete.

The second generation of the robot is still too complex for the operator to control. Thus, the requirement of a skilled operator becomes critical to manipulate the machine properly. Also, operator training is another problem that has to be solved for applying the robot. Concluding the results of utilization, the concurrent model has two major drawbacks for the job site practice : (1) the control board has too many joint sticks and buttons for the operator to control, (2) due to the poor visibility, the operator is hard to place the nozzle to the spraying position.

3.2 IMPROVING PLAN

According to the problems addressed, a plan is developed and classified in two stages to improve the concurrent model. So far, the first stage of modification is completed and the second stage is underway. In the first stage, the model is investigated and a proposal is developed to improve the robot based on the results of the field practice. The control system of the semi-automated robot is improved by reducing the number of joint sticks from six to two. Figure 1c shows the improved control board. Rod B replaces the functionality of Rod 3. Rod A combining Rod 1, 2, and 5 of the original board can be controlled in four directions. In vertical direction, Rod A controls the height of the solid arms. The principle

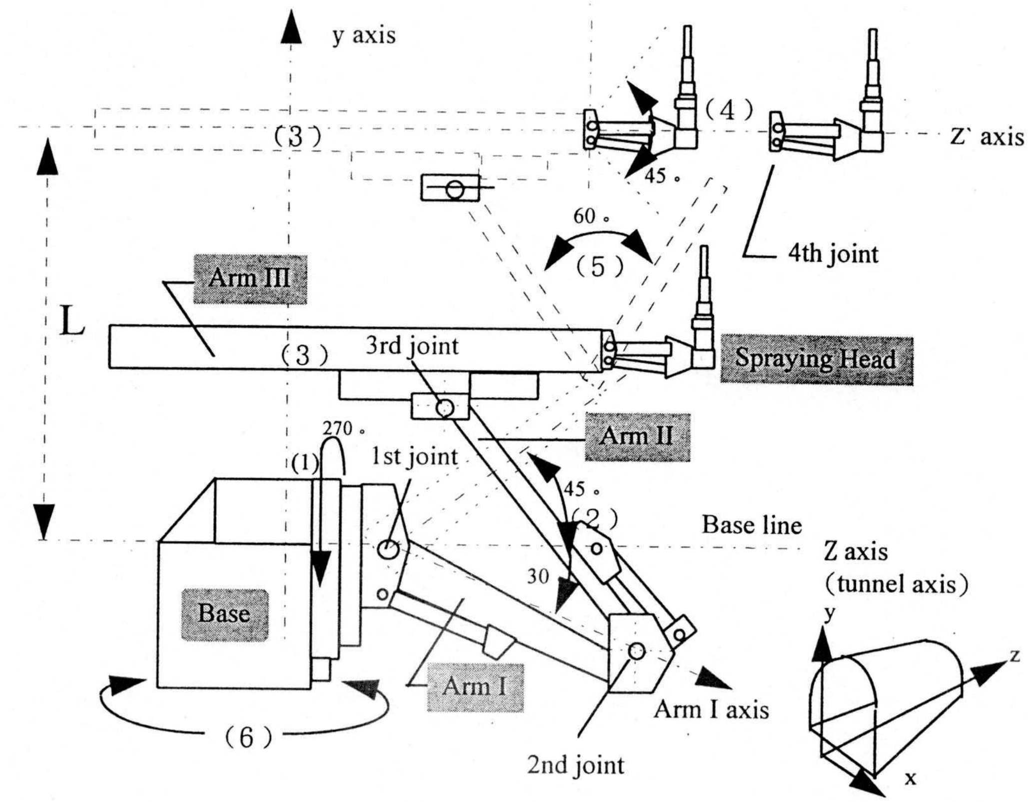
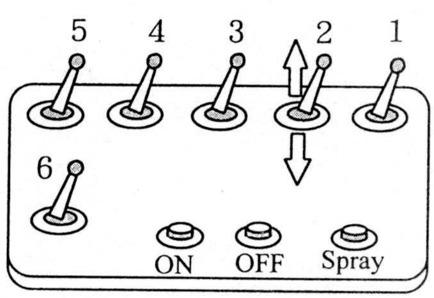


Figure 2 (a) Mechanisms of Spraying Arm



Rod 1 270 ∘ Arm I Rotate around Z axis
Rod 2 75 ∘ Arm I Rotation along X axis
Rod 3 1.7M Telescopic Lance
Rod 4 45 ∘ Spraying Head Rotation in X axis
Rod 5 60 ∘ Arm II Rotation along X axis
Rod 6 360 ∘ Base Rotation along Y axis

Figure 2(b) Original Control Board

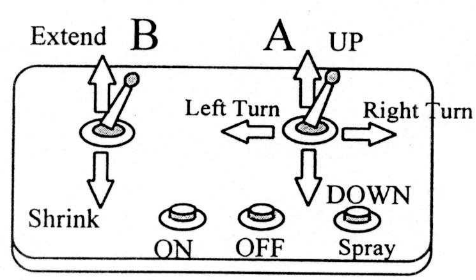


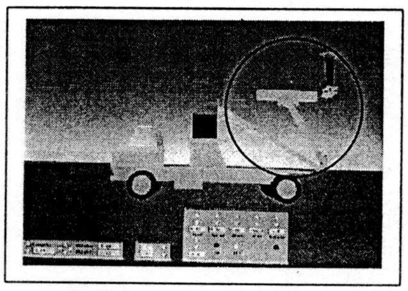
Figure 2(c) Modified Control Board

of moving arms is always to keep Arm III horizontal. Arm I, II, and III are combined as a related unit. When Arm I lifts one degree in counter clock direction, Arm II rotates in clock direction for one degree and Arm III rotates simultaneously in counter clock direction for one degree. In horizontal direction, Rod A replaces the function of Rod 1 which can rotate the solid arm 270° around tunnel axis. To reduce the development cost and risk, a real time computer simulation model is developed to identify the feasibility of the proposed model. The graphical animated model is applied for in-house training after the improved model is completed.

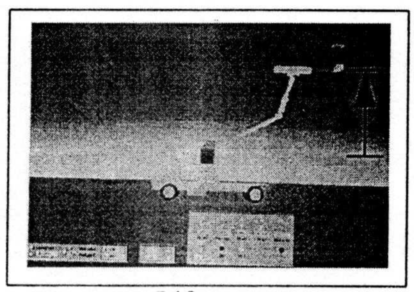
In the second stage, the robot is improved from semi-automated to fully automated. An automated profile measuring instrument is used to measure the excavation surface. Based on the measurement, the simulation model calculates and identifies the path of nozzle for shotcreting. The automated shotcreting robot is achieved by integrating the graphical model with the robot control system.

3.3 COMPUTER GRAPGICAL SIMULATION AND ANIMATION

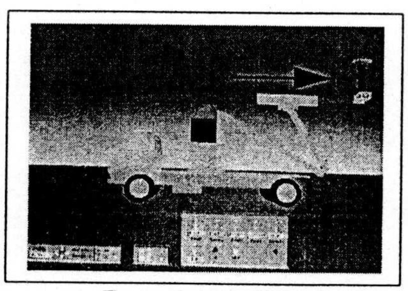
The main purpose of developing a computer simulation model is to identify the feasibility of the proposed model before the plan commences. Besides reducing the development cost and risk, the animated model can also be used for in-house training. Through simulation, the imagination is transformed to a reality and the standard process of shotcreting can also be established. Moreover, it is one of the best ways for the nozzleman to understand the shotcreting process and learn how to manipulate the robot. Figure 3 shows the animated model. The model was developed on SiliconGraphics workstation using ModelGen software to create the 3D model and PERFORMER software to animate the model. The development procedures are described as follows (Figure 4):



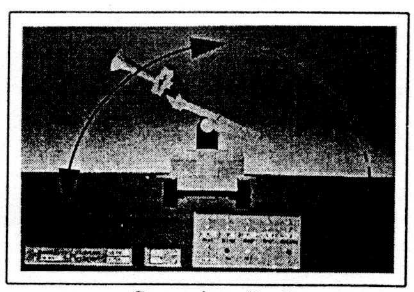
Solid Arm in Position



Lift Arm



Extend Arm III



Spraying Path

Figure 3 Graphical Animated Model

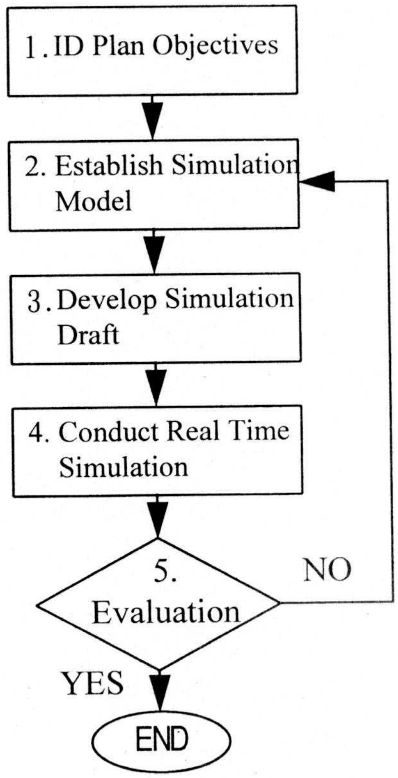


Figure 4 Development Procedures for Graphical Simulation Model

Identify the plan objectives: the mechanisms of the arm motions and control system are first investigated before the improvement of the model. Secondly, to achieve the objectives of increasing the arm's energetic and ease for control, the moving path of the arm motion is studied. Thirdly, a graphical simulation model is developed to verify the feasibility of the improved plan and also identify the potential problems in advance.

Establish the simulation model: the hierarchy of the robot mechanisms is first established and broken down into different levels to create the robot geometry database. The relationship between different layers is a master and slave relation. The higher entity is the master of the following entities (slaves). As the master moves, the slavery entities also move relatively to keep the arm as one unit. After identifying the mechanisms of the solid arm and the relative coordinate for each mechanism, mathematics functions for each mechanical motion are established to assure the movement of the mechanisms as planned.

Develop the simulation draft: the simulation draft is developed according the construction process of the field practice. The sequence of the robot movements is defined for conducting the simulation. Also, considering the complexity of the site conditions, the robot can be controlled by the boards in a real time bases.

Conduct the real time simulation: the scene of the site is created and the initial position of the robot is determined to conduct the shotcreting simulation. The control board of the concurrent model and the modified board are parallelly connected and placed on the screen. Hence, if some of the angles and positions that the arm couldn't reach using the modified board, the original board can be applied to fill the gap.

Evaluate the model: based on the cycle of plan, do, check, and action, the model is repetitively evaluated and modified to assure that the expected objectives are achieved.

3.4 IMPROVED MODEL

The arm mechanisms and control system of the robot are modified after the improving plan is verified according to the simulation results. Figure 2a and 2c show the improved model and control board. The principle of operation is based on the parallelogram system. The solid arm system is made to rotate around the tunnel axis, permitting the placement of the shotcrete over the entire tunnel section and in the invert area. Thus, the controlled guidance of the nozzle is facilitated. Automatic spraying movement can be used to achieve a uniform application of shotcrete at high placing rates.

3.5 FIELD TEST

This section presents the results of the field test. The improved shotcreting robot was tested in San-I tunnel project for Taiwan Railway Administration. Ret-Ser Engineering Agency designed and built the project with a turnkey contract. A comparison of the improved model versus the prototype was conducted by identifying the advantages of applying the modified robot in shotcreting. The advantages of the improved robot include:

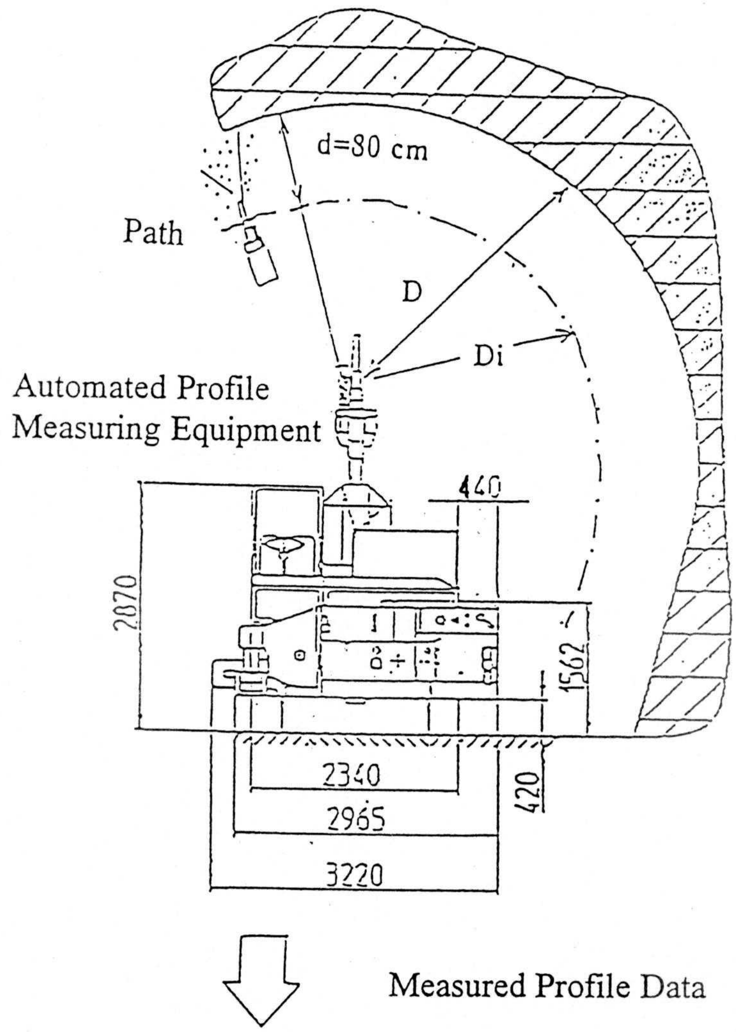
1. The path of the arm motions is better and more easy to control.
2. Due to the simplicity of the control board, the nozzleman can easily learn how to manipulate the machine in a short period of time.
3. The construction productivity of shotcreting is significantly increased.
4. The safety and hygiene of the working environment are improved.

3.6 IN-HOUSE TRIANING

The animated model is applied for in-house training after the robot is improved. Operators can learn how to control the machine through the simulation of the computer model. Through repetitive practice, errors and unexpected risks caused by the nozzleman can be decreased to a minimum. Conducting simulation, operators can manipulate the robot for different job site conditions and training cost is reduced.

4. AUTOMATED SHOTCRETING ROBOT

Currently, the first stage of improvement of the shotcreting robot was completed. The second stage is underway to improve the robot from semi-automated to fully automated. To achieve the objective, an automated profile measuring instrument is applied to measure the excavation surface (Figure 5). The survey instrument is placed on the spraying head. Considering the effects of airborne dust and rebound, the measuring equipment will be removed from the spraying head before shotcreting commences. The coordinates of the excavation surface are identified and stored as a spreadsheet in a PC. The contents of



Shotcreting Path Table

Angel	Distance D	Vertical Projection Y	Horizontal Projection X	Spraying Path Di=D-d
0.00	3.29	3.10	3.29	2.49
3.60	3.38	3.31	3.38	2.58
7.20	3.55	3.55	3.52	2.75
10.80	3.58	3.77	3.516	2.78
...	...	...	...	...

d=0.8m

Figure 5 Path Planning for Automated Shotcreting Robot spreadsheet including angle, distance, and coordinate projection in vertical and horizontal directions are transferred to the workstation. Based on the results of measurement, the simulation model calculates and identifies the path of nozzle for shotcreting. Then, the robot sprays shotcrete according the path identified. The automated shotcreting robot is achieved by integrating the graphical model with the robot control system. Figure 6 describes the automated shotcreting process. The length of each excavation unit for shotcreting is 3 meters and the width for each spraying round is 50 cm. Thus, the robot has to spray six rounds for each excavation unit.

5. CONCLUSIONS

The objectives of this study are achieved by reducing the number of control sticks for shotcreting robot from six to two. According to the results of field test, the control mechanisms are improved and the learning curve for training is reduced. A real time animated model is proved to be very useful in the development of a robot. Through simulation, operators can test and manipulate the robot for different job site conditions. The simulation model can be used for in-house training as the model completed. Using robot, the hazardous and time-consuming scaling operation can not only be avoided, but more importantly, the risk of a cave-in, triggered by the removal of "key-stones", is eliminated. Thus, the replacement of the manual spraying method with the robot shotcreting significantly improves the construction productivity, safety, and working place hygiene for the nozzle operator.

6. REFERENCES

1. ACI, "Guide to Shotcrete", Reported by ACI Committee 506, 1985.
2. Alberts C., "Use of Remote Controlled Spraying Nozzle", Proceedings of the Engineering Foundation Conference, pp. 65-78, Maine, 1973.
3. Alberts C., Kramers M., "Swedish Shotcrete Equipment and Developments in Fibrous Shotcrete", Proceedings of the Engineering Foundation Conference, pp. 254-268, Maryland, 1976.
4. Bawa K.S., "Development of Shotcrete for Metro Construction in Washington", Proceedings of the Engineering Foundation Conference, pp. 33-49 , Maine, 1973.
5. Bates R.C., "Shotcrete Safety and Environmental Control", Proceedings of the Engineering Foundation Conference, pp. 130-142, Maine, 1973.
6. Black H.S., "Modulation Theory", Van Nostrand, Princeton, N.J., 1955.
7. Couch II L.W., "Digital and Analog Communication Systems", Macmillan, New York, 1987.
8. Jordan E.C., "Electromagnetic Waves and Radiating Systems", Prentice-Hall, Englewood Cliffs, N.J., 1950.
9. Schwartz M., "Telecommunication Networks: Protocals, Modeling, and Analysis", Addison-Wesley, Reading, Mass., 1987.
10. Schwartz M., "Information Transmission, Modulation, and Noise", 4th edition, McGraw-Hill, New York, 1990.

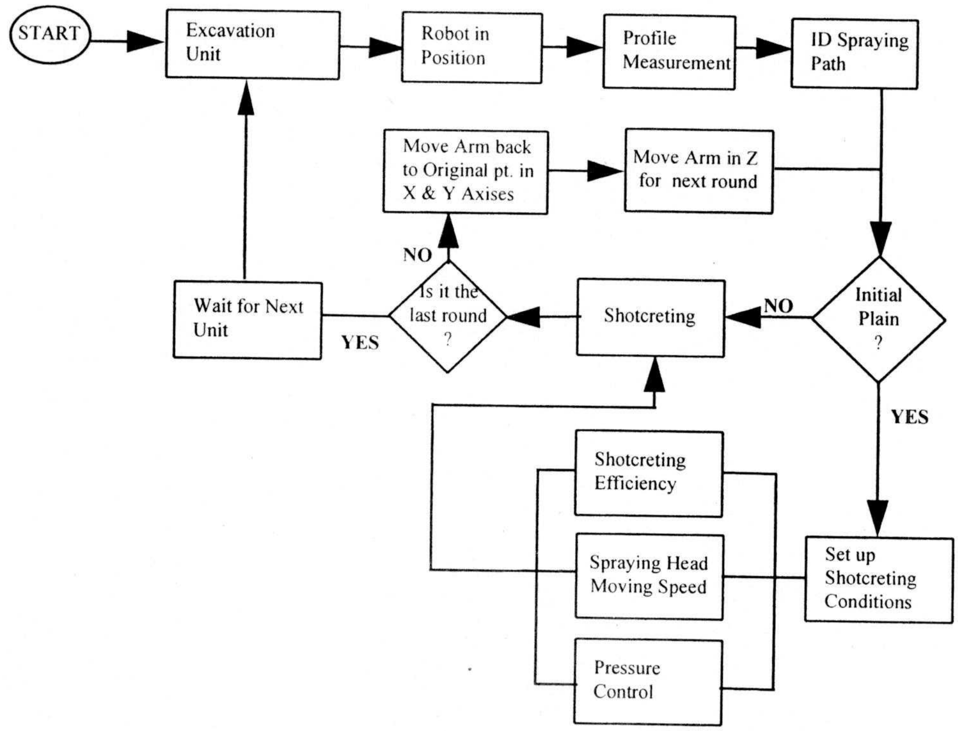


Figure 6 Automated Robot Shotcreting Process