Robotic Machine for High-Quality Shotcreting Process

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Abstract

This paper summarizes the development of the technologies used to produce high quality sprayed concrete layers by robotizing a commercial shotcreting machine and automating the process used in the tunnelling construction industry. The proposed method provides the control system with the information of the properties of the pumping process, controlling the quality of the concrete layer by adjusting in real-time the trajectory of the shotcreting machine. Given the unstructured nature of the tunnelling construction method there is an inherent difficulty in the automation of the shotcreting process. A complete description of the implemented control architecture of the shotcreting machine, the automated shotcreting process, the real-time quality layer prediction and the analysis of the tests made in real sites are shown in this paper.

1 Introduction

In the underground construction branch of civil engineering and mining there are different types of tunnelling methods, and one of the major ones, known as drill & blasting, often include the process of concrete spraying -or shotcreting- process. This tunnelling method consists of three main stages: Drilling and blasting, loading and hauling of blasted rock and supporting of the newly open cavity. In the third step, shotcreting is often the method of choice for providing temporary support.

This process consists on spraying concrete mix on the surface of the new cavity, quickly creating a supporting structure. The shotcrete surface can be used as temporary support until a final concrete lining is cast, or even as the final lining of the tunnel if additional structural shotcrete is added.

Nowadays, for performing the shotcreting process specialized machinery is controlled by qualified operators, which create shotcrete layers of specific properties based on their experience. The properties and the quality of the layer depend on the type of the lining needed, and basically the quality of the layer is measured in terms of homogeneity and thickness. In the last years there has been an increasing interest on the real time determination of both the homogeneity and thickness of shotcrete layers. There are both technical and economical reasons that justify this interest: On the one hand there is the need of guaranteeing a minimum shotcrete thickness [1], while having the minimum required structural strength. On the other hand, contractors also do not want to place extra shotcrete on the walls, for usually they will not get paid for it.

Additionally the development of different acquisition technologies during the past few years has made plausible the introduction of automation techniques in the underground construction process. Different approaches have been described for shotcreting automation and thickness estimation [2][3][4]. The proposed method provides the control system with the information of the properties of the pumping process, controlling the quality of the concrete layer by adjusting in real-time the velocity of the trajectory of the shotcreting machine.

Figure 1 Sika®-Putzmeister PM-407 [5].

The industrial machine Putzmeister-Sika® PM-407 (see Fig. 1) has been used as a test platform for the development of the shotcrete automation.

2 Process automation and control system of the shotcreting machine

In tunnelling, after the advancement (drilling and blasting) stage, shotcrete is used to cover the surface of the roadway to create a support on the working area inside the tunnel. The advancement stage is made by introducing explosives in the face of the tunnel and making a controlled blast. But, as controlled as the blasting can be, the dimensions of the resulting surface are completely unstructured and thus, one of the implicit difficulties involved in the shotcreting process that has avoided its automation.

Three steps have been defined for the automated shotcreting stage:

1. Pre 3D LADAR scan of the working area.
2. Automated shotcreting process.
3. Post 3D LADAR scan and layer quality evaluation.

The first step of the automated process is basically done by imaging the working surface of the tunnel with a 3D LADAR scanner (the LIDAC-16 developed by AITEMIN). The information acquired from the first scan is then used by the main control system of the machine to generate the trajectories to shotcreting a layer. Finally a second scan is made in order to evaluate, subsequently, the quality of the layer and the amount of concrete used. This information can also be used to optimise the control parameters of the automatic shotcreting system.

2.1 Robotization of the shotcreting machine

The shotcreting machines are based on manipulators that as an end tool they have a nozzle to spray the concrete fed by a concrete pump. It is to be noted that the best way to spray the starting mix into a wall is by keeping the spraying vector perpendicular to the surface of the selected area, at a certain distance that may vary between 1 and 1.5m.

Furthermore this type of machinery hasn't been designed for automation purposes but for manually controlled labour. This implies that some additional factors like mechanical deformations, backlashes, or the control type of the actuators have to be taken into account in the control system of the machine for precise positioning.

The proposed control system has been designed to use the real-time layer thickness estimator and the roadway geometry information to feedback and adapt the trajectory control according to the conditions in order to produce high quality concrete layers.

2.1.1 Mechanical configuration of the manipulator

The arm of the shotcreting machine is made of 5 degrees of freedom (DOF) of hydraulically actuated joints (see Fig. 2). The first three are configured as a spherical manipulator (2 rotational and 1 prismatic joint), and the last two rotation joints from the end tool, are specially configured to help the operators to maintain a certain orientation without having to move many joints simultaneously.

There is an additional sixth joint at the end of the tool that generates an eccentric rotation of the nozzle. This joint was originally design to help the operators to increase the smoothness of the spraying, but it is not going to be taken into account for automatic control purposes and it is considered the nozzle in the centre.

Another property of the system is that it is only possible to control the velocity of the first two DOF according to the control type of its hydraulic valves (see Table 1). The rest of them they just have on/off valves. This configuration affects the way the velocity of the movement of the manipulator is controlled (as explained later in section 2.1.2.2).

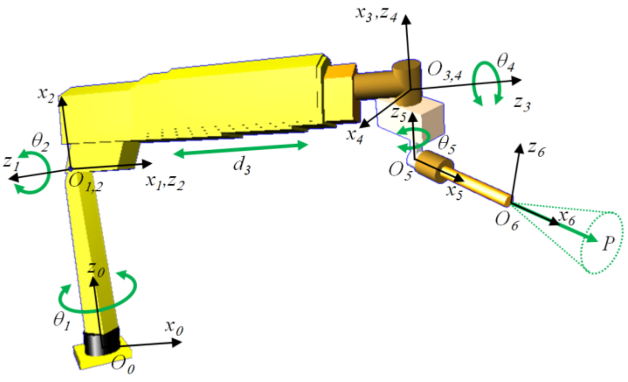
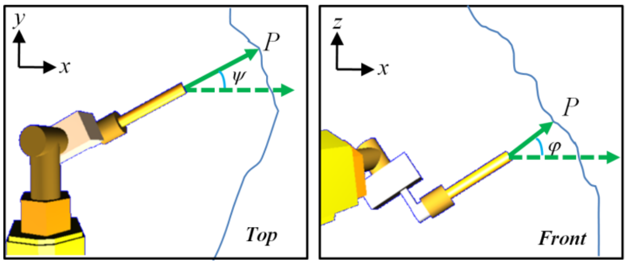


Figure 2 D-H configuration of the PM – 407 manipulator.

Table 1 D-H Parameters for shotcreting manipulator.

Joint *i*	α_i	a_i	θ_i	d_i	**Ranges**	**Control Type**
1	$\pi/2$	$-a_1$	θ_1	d_1	-158° - 171°	Proportional
2	$\pi/2$	0	θ_2	0	19° - 154°	Proportional
3	0	a_3	0	d_3	0 - 2094 mm	On/Off
4	$\pi/2$	0	θ_4	0	0 - 360°	On/Off
5	0	0	θ_5	$-d_5$	-47° - 204°	On/Off
6	0	a_6	0	0	-	-

The direct kinematics of every joint is known by applying the Denavit-Hartemberg [6] convention, according to the joint configuration (see Table 1), where the target position will result by adding to a_6 the desired distance between the nozzle and the tunnel surface (*r*). But to control the manipulator in position, velocity and orientation according to desired target position vector (*P*), by evaluating its inverse kinematics, some details have to be taken into account.



a. b.

Figure 3 Yaw (ψ) and pitch (φ) angles of the nozzle during spraying. a) Top view and b) Front view.

First of all, $P(O_{6r},R(\psi,\varphi))$ is a vector defined by two elements, the position (X, Y and Z) of and the attitude (ψ,φ) for the target of spraying; this elements are specified according to the coordinate system of the origin of the manipulator (O_o) (see Fig. 3), and they are provided by the LADAR system.

The inverse kinematic problem has been solved using the decoupling technique [7]. As in this problem O_6 and the orientation of the nozzle are known, it is possible to solve the position and orientation of the nozzle by evaluating O_5 using an analytical approach by the given equation:

$$x_5 = \quad x_6 - (a_6 Cos(\varphi) * Cos(\psi))$$
$$y_5 = \quad y_6 - (a_6 Cos(\varphi) * Sin(\psi))$$
$$z_5 = \quad z_6 + a_6 Sin(\varphi)$$

The inverse kinematic problem must proceed finding O_3. Given the fixed distance $O_{63} = sqrt(a_6^2 + -d_5^2)$ and its orientation $\gamma = atan(-d_5, a_6)$, O_3 can be directly solved by the equations:

$$x_4 = x_3 = x_6 - (O_{63} Cos(\gamma + \varphi) * Cos(\psi)),$$
$$y_4 = y_3 = y_6 - (O_{63} Cos(\gamma + \varphi) * Sin(\psi)), \text{ and}$$
$$z_4 = z_3 = z_6 + O_{63} Sin(\gamma + \varphi).$$

Then, the three first parameters can be evaluated just with the position of O_3, indeed $\theta_1 = Atan(O_{3y}, O_{3x})$. In this case there is just one solution for θ_1 because of the constraint on the joints. Normally $\theta_1 = Atan(O_{3y}, O_{3x}) + \pi$ is also a possible solution but if this solution is chosen, it will give automatically a negative solution for θ_2 and this is not allowed by the constraints of the machine.

Hence, there is just a unique θ_1 it is possible to evaluate O_1 according to the next equation:

$$O_1 = (-a_1 Cos(\theta_1), -a_1 Sin(\theta_1), L_1),$$

and so is the distance O_{31}. According to this the distance of the prismatic joint can be evaluated by $d_3 = sqrt(O_{31}^2 - a_3^2)$, and finally, θ_2 can be evaluated by the equation:

$$\theta_2 = Atan(n,q) - Atan(a_3, d_3) + \pi/2$$

where $n = O_3 - O_1$ projected on y_1 and $q = O_3 - O_1$ projected on x_1.

Now that θ_1, θ_2 and d_3 have been found, the transformation matrix T_0^3 can be evaluated and therefore the position and the orientation of O_3 are known. Moreover, the matrix between the O_3 and O_6 is also known according to the transformation matrix T_3^6. In this way it can be determined that $\theta_4 = Atan(T_3^6(1,3), -T_3^6(2,3))$ and $\theta_5 = Atan(T_3^6(3,1), T_3^6(3,2))$.

The problem with this method is that in order to be correct there is a condition that has to be fulfilled and it is that z_3 must be perpendicular to z_5 and therefore to z_6. This is determined by the geometry configuration of the manipulator and in fact there are very few circumstances in which this condition coincides with the previous inverse kinematic evaluation.

Therefore it is necessary to find an O_3 that may fulfils the perpendicular condition between z_3 and z_6. This problem is solved by recursive iterations where the reference system $O_6 = O_6 * R_z(\phi)$ (where $R_z(\phi)$ is the rotation matrix or the roll angle of the nozzle) is rotated around z_6 until the dot product $z_3 . z_6 = 0$.

This means that the link between O_3 and O_5 is rotated around z_6 adding in each iteration a constant value to ϕ, changing the position of O_3 and O_1, and therefore changing the value of θ_1, θ_2, d_3, θ_4 and θ_5. Each of these positions must be evaluated every iteration, according to the equations shown before, until the perpendicular condition is satisfied.

This process may take to much CPU time if it is not done with certain logic. For example the direction of the rotation may be selected according to the attitude of the nozzle and the quadrant where it is located.

Additionally, the time of the process may decrease by increasing the rate of ϕ and using statistical strategies to average the value of the product between iterations. This is the case when, for example, the value of the dot product passes through zero between iterations.

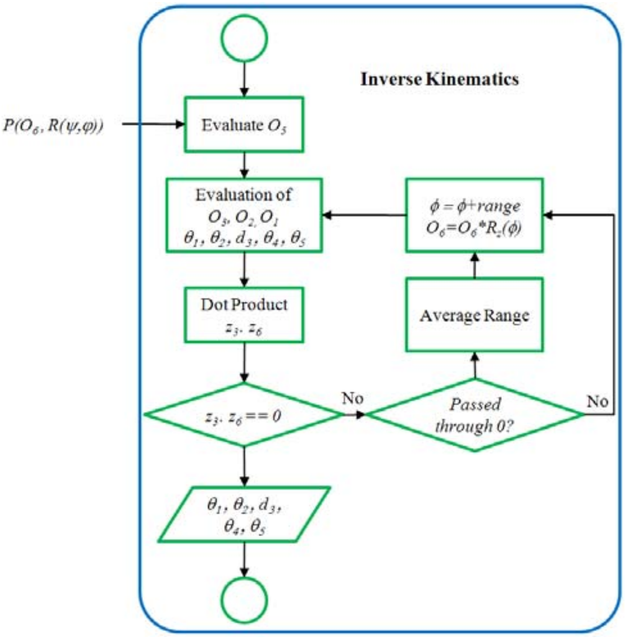


Figure 4 Flowchart for the inverse kinematics resolution for the shotcreting machine's manipulator.

2.1.2 Control architecture

The main control is based on a computer (master controller) which, through the information provided by multiple sensors and measurement systems, is responsible for moving the arm of spraying at a determined velocity by evaluating the position and attitude of the nozzle tip with respect to the surface of the tunnel, having defined previously the work area and the thickness of the layer.

It has a distributed structure which is designed to interconnect the interfaces that are designed to monitor and control the shotcreting machine, its manipulator and to add additional control elements (see Fig. 5).

It is divided in four main modules: the manipulator's interface, the pumps' interface, the additional elements (LADAR scanner or the remote control), and the main controller that has a visual based Human Machine Interface (HMI), designed for its use in construction sites, and that it is in charge of the control system of automated shotcreting process.

The system is capable of running in three modes of operations: a) Automatic mode where the complete process is done in an autonomous process; b) Semiautomatic mode, where the operator can move the manipulator using a remote control but is assisted by the main control system in order to guide him to maintain the correct attitude and position of the nozzle according to the surface of the tunnel;

and c) the manual mode, that is the last mode of operation, where the operator uses the remote control to move freely the manipulator but it is assisted by the control system in order to move the joints with coordinated movements instead of one joint at a time (as it is done in the operation without any automation).

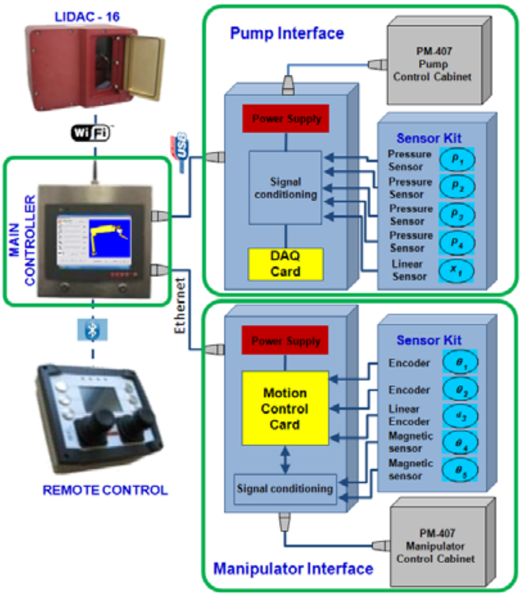


Figure 5 Main control architecture.

The last two modes of operations were implemented in case unexpected issues arises inside the tunnel construction process (like faults or water leaks) and the automated control system is not able address them. These modes won't be discussed further in this document.

2.1.2.1 Main controller and HMI

The main controller is based con an industrial PC and it is designed to control the automated shotcreting process interacting with the different interfaces and additional components of the installed on the machine.

The windows based control application (see Fig. 6) is designed to be used by construction workers and provides the user with a user friendly HMI which is accessible through a touch screen panel.

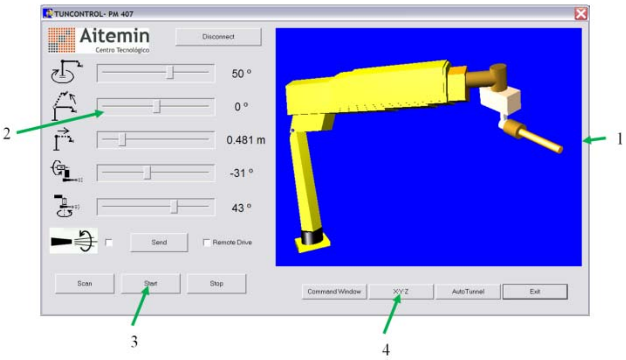


Figure 6 HMI controller.

It has a main VRML model of the manipulator (1) that shows its position in real time during the automated shotcreting process. It can also be configured to monitor the progress of the process while moving the manipulator in semiautomatic or manual operation mode.

Maybe this functionality doesn't make much sense if the main controller is installed onboard; but one of the main objectives of the complete development is to prevent that the operator gets near the working area and may be able to operate from a remote location, as it is intended in further developments.

The application also has an independent control for each joint (2), high level macros for different operations like the automated shotcrete process or locating the manipulator by entering the desired position and attitude according to the machine's coordinates (3), and different options for the system configuration (4).

2.1.2.2 Manipulator's interface

The interoperability between the application software and the movement of the manipulator's joints is made by an interface (see Fig. 6) which main functionality is based on a motion control card, which has a dedicated PID filtered position and velocity control for the proportional actuated joints, and has been programmed to accurately process a time based control of the position of each on/off actuated joint (see Table 1).

It also provides the control software with the information of the different encoders and positions sensors and it has been programmed to evaluate the velocity of each joint in order to get to the desired position making coordinated movements at the desired velocity.

This interface was designed to minimize the main CPU time of usage for processing low level information. The configuration makes suitable the use of the main controller with non real-time based operation systems.

It is connected to the main controller through an Ethernet which is intended to which minimize the signal distortion produced by external noise sources, but instead it decreasing transfer rate. Nevertheless the transmission rate is made between 100 and 200 samples per second.

So when the an automated spraying process has to be made, first the complete set of target positions and the shotcreting speed is evaluated a priori by the main control system and then sent to the motion control card. During the spraying the desired velocity can be modified in real time in order to adapt the spraying according to the mix pumpability conditions, meanwhile it feedbacks the main controller with the position of the joints of the manipulator to visually monitor the process from the HMI.

2.1.2.3 Pump's interface

This interface (see Fig. 6) has been designed only to measure the different values used to evaluate the amount and the velocity of the pumped concrete and send them to the main control system through an USB connection.

A set of sensors have been installed in the machine in order to measure different parameters (pressure, concrete flow, etc.). These parameters are measured not only for quality control purposes, but also for detecting the pump needs for a given mix and therefore to regulate the pumping parameters (concrete flow) accordingly [8][9].

In this case it is the main control system the one that it is in charge of evaluating the properties of the concrete according to these parameters.

In order to guarantee a fast rate of acquisition, the interface is based on a data logger and it uses the USB connection for fast transmission as it is necessary to monitor the pumping parameters with a rate of transmission (up to 5000 samples per second but not the complete rate is used).

3 3D LADAR scanner and trajectory generation

As described before, in the machine a LADAR scanner has been installed in order to acquire the information of the conditions of the working area by scanning the surface before and after the shotcreting process.

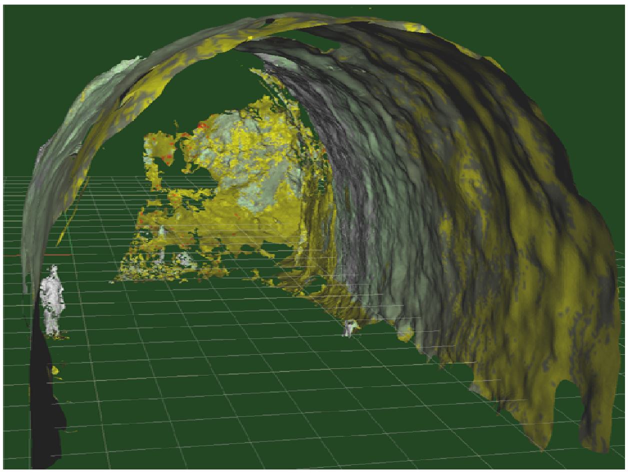


Figure 7 Rendered image of the scanned surface of a tunnel using the LIDAC – 16 by AITEMIN.

The purpose of the first scan is to provide the automated control system with the detailed information about the position and orientation of the surface of the tunnel in Cartesian coordinates according to the origin of the manipulator O_0 (see Fig. 2) in order to generate a shotcrete trajectory profile.

After the raw cloud of points is available from the LADAR scanner a polyhedral mesh can be fitted into it, and then rendered to a continuous surface (see Fig. 7). Once the cloud of points is processed and filtered to represent the tunnel with a reasonable size, complexity and smoothness it is possible to evaluate the proper shotcrete trajectory. Even though the geometry can evaluated from the scanned information, sometimes the representation of the surface is not smooth enough for extracting a true or sensible normal vector. When this occurs a proper solution is to apply the design profile of the tunnel, which allows assigning the normal to each point quite straightforwardly [8]. This design of the tunnel profile is usually made from tangent arcs that intersect between each other.

The trajectory generation starts by defining its shape and it continues by evaluating a path according to some initial parameters and the shape of the tunnel. Usually the most convenient trajectory should follow a squared shaped form.

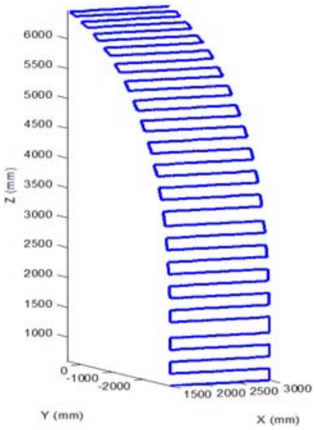


Figure 8 Example of a desired shotcrete trajectory based on the geometry of a tunnel.

The initial parameters are:

P_0: Initial target position of the trajectory.
w: Width of each line of the trajectory in x direction.
d: distance between lines of the trajectory.
n_w: Number of points for each line of the trajectory according to its width.
n_d: Number of points in each line of the trajectory through its high (usually $n_w = n_h$).

The sequence starts when the operator selects the initial P_0 that it should be the closer point to the machine in x direction; w is the width of the advancement that it should be made in each pace of the tunnel construction process (usually from 1.5 to 2m); this means that if in x direction there are defined n_w points to from a line of spraying each target point would be defined at a w/n_w distance. The target point may be modified in y direction adapting each position according to the scanned points.

The same sequence used to find target points vertically at a d/n_d distance. This distance is not necessarily the high in z direction but the perimeter of the arc defined by the geometry of the tunnel. It is implicit the fact that in each target point the orientation is included.

The trajectory generation process finishes when the orientation of the target point according to the geometry of the tunnel has a vertical orientation. The inverse kinematics has to be evaluated for each target point and the set of positions for all the joint is sent to the manipulator's interface.

This is why the importance of the optimisation the process time for the inverse kinematic evaluation. In this case the time needed to generate the complete shotcrete trajectory of around 900 target points and evaluate the position for all the joints by inverse kinematics, including the downloading time to the manipulator's interface, goes from 15 to

20s, which from a real tunnel construction point of view it is fair to say that it is a very efficient process.

4 Real-time layer thickness estimation

The control system of the automated shotcreting machine has been designed with the possibility of the adjustment of the velocity of the coordinated movements (used in linear trajectories) between the joints of the manipulator in real time (see Fig. 9).

Such property may be useful for remote teleoperation alternatives (*e.g.* a remote control) or as stated in this document, for the adjustment of the velocity of the movement of the manipulator during spraying, in order to maintain the homogeneity of the thickness of the concrete layer by evaluating different variables provided by the pump and the manipulator control interface.

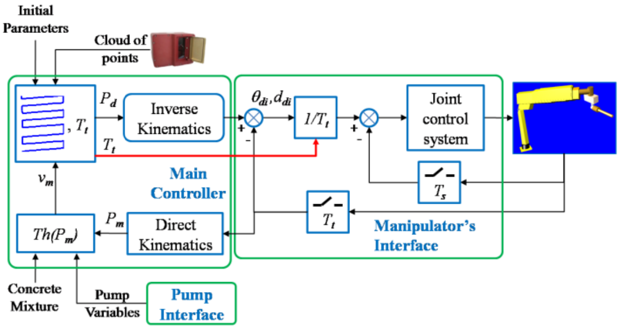


Figure 9 Block diagram for high-quality automatic shotcreting process.

The thickness of the shotcrete is estimated at a point P_m by the semi empirical equation [13]:

$$Th(P_m) = \int_{t_0}^{t_1} M(\beta_1, \beta_2 \ldots) F(t) \Psi_\alpha(r(t), K) dt$$

where $r(t)$ is the distance between the nozzle axis and P_m, $F(t)$ is the instantaneous concrete flow given by machine's concrete pump, and $M(\cdot)$ is a function that models all remaining factors affecting shotcreting performance (*e.g.* mix design, rebound, nozzle attitude, wall position, etc.). $\Psi_\alpha(r, K)$ is a density function (in the statistical sense) that represents the probability of the volume of the sprayed concrete landing on a differential area defined by the equation:

$$\Psi_\alpha(r, K) = \frac{1}{G_\alpha}\left(1 - \left(\frac{r}{K}\right)^\alpha\right)^2 \quad if \quad 0 \le r \le K,$$

$$\Psi_\alpha(r, K) = 0 \quad if \quad r > K$$

The distance to the wall, compressed air flow and part of the effect of the orientation of nozzle when it is not perpendicular to the surface by the effects of the position errors caused by deformations or backlashes, are accounted in the parameter K [8]

And finally G_α is defined by:

$$G_\alpha = \int_0^K 2\pi r \Psi_\alpha(r, K) dr$$

By modifying α and K it is possible to adjust the model to the actual spraying pattern of any given machine, nozzle and operating conditions.

The spraying velocity is determined empirically by comparing the type of concrete mix and the shotcreting velocity. Usually the construction companies use the same type, or at least known types, of concrete mixes for their shotcrete operations. But some circumstances (*e.g.* mechanical changes on the machinery, the use of additives, etc.) may compromise the stated velocity values.

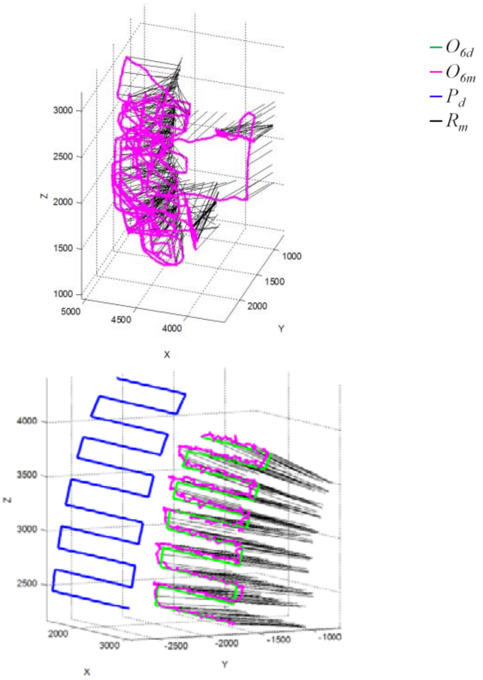
That it is why, after the shotcreting process is completed, a second scan of the surface is made. One of the meanings of this second scan is to verify the quality of the shotcrete layer. If the layer doesn't match the required quality, the automated shotcreting parameters can be changed by adjusting α and K from the real time thickness estimation.

5 Experimental results

For the validation of the system several experiments where made in a real scale test facility for tunnelling construction purposes.

5.1 Automatic shotcreting process

The first step was to test the complete automated shotcreting process based on the geometry of the tunnel and compare it to a manual shotcreting carried out by an operator.



a. b.

c.

Figure 10 Shotcreting trajectory examples. a) Operator's shotcreting b) Sample of automatic shotcreting and c) Automatic shotcreting image.

According to the results given by the measurements made during various shotcrete operations (see Figure 10) it is notable the differences between the attitudes of the nozzle maintained by the operator a) and the automated process b).

The operator has to control independently each joint of the manipulator, thus it is easier for him to move the last rotation of the nozzle than the rest of the joints. This situation may lead to the radial attitude of the boom and consequently to the semi-spherical geometry of the spraying.

On the other hand, it is also noticeable that with the automatic spraying it is possible to maintain the correct position and attitude of the nozzle during the whole process.

There are imprecise positions encountered during the shotcrete that are caused mainly by the difficulty in the on/off position control of the prismatic joint, the fact that the hydraulic supply of the manipulator is not powerful enough to move all the joints simultaneously at the desired speed and the mechanical deformations of the structure. This may lead to positions errors of up to 50mm, but this level of precision is admissible for this kind of process.

5.2 Thickness estimation

The estimation of the thickness of the layer has been evaluated using the results of different automatic shotcrete processes in a determined test area.

To test the fitness of the estimation, in every spraying stage the surface of the tunnel has been scanned with the LADAR (see Fig. 11). By using a common squared function to evaluate the differences of the thickness estimation it is possible to find the amount of concrete used in a shotcrete process.

Table 2 Summary of sprayed volume estimations [8].

Stage	Measured Volume (l)	Estimation from stage #1	Estimation from stage #2	Estimation from stage #3
#1	432	-	503	508
#2	498	573	-	503
#3	507	582	502	-

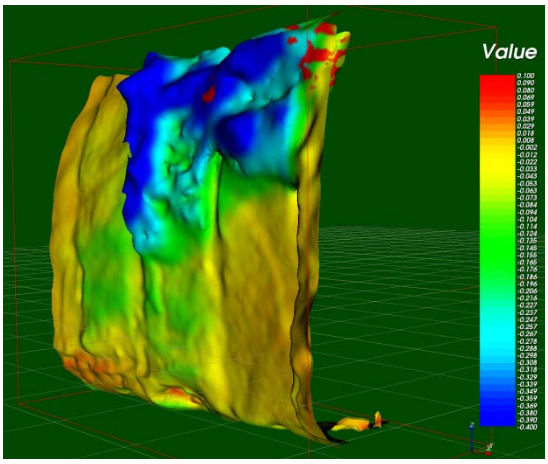


Figure 11 Difference between two successive 3D scanned images [1].

It can be noticed from Table 2 that the volumes estimated from stage #1 data seems less accurate. This is caused by the effect of wire mesh and lack of scanning data in the upper part of the working area before spraying for first time. For this reason, and most probably, the values of estimated volume are closer than the measured ones. On the other hand, estimations from the stages #2 and 3 are more accurate and the maximum error of the differences between the measured and the estimated volume is 5*l*.

6 Conclusions and future work

There is a notable improvement in the quality of the layer using robotization techniques that are not only shown in the analysis of the differences in the position between the manual and the automated process, but they have been also noticed on the real shotcreted surfaces.

Nevertheless, the robotization of a machine that it is not designed for automation purposes usually presents unexpected difficulties. For example, even though the precision of its movements are adequate for this process, the smoothness of the trajectory may be improved by giving the shotcrete manipulator enough hydraulic power and proportional controls in all its joints.

On the other hand, the models presented for the thickness estimation, deduced from empirical equations, presents several advantages like the fact that they do not take into account the possible variations caused by changes of the starting mix or any other circumstances that change from one to other jobsite.

Finally and as a result of the different experimental tests carried out to measure the different possibilities that the automation of the shotcrete process may offer to the tunnel construction industry, it is planned to take the next step in the implementation of the method and use it to robotize heavier shotcrete machinery.

This may provide the industry with a standardised system for the development an unstructured tunnel construction process, which may lead to the optimisation of time and costs and quality of the tunnel support layer, while improving the working conditions and the security of the operators inside the construction site.

7 Acknowledgements

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