AUTONOMOUS THIN SPRAY-ON LINER APPLICATION IN IRREGULAR TUNNEL AND MINE ROADWAY SURFACES

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ABSTRACT

An autonomous spray application system for a structural Thin Spray-on Liner (TSL) is targeting productivity and safety on underground coal continuous miners by potentially replacing steel mesh, and has broader applications as surface support and confinement in metalliferous mines and civil tunnelling. Polymer chemistry, coating formulation, geotechnical assessment and the autonomous application system are being developed as an integrated package as part of a continuous miner automation project. This polymer-based TSL system has significant benefits over conventional steel mesh skin confinement, including being more automatable by spray application, providing complete skin confinement and active skin reinforcement as a fast-curing composite with substrate, and having effective fire retardant properties for the polymer and the underlying coal. This paper presents a preliminary assessment of distance sensing systems that would enable autonomous adaptation of a nominal spray path to spray a consistent thickness of TSL (nominally 5mm) over an irregular topography. Two alternate sensors are assessed; firstly, a 2D LIDAR mounted on a linear axis is used to produce a 3D surface profile for generating an adapted spray path; and secondly, a robot end-effector-mounted ultrasonic sensor is assessed for wall following techniques to dynamically adapt a nominal spray path.

KEYWORDS

TSL, Skin confinement, Strata support, Roadway development, Sensors, Robotic spray, Mobile robot

INTRODUCTION

Thin Spray-on Liner (TSL) applications in civil and mining tunnels range from surface sealing, to confinement and structural support. (Spearing, 2003) has proposed a performance-based categorisation of TSLs that classes this TSL as very reactive, very high strength and flexible, making it a potential alternative to steel mesh and fibercrete. Advantages over fibercrete include; higher tensile strength, flexural strength and elongation, less material to transport and apply, and faster application and advance rates due to much quicker cure. The load bearing capacity of this TSL, and thus its ability to secure small-scale rock falls, is directly related to its application thickness. Coating thickness of around 5 mm brings a new level of focus to thickness control being an order of magnitude less than a conventional shotcrete application. As a result, it is essential that a controllable and consistent skin thickness is achieved during spray application to ensure the integrity of the mechanical strength of the skin confinement while minimising excess thickness. Spraying an irregular topography using a series of straight, generic, adjacent spray paths (see Figure 1) is expected to produce unacceptable variation in coverage, thickness and overlap. This may be properly compensated by adaptation in 3 axes to maintain a constant stand-off distance and perpendicular application angle in both the longitudinal and transverse directions.

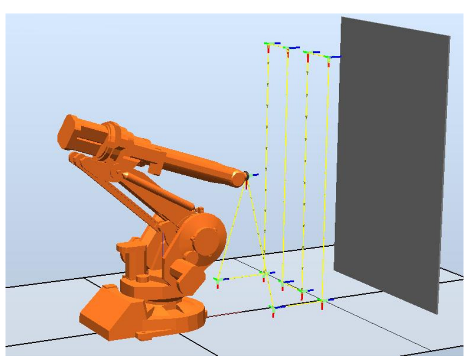

Figure 1 – Pre-determined nominal spray path using ABB Robot Studio

One strategy for an autonomous spray manipulator guiding system is to measure the profile of the spray surface, and pre-generate a spray path that maintains standoff distance and application angles within limits. (Ralston, Hargrave, & Hainsworth, 2003) demonstrated the use of a 2D Light Detecting And Ranging sensor (LIDAR) to generate a 3D profile of a coal mine roadway using the continuous miner tramming for the third axis. A concept similar to this is proposed, except with the LIDAR mounted on a linear axis on the continuous miner. Each 1 m section of tunnel to be sprayed would first be laser profiled while the miner is stationary. The LIDAR would be mounted on a common base with the spray manipulator to act as a calibrated, integrated module. It is anticipated that a continuous miner would have two such spray modules, one on each side, to manage practical limitations of manipulator reach and LIDAR sensor range. This is also practical to avoid centre obstacles on the miner.

An alternative concept is dynamic adaptation of a nominal spray path. Autonomous dynamic control of robotic systems in unfamiliar environments can be achieved through the implementation of wall-following techniques (Braunstingl , Sanz , & Ezkerra 1995). Use of end-effector mounted sensors utilising roof and rib following techniques would provide dynamic adaptation of a robotic spray path.

This paper aims to provide a preliminary assessment of the two alternative distance sensing systems introduced above. One specific sensor is selected for each concept to allow basic investigations. Each system would enable an autonomous spray manipulator to apply a consistent thickness of TSL (nominally 5mm) onto an irregular, unknown topography. Scoping the key focus areas for further research will be a key outcome of this paper.

EXPERIMENTAL

(Slob & Hack, 2004) recommend phase-based LIDARs for thickness monitoring and control of shotcrete due to higher accuracy and speed, while (Slob, Hack, & Turner, 2002) note that measurement specifications vary greatly between different makes. The Hokuyo URG-04LX ultrasonic sensor was selected for its resolution, serial output and lower cost. Accuracy and repeatability was evaluated for a rough piece of black coal and repeated on a smooth flat white piece of paper for each sensor.

A 3D surface profile was constructed with a series of steps and ramps designed to test sensor and spray performance. This test profile sheet was attached to the roof of a frame with a sheet of white cement fibro board attached to the wall. The LIDAR was fixed to a linear axis, with the LIDAR being attached to produce a vertical scan field. The linear axis was incremented 5mm and repeated for the width of the simulated tunnel section.

Ultrasonic sensors continue to be used in autonomous robotic applications relating to path planning (Liu, Lin, & Zhu, 2008; Mishrs, Sujith, & Mall, 2010). Ultrasonic sensors use either a pulse wave ToF principle, or a continuous wave phase shift principle for determining distance range measurements (Hua, Wang, & Yan, 2002). Limitations in the directional resolution are well documented (Braunstingl , et al., 1995). A solution demonstrated by (Lee, Choi, Park, Park, & Lee, 2007) incorporates the use of velvet tube lengths to reduce the beam width. (Gary et al., 2008) utilise narrow-beam sonars, 2° beam-width, to increase directional resolution for 3D spatial maps of underwater caves. Sonar range measurements were noisy and low resolution whilst the update rate and point density resulted in a more difficult mapping process compared to laser scanners.

A Maxbotix HRLV EZ1 was selected for its stated accuracy of +/- 1mm, 10 Hz measurement cycle and compact size and relative low cost. This sensor has a serial output and incorporates calibrated acoustic detection zones, reducing the effective beam width pattern detecting objects. Tubes of 17mm inner diameter PVC pipe (see Figure 2) were lined with velvet cloth and affixed 10 mm onto the barrel of the ultrasonic sensor, forming a tight fit. The sensor was mounted on the linear axis facing perpendicular to the axis at a narrow vertical target strip at 600 mm range. The axis was side-shifted in each direction until the sensor output shifted to the background distance, indicating the edge of the beam pattern.

Figure 2 – Ultrasonic Sensor with velvet-lined tube and mounted on the linear axis

(Carelli & Oliveira Freire, 2003) utilised the wall following technique for the navigation of autonomous robots to transverse through unknown passages, hallways and roadways. Similarly, ultrasonic sensors attached to the end effecter of the robotic manipulator arm may be used to dynamically adjust a pre-determined spray path to maintain the spray stand-off distance and application angle from the roof and ribs. Adaptation points were added to the robot spray path at 10mm increments. The robot was then passed over a series of square blocks, to establish basic wall following capability.

RESULTS

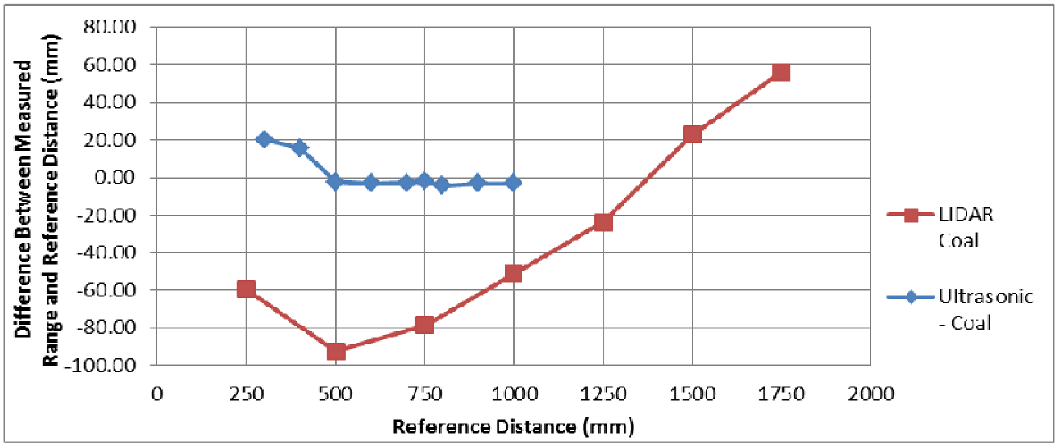

Figure 3 – Raw accuracy of the LIDAR and ultrasonic sensors for the black coal piece

The Hokuyo LIDAR accuracy results for white paper were a reasonable -0 to +20 mm across the tested range from 250 to 2000 mm. For black coal the accuracy deteriorated to -90 to +60 mm (see Figure 3) and the reduced reflectance limited the range to 1500 mm. Standard deviation for coal was 4 mm for range less than 1000 mm, increasing to 0.5% for ranges above 1000 mm. The Maxbotix ultrasonic sensor had a large non-linear error between minimum range and 500 mm. Above 500 mm the accuracy was steady at 3 mm below actual and a standard deviation of 0.9 mm.

The 3D surface profile plotted in Figure 4 was generated from a series of 2D LIDAR scans along the linear axis. The irregular test surface series of ramps and steps on the roof are clearly represented. A repeat profile was attempted after painting the surface, however, signal strength became too weak from the low reflectance of matt black, further demonstrating the sensitivity of LIDAR to visual properties.

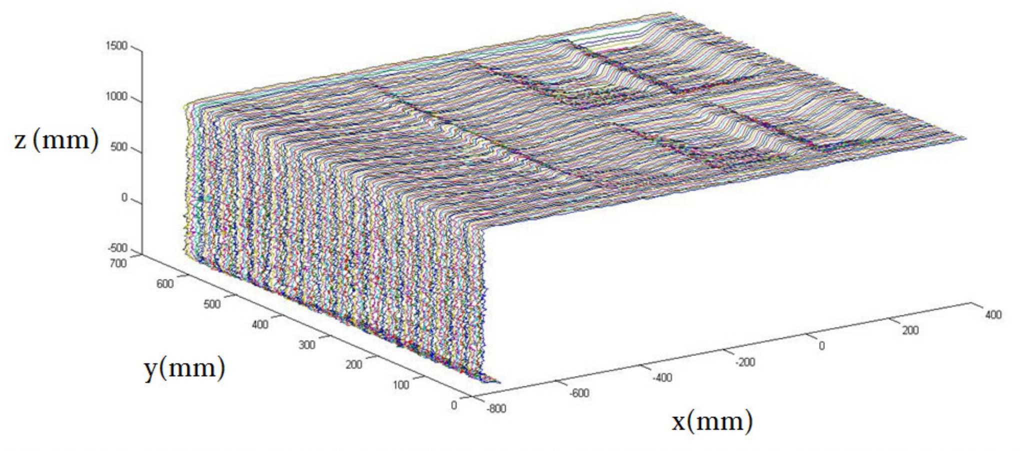

Figure 4 – 3D surface profile from a series of 2D LIDAR scans prior to spraying matt black

The basic wall following technique was demonstrated. Range measurements were automatically trimmed the end effecter position to maintain stand-off distance as the robot passed over some steps along the spray path. However, it was observed that the robot prematurely moved the end effecter prior to being in alignment with the rising edge of a step and lagging in adjustment once past the falling edge of a step. This problem was addressed by the angular resolution modification to the ultrasonic sensor.

Dynamic performance of the IRB1400 ("Product On-line Manual, IRB 1400,") was observed to be impractical for dynamic adaptation. At each 10mm increment, where a range measurement was taken, a significant pause was incurred by a serial communications issue, which will be readily resolved with updated hardware and software. Collision avoidance was demonstrated as the ultrasonic sensor detected the protruding steps early with the wide-angle beam, ensuring that the robotic arm would maintain the programmed off-set distance and not collide.

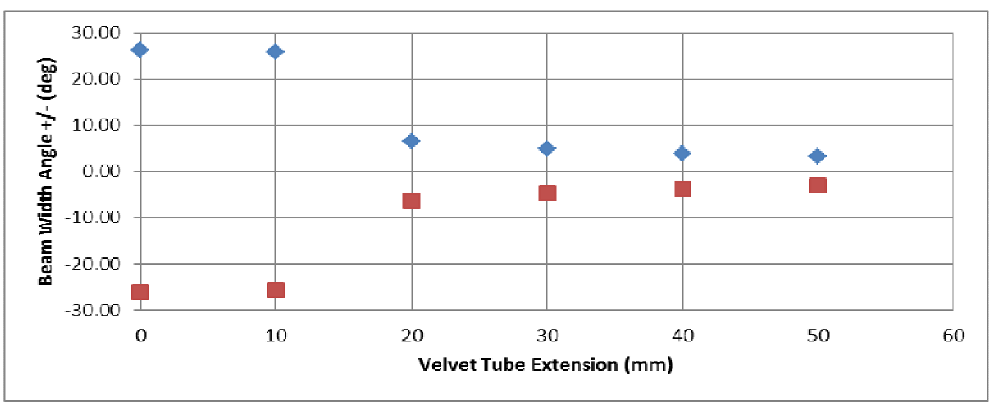

Figure 5 – Maxbotix ultrasonic sensor beam width modification by velvet tube extensions

The ultrasonic beam angle modification trial results are plotted in Figure 5. Beam half-width at is remarkably reduced from 148 mm to 16 mm (±3.2°) by adding a 50 mm velvet tube extension. Velvet tube extension length did not impact accuracy or repeatability of the measurement. Greater than 50mm tube extension yielded invalid range measurements as the reflected wave signal was too weak after passing through the long velvet tube twice before being received back to determine a range.

DISCUSSION

Care needs to be taken to avoid the trap of direct comparison of the two selected sensors. Each sensor should be observed in light of the particular thickness application control concept for which it has been selected. So first, consider the sensors in combination with the spray nozzle, which is expected to produce either a cone or flat pattern of around 400 mm diameter/width at 600 mm stand-off distance. Spray incidence angle at the substrate will vary by around ±20° across the width of the spray pattern. Compare the spray foot print to the field of view for a single point reading of each sensor. The LIDAR spot is 10 mm diameter and the spacing between readings is <20 mm (10 rev/s, 1024 points per rev, measuring distance range of 1500 – 3000 mm). The un-modified ultrasonic 'spot' is around 300 mm diameter, and spacing between consecutive readings is at least 100 mm (for 10 Hz measurement frequency at 1 m/s spray gun velocity), and returns only a single, minimum distance from all valid distances within the spot. Although the ultrasonic sensor yields far better accuracy and repeatability for a single point result, the LIDAR yields a far denser field of points to characterise the surface more thoroughly.

Pre-generation of Adapted Spray Path from LIDAR Surface Profile

The Hokuyo LIDAR sensor maximum range was found to suffer significantly with changing physical surface properties from white paper to coal. The low reflectance of the coal reduces maximum measuring range from 4000 to 1500 mm. Variation in incidence angle further scatters the reflected signal. The significant accuracy variation for coal is of particular concern and requires further investigation. Repeatability remains within specification, suggesting that these inaccuracies may potentially be addressed with material-specific calibration. These accuracy and range limitations for coal seriously compromise the Hokuyo HRLV sensor's ability to produce an accurate 3D tunnel profile. (Slob, et al., 2002) found that the electrical components have a major influence on the quality of generated data. Further research is required to assess the accuracy and range across the spectrum of relevant measurement surfaces for a high resolution phase-based LIDAR.

The envisioned constant speed linear axis integrated with 2D LIDAR would generate a continuously advancing spiral of cloud data points, which is more complex than the discrete 2D circular scans at even linear spacing. This has implications for point cloud data manipulation and is an area requiring significant further study. Time to produce the point cloud for a 1 m advance is estimated at 5 s, based upon 10 rev/s and 20 mm pitch/rev. Allowing for return stroke and data manipulation, the spray manipulator could be ready to spray a custom adapted path less than 10 s after starting to measure the surface profile. This is a reasonable fit with the target 60 s for the complete spray cycle time. Collision avoidance algorithms would also need to be considered to protect the robotic spray arm from any protruding obstacles or obstructions within the generated spray path.

Dynamic Adaptation of Spray Path using Ultrasonic Sensors

Ultrasonic sensors are inherently more robust to variation in surface physical properties since they are based upon reflection of longitudinal ultrasonic pressure waves from solid surfaces. Light, colour and reflectance have no significant impact. Irregular and rough surfaces do reduce the range due to increased signal scatter, but do not impact accuracy. Air temperature and humidity may have significant impact on accuracy, though this was not tested. The Maxbotix HRLV is equipped with an inbuilt temperature sensor to compensate for these variations. However, internal heating from the electronics may cause false compensation, so it is recommended that the HR-MaxTemp external temperature sensor be used instead. Further environmental factors, such as air-borne dust and mist will be considered in future research.

The ultrasonic beam-narrowing results are particularly significant to further development of this adaptive spray control strategy. The far smaller spot size of 67mm at 600mm stand-off greatly improved the performance of the 1-Dimensional stand-off distance adaptation system over the steps and ramps. The narrow beam also opens up the opportunity to measure and dynamically adapt for angle of application in 2 planes by using 4 sensors arranged in a square pattern. The overall average would be used for the stand-off distance trim; the difference between west average and east average will give the E-W angle trim and similarly using the north and south averages for the N-S angle trim. Mine roadways with reasonably uniform surfaces and small angle variations may not require spray application angle adaptation. However, many mine tunnelling situations would greatly benefit from the adaptive angle trims.

Dynamic response and strategy is a significant fundamental area of future development for this wall following system. The measurement update rate for the HRLV is only 10 Hz. If the spray gun is traversing at 1.0 m/s, then the sensors and gun have translated 100 mm between distance measurements. This will produce very jerky, stepped adaptation movements, so a faster measurement frequency is necessary for successful operation. It is proposed that the end-effector-mounted sensors would be mounted forward of the spray nozzle in the spray gun traverse direction. This provides the opportunity to use feed-forward control algorithms to assist with relatively high-speed wall following techniques potentially demanded by this adaptive spray path application.

Finally, wider utilisation of either of these sensor systems within the greater picture of an autonomously guided continuous miner is noted. A second pass of either sensor system after the TSL has been applied would generate a coating thickness map, so long as distance precision and angular resolution are adequate. Also, a high density point cloud data set from a high resolution LIDAR offers the added value of a geotechnical surface record of strata condition prior to coverage. Finally, the same sensors could also be used by an autonomous miner guiding system as discussed by (Ralston, et al., 2003). These alternate functions remain secondary concerns for this research and should not compromise the drive for sensor performance criteria to achieve the primary goal of autonomous application with good thickness consistency.

CONCLUSION

Two alternate thickness control concepts have been presented for the autonomous application of a new high strength polymer-based thin spray-on liner. A preliminary assessment of two distance sensors has highlighted key performance merits and limitations to focus the scope of ongoing research on this integrated TSL system development. A relatively low-cost 2D laser sensor has been used to generate a 3D surface profile map. Further research is planned to manipulate the point cloud profile data to generate an adapted robotic spray path for TSL thickness consistency onto the irregular topography. Serious degradation of accuracy and range occur when measuring coal. A high resolution LIDAR is recommended for further research.

An ultrasonic sensor produced an adequate calibrated accuracy of ±1 mm. The 10 Hz measurement frequency is inadequate for dynamic adaptation of spray path, so faster response sensors will be required. Very rudimentary 1-Dimensional wall following and simple collision avoidance were demonstrated with a robot. Standard ultrasonic sensors have beam patterns well suited to object detection and collision avoidance, but were found to be inadequate for wall following. A simple external modification has reduced the effective half-beam angular resolution from ±26° to ±3.2°. Wall following performance became practicable, but the collision avoidance capability became ineffective. A five-sensor solution is proposed to maintain the target stand-off distance, perpendicular spray application in two planes, and collision avoidance. A feed-forward adaptive control strategy is proposed to help address potential dynamic response challenges. Autonomous TSL application is a core component of the product system, which in turn may become a very significant enabling technology for improving safety and productivity in coal mine roadways, metalliferous mines and civil tunnelling.

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