DEVELOPMENT OF AN END-EFFECTOR SYSTEM FOR AUTONOMOUS SPRAYING APPLICATIONS AND RADIATION SURVEYING

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ABSTRACT

This paper presents the design and testing of a scale proof-of-concept prototype robotic end-effector system for autonomous robotic shotcrete application and radiation surveying in underground uranium mining environments. The system presented consists of two functionally distinct prototype tools that achieve the independent tasks of autonomous robotic spray pattern control and surface radiation surveying. The first prototype tool presented is a novel, robotic shotcrete spraying tool that is capable of autonomously maintaining and adjusting its circular spray pattern diameter on target surfaces in response to changes in target surface distance. Physical testing of the prototype tool empirically verified its ability to maintain circular spray pattern diameters at various target distances and demonstrated its application potential. The second prototype tool presented is a Geiger Muller tube based radiation detection tool that uses lead shielding and a single hole collimator in combination with precise robotic positioning in order to capture localized radiation measurements of surfaces within radiation rich environments. Physical testing of the prototype tool demonstrated its ability to create radiation survey profiles that distinctly characterized the radiological profile of test target surfaces embedded with various radioactive sources.

Keywords: shotcrete; nutation; autonomous.

DÉVELOPPEMENT D'UN D'ORGANE TERMINAL POUR LES APPLICATIONS DE PULVÉRISATION AUTONOME ET DE DÉTECTION RADIOLOGIQUE

RÉSUMÉ

Cet article présente la conception et les tests d'un prototype à l'échelle d'un organe terminal robotique destiné à l'application robotisée de béton en jet pulvérisé et à la détection radiologique dans des environnements d'extraction souterraine d'uranium. Le système présenté se compose de deux outils distincts sur le plan fonctionnel qui permettent de réaliser les tâches de façon indépendante, c'est-à-dire le contrôle autonome de l'application robotisée de béton en jet pulvérisé et la détection du rayonnement de la surface. Le premier outil présenté est un nouvel outil robotisé de pulvérisation de béton capable de maintenir et d'ajuster de manière autonome le diamètre circulaire de son jet sur les surfaces cibles en fonction de la distance entre l'outil et la cible. Les tests de l'outil prototype ont vérifié de manière empirique sa capacité à maintenir des diamètres de pulvérisation circulaires à différentes distances cibles et ont démontré son potentiel d'application. Le deuxième outil présenté est un outil de détection de rayonnement basé sur un tube de Geiger Muller qui utilise une protection en plomb et un collimateur à un trou en combinaison avec un positionnement robotique précis afin de capturer des mesures de rayonnement localisé sur des surfaces riches en radiation. Les tests physiques de l'outil prototype ont démontré sa capacité à créer des profils de rayonnement qui caractérisent de manière distincte le profil radiologique de différentes surfaces cibles incorporées de diverses sources radioactives.

Mots-clés : béton pulvérisé ; nutation ; autonome.

1. INTRODUCTION

Uranium finds its place in the modern world as a source of nuclear fuel, its inherent utility and relative abundance makes it an essential resource for modern life. However, despite uranium's many benefits to human life, its procurement from the natural environment does not come without hazard. This paper presents the key research outcomes of a MASc thesis project centered around the development of a robotic end-effector system for an autonomous mobile-manipulator system capable of removing mining personnel from hazardous environments within the underground uranium mining industry [1]. This mobile-manipulator system is referred to as the Mobile Autonomous Scanning and Shotcreting robot, or MASS for short. The development of the scale prototype MASS robot is currently in progress at the Mechatronic and Robotic Systems Laboratory at the University of Ontario Institute of Technology (UOIT) in cooperation with Cameco Corporation. The MASS is capable of navigating a mine drift and using its on-board laser scanner to create a 3D map of the drift walls. The MASS then uses this 3D map to generate spraying and scanning trajectories for its on-board 6-axis manipulator arm to follow in order to either coat the mine walls with shotcrete or systematically scan them for radiation. The end-effector system presented in this paper directly builds upon previous work on the MASS that developed the control systems that allow the MASS to: localize, navigate, scan, and follow generated spraying and scanning trajectories with its manipulator arm (see [2, 3]).

The MASS project focuses specifically on mitigating the hazards to mining personnel present during the surveying and tunneling processes that are used to extract uranium ore in underground hard-rock mining scenarios. As an underground uranium mine expands, its newly excavated drifts (tunnel sections) must be both reinforced and shielded in order to prevent collapse and to protect mine personnel from radiation exposure. Reinforcement and shielding is provided with the use of spray-able concrete (commonly referred to as shotcrete). Human workers known as Nozzlemen with the aid of industrial shotcrete spraying equipment, coat the walls and ceiling of the drift with shotcrete. As the shotcrete sets it forms a protective shell that internally supports the drift. Due to the density of shotcrete, it has the capacity to attenuate some of the harmful radiation that is naturally emitted from the mine's surfaces [4]. In all, the shotcreting process creates a safe underground environment with reduced levels of harmful radiation. The caveat, however, of the shotcreting process is that the initial hazardous conditions that it aims to protect mine workers from are the conditions it subjects the shotcrete operators to during the spraying processes. Additionally, before shotcrete application begins, the drift face must be manually surveyed for radiation by the mine's geologists. Pre-shotcrete radiation measurements are useful in aiding mining geologist and engineers in determining the nature of the uranium ore body, thus enabling them to more effectively plan mining operations. This manual surveying process, however, further subjects mining personnel to the aforementioned hazards associated with the unsupported and unshielded drift surfaces.

A key requirement of the shotcrete application process is to ensure maximum surface adhesion while minimizing shotcrete rebound, this is achieved through the use of correct application technique by the Nozzleman. Correct application technique requires that the nozzle be at all times maintained within 1-2 meters and at a 90-degree approach angle to the target surface. In addition, to ensure a homogeneous result, spraying must be carried out with even circular nozzle motions, known as nutation [5]. The trajectory generating control system on the MASS robot outlined in [3] handles the first two aspects of correct application technique. It ensures a 90-degree approach angle and gives the system the capacity to maintain a known distance from the manipulator arm's control point to the target surface. Ensuring an even circular spray pattern and controlling rebound during the spraying process is a complex problem and is in fact largely controlled by the skill and experience of the Nozzleman [6]. This makes the systematic control of shotcrete rebound and layer homogeneity particularly challenging to ensure during a fully autonomous application process. This is further complicated by the need for varying spray pattern sizes for spot filling different sized surface cracks and holes, which in a non-automated process, is controlled by the visual judgment of the Nozzleman. Hence,

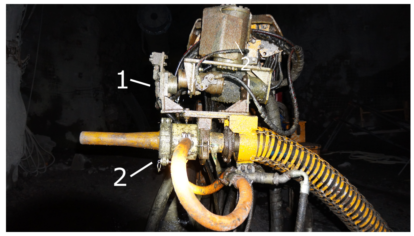

Fig. 1. MacLean Mine-Mate^{TM} SS-2 Passive Type Shotcrete Nozzle System Used by Cameco Corporation (1: Passive Nutation Generation Mechanism, 2: Shotcrete Nozzle and Hose Assembly)

to ensure a strong and homogeneous result in a fully automated process, there is a need for some form of automated control over the physical size of the circular spray pattern generated by the shotcrete spray head. Therefore, the main goal of the research conducted was to develop a prototype control system and a proof-of-concept robotic end-effector specifically designed to provide automated control over the magnitude of nozzle nutation in relation to target surface distance. The goal of this control system was to emulate the decision making that a skilled Nozzleman would use in order to maintain a constant spray pattern size on a target surface.

Additionally, the secondary goal of the project is to enable the MASS to survey the radiation profile of the target surface before and after the shotcrete application process. Radiation surveying is a relatively simple task with the use of modern day portable radiation detection instruments, such as Gieger-Mueller and NaI scintillation detectors [7]. Special consideration must be taken within a radioactive environment to ensure that the radiation survey of the target surface is not influenced by external radiation sources within the immediate vicinity. Therefore, it was the specific secondary goal of the research to incorporate radiation scanning equipment outfitted with directional shielding into the design of the prototype end-effector system.

2. SYSTEM DESIGN - THEORETICAL BACKGROUND

The prototype robotic end-effector system developed for the MASS robot has two distinct functional capacities: autonomous control of the shotcrete spray and the detection of target surface radiation. The end-effector system's capacities do not directly correlate in a functional sense. Therefore, they can be thought of as two separate subsystems and shall be explained as such for the remainder of this paper.

2.1. Autonomous Control of Shotcrete Spray

In order to achieve a homogeneous shotcrete layer on the target surface, spraying must be carried out with even circular nozzle motions. Current operator controlled automatic shotcrete nozzle systems generate the required circular spray pattern through the use of passive mechanical mechanisms. Figure 1 shows an industry standard design of one such passive system from a MacLean Mine-Mate^{TM} SS-2 shotcrete sprayer.

From Figure 1 it can be seen that the operator controlled automatic shotcrete nozzle system is comprised of two main components. The first being the shotcrete nozzle and its shotcrete hose assembly. The second being the passive nutation generation mechanism that the nozzle and hose assembly is suspended from. Close analysis of Figure 1 shows that the nutation mechanism is driven by a hydraulic motor. The shaft of the motor is connected to a rotational joint whose centre is offset from the motor's axis of rotation. The rotational joint is connected to a hangar bracket from which the shotcrete nozzle and hose assembly are suspended. This hangar bracket is affixed with a flexible rubber member to a solid mounting point that is directly behind and coaxial to the hydraulic motor. This effectively creates a central pivot point for the nozzle assembly. As the hydraulic motor rotates, the offset rotational joint produces an oscillating displacement amplitude in the hangar bracket. Due to the hangar bracket's central rubber pivot point, this causes the

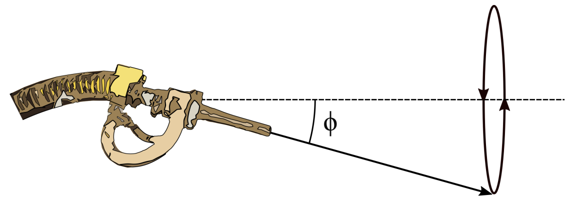

Fig. 2. Nozzle Nutation and Circular Spray Pattern

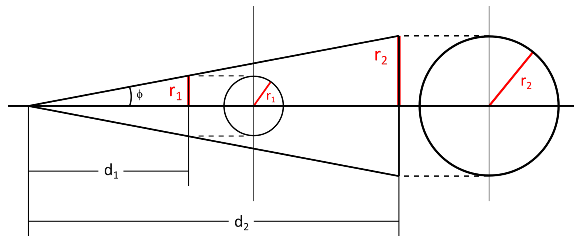

Fig. 3. Effect of Target Distance on Spray Pattern Size

nozzle tip to nutate about the pivot point. The nutation of the nozzle tip creates the desired even circular spray pattern on the target surface with the projected shotcrete spray. Figure 2 depicts the result of nozzle nutation on the projected spray of shotcrete.

As seen in Figure 2, the nutation action of the shotcrete nozzle can be visualized as a cone whose projected circular base is the resultant spray pattern of the shotcrete spray on the target surface. The described passive nozzle nutation mechanism is effective. However, its caveat is that the amplitude of nozzle tip nutation is fixed by the offset distance of the rotational joint connected to the hydraulic drive motor. This can be visualized in Figure 2 as ϕ remains constant. This is not a problem if the shotcrete head remains at a fixed distance from the wall. However, if the distance from the nozzle nutation centre to target changes, due to the geometric relationship, the size of the projected spray pattern will change as well. This relationship of spray pattern size to target distance is illustrated in Figure 3.

Figure 3 is a 2D representation of the effect that target distance has on spray pattern radius when the magnitude of nozzle nutation is held constant. In the Figure 3, ϕ represents the angular magnitude of nutation being applied to the nozzle tip. Initial target distance is represented by d_1 (which is measured from the target face to the nozzle's central point of nutation). The resulting circular spray pattern is described by the radius value r_1. Parameters d_1 and r_1 represent the initial set-points of a desired spray pattern size given the nutation magnitude ϕ. Due to the trigonometric relationship between r_1, d_1, and ϕ, any change in d_1 without a change in ϕ will result in a change in spray pattern radius r_1. This effect is represented in Figure 3 by parameters d_2 and r_2. It can be seen that at the increased target distance d_2, the projected spray pattern radius has increased in size to r_2. Conversely, the opposite effect occurs when the target distance is decreased from the initial set point, the radius of the projected spray pattern reduces.

In an operator controlled system, the effect of target distance on spray pattern radius is managed by the visual judgment of the shotcrete Nozzleman. The Nozzleman is capable of manipulating the nozzle's distance from the target surface to maintain a constant spray pattern radius in order to achieve even coverage. This presents a problem for a purely autonomous system, unless said system has the capability to control the nutation magnitude ϕ in response to a change in target distance d_1. The concept of adjusting the nozzle nutation magnitude in response to changes in target distance is what this research refers to as "Active Nozzle Nutation Control". It is the core principle behind the control strategy and robotic shotcrete end-effector that was developed for the MASS robot.

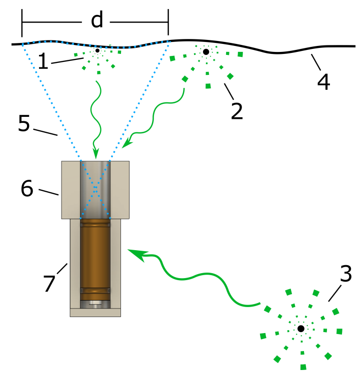

Fig. 4. Shielded Detector With Collimator (1: Target Surface Source Within Desired Detection Region, 2: Target Surface Source Adjacent to Desired Detection Region, 3: External Gamma Radiation Source, 4: Target Surface, 5: Actual Detection Region, 6: Tube Collimator, 7: Lead Encased End-Window Geiger Muller Tube)

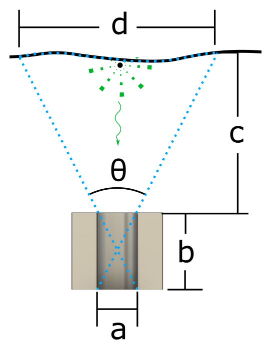

Fig. 5. Influence of Collimator Design and Distance on Detection Region Size (a: Diameter of collimator Opening, b: Collimator Length, c: Collimator Distance From Target, d: Projected Diameter of Detection Region on Target Surface)

2.2. Surface Radiation Detection

Preventing the influence of external sources outside of the region of interest is the primary concept behind the design of the radiation survey tool that was developed for the MASS. It was theorized that by adding appropriate shielding to the MASS robot's end-window Geiger Muller (GM) tube based radiation detector, its surface detection zone could be focused and limited to detecting radiation only within the specified region of interest on the target surface.

As shown in Figure 4, the addition of circumferential lead shielding and a single hole lead collimator to the GM tube detector greatly restricts the detector's field of view. Only radiation traveling at an angle within the range described by the dotted boundaries in Figure 4 may actually enter the detector un-attenuated. This theoretically achieves the reduction of external radiation influence from target surface sources and has the added benefit of restricting the detection region to a known size. The 2D representation of the the un-attenuated detection zone can be seen in Figure 4, it is described by the dotted triangular lines. Given the circular shape of the detector and collimator tube, this can be visualized in 3D as a cone whose base is described by the value d. The value d represents the diameter of the base of the cone that is projected onto the target surface (the span of the detection region). The finite size and shape of the detection region is defined by the collimator's geometric dimensions and its relative distance to the target surface. Figure 5 depicts these key dimensions in relation to one another.

As indicated by the value θ in Figure 5, the maximum included angle (spread) of the detection region

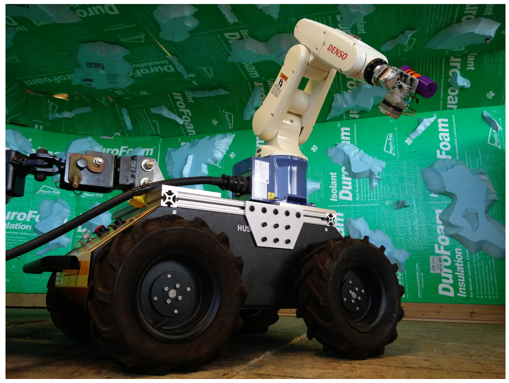

Fig. 6. Scale MASS Robot Prototype with Integrated End-Effector System

is defined by the diameter of the collimator opening a and its length b. The spread can be increased by either increasing the diameter of the collimator opening or decreasing the collimators length. Conversely, decreasing the diameter of the opening or increasing the length of the collimator decreases the spread of the detection region. Lastly, the span of the detection region on the target surface d is dictated by the relative distance of the target surface from the collimator c. Due to the identical triangular projection geometry, the span of the detection region d is affected by target distance in the same manner that the circular shotcrete spray pattern size is affected by relative target distance. As the distance c increases, the span of the detection region d will proportionally increase, the opposite is true as well. The implications of these dimensions, in relation to the intended function of the MASS's radiation surveying capacity, is that their manipulation allows for control over the size and shape of the detection region, thereby providing control over the accuracy of the generated radiation profile of the target surface. Once the dimensions of the collimator are specified in the design process, the angular spread of the detection area will be defined. From this point, the remaining dimension to specify is the desired span of the detection region across the target surface. Given that this dimension is driven by the relative target distance, the positioning control of the MASS's manipulator arm can be leveraged in order to accurately position the detector relative to the target surface, effectively providing the MASS system with control over detection region span on the target survey surface.

3. PHYSICAL PROTOTYPE

Figure 6 shows a full view of the MASS prototype with its two end-effector tools integrated into a single end-effector system.

3.1. Robotic Shotcrete Spraying Tool Physical Prototype

Figure 7 shows the final physical prototype of the robotic shotcrete spraying tool. The prototype makes use of two Nema 17 stepper motors positioned in a pan-tilt configuration. Each stepper motor possesses a homing switch allowing the system to reference a home position and track the relative positing of each axis of the robotic shotcrete spraying tool. Nozzle nutation is achieved through coordinated actuation of the two stepper motors. As spraying shotcrete in an indoor laboratory environment was not practical, and to allow for repeatable testing, it was decided to simulate the central control point of the shotcrete spray with a low-power blue laser.

3.1.1. Active Nozzle Nutation Control Algorithm

In order to develop a set of autonomous control equations for the prototype shotcrete tool, the relationship between the size of the projected circular spray pattern on the target surface and the distance of the target

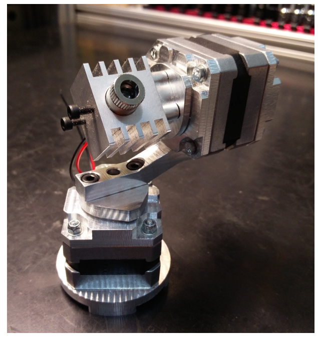

Fig. 7. Robotic Shotcrete Spraying Tool Final Physical Prototype

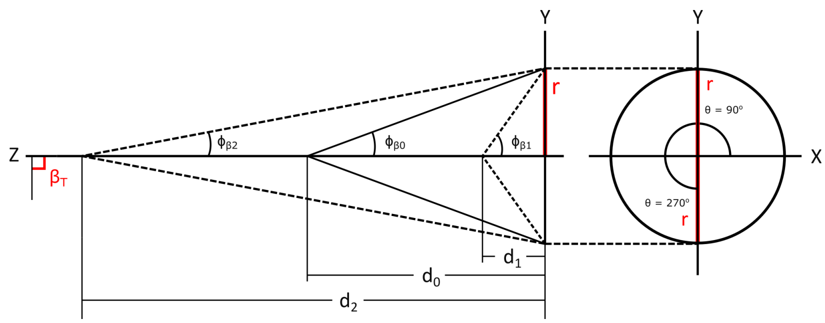

Fig. 8. 2D Spray Pattern Analysis of Pitch Actuator

surface had to be derived. This was achieved by performing a 2D geometric analysis on a projected shotcrete spray pattern of fixed diameter at various target distances. Figure 8 shows this geometric analysis.

Figure 8 provides a 2D analysis of the projected spray profile from the shotcrete tool's pitch actuator. It is noted that the 2D analysis assumes that the target angle β_T of the pitch actuator is presented square to the target surface. Additionally, it is assumed that the analysis is being conducted when the pitch oscillation values are at their positive and negative maximums ($\theta = 90°$ and $\theta = 270°$). It is also noted that due to the symmetry of the nutating spray motion, the analysis of the pitch actuator holds true for the yaw actuator as well. The analysis seen in Figure 8 is conducted from an XYZ reference frame located at the centre of the projected circular spray pattern on the target surface. From the 2D analysis depicted in Figure 8, the following control equations were established:

$$\alpha = \alpha_T + \left(tan^{-1} \left(\frac{d_0 \, tan \, M_T}{d} \right) \right) cos\, \theta \tag{1}$$

$$\beta = \beta_T + \left(tan^{-1} \left(\frac{d_0 \, tan \, M_T}{d} \right) \right) sin\, \theta \tag{2}$$

where α is the yaw actuator angle, α_T is the target yaw angle position set by the user joystick, β is the pitch actuator angle, β_T is the target pitch angle position set by the user joystick, M_T is the magnitude of the nozzle nutation (set point value between $0° - 15°$) [6], and θ is continuously looped from $0 - 2\pi$ by 0.01 radian increments. Variable d represents the nozzle system's current distance to the target surface, while variable d_0 represents the nozzle system's initial distance to the target surface at which the operator established the desired spray pattern radius for the application.

Equations (1) and (2) represent a set of open loop control equations for fully autonomous control of the shotcrete tool's yaw and pitch actuators in response to changes in target distance. The equation set

Fig. 9. Radiation Detection Tool Final Physical Prototype

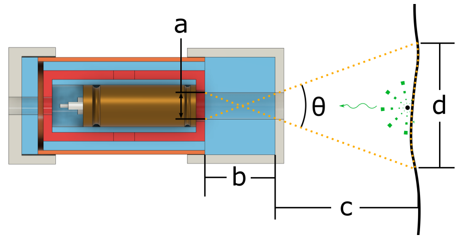

Fig. 10. Prototype Collimator and Detection Region Dimensions (a: 0.375" (9.53 mm), b: 1.00" (25.40 mm), c: 1.50" (38.10 mm), d: 1.50" (38.10 mm), $\theta : 41.1^{o}$)

allows the system to vary the magnitude of nozzle nutation in order to maintain a calibrated spray pattern radius based on the current distance to the target surface d. Equations (1) and (2) allow the autonomous control relationship over spray pattern radius to be established at any initial target distance d_0 and any initial magnitude of nozzle nutation M_T. This allows the system to be updated with new input data based upon the user desired spray pattern radius for the given situation.

3.2. Radiation Detection Tool Physical Prototype

Figure 9 shows the final physical prototype of the radiation detection tool and Figure 10 shows the dimensions used in the design of the collimator for the physical prototype.

As shown in Figure 10, the dimensions of the prototype collimator result in a detection region with approximately 41.1° of spread and a span of 1.50" (38.1 mm) across the target surface when the detection tool is held at a relative target distance of 1.50" (38.1 mm). The diameter of the collimator opening was chosen to be 0.375" (9.53 mm). This dimension was chosen as the maximum effective diameter of the chosen GM detector's (LND-712) end-window is 0.360" (9.14 mm). The intention was to prevent the collimator from limiting the maximum possible geometric efficiency of the LND-712 detector. The 1.00" (25.4 mm) length of the collimator was chosen to give the resulting detection zone span of 1.50" (38.1 mm) at 1.50" (38.1 mm) from the target surface. The dimensions of the detection zone were chosen to allow the detection tool to cover larger areas of the target surface during testing.

4. PROTOTYPE TESTING

An XY test platform was developed in order to create a controlled testing environment to establish the baseline performance metrics of the end-effector system's prototype tools. Given that at the time of this work the MASS system was still under development, independent system testing was the only viable method for establishing reliable experimental results of the end-effector system. The X axis of the platform was responsible for simulating the end-effector system being carried across the target surface. The Y axis of the platform was responsible for simulating the positioning of the end-effector system relative to the target surface. The XY platform effectively emulated the positioning that would be normally provided by the MASS robot's on-board DENSO-VP6242 manipulator arm. The continuously tracked position of the Y axis

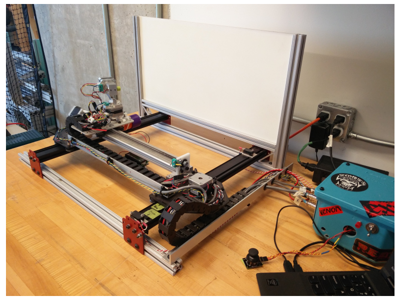

Fig. 11. XY Test Platform

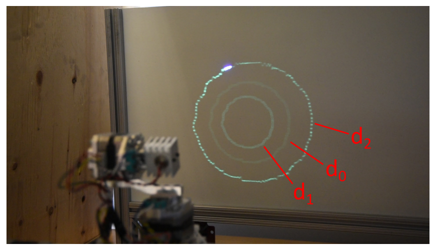

Fig. 12. Static Spraying Tests Results for a Fixed Nutation Circular Spray at: d_1: 11cm Target Distance, d_0: 21.0 cm Target Distance and d_2: 31.0 cm Target Distance

served as the system input for the robotic shotcrete tool when it was being tested in its fully autonomous operation mode. This simulated the incoming distance to target information that would normally be provided via the MASS's generated trajectory data. Figure 11 shows the XY test platform.

4.1. Robotic Shotcrete Spraying Tool Experimental Testing and Results

The target surface used for testing the prototype robotic shotcrete spraying tool was coated in a photochromic pigment paint (see Figure 11). The photochromic paint would illuminate when energized by the prototype's blue laser, allowing the path of the simulated shotcrete spray's central control point to be captured and then physically measured.

The prototype robotic shotcrete spraying tool's ability to autonomously maintain a fixed size circular spray pattern on a target surface was tested by positioning the prototype tool on the XY test platform at the three key target distances (d_0, d_1, and d_2) as detailed in Figure 8. The first position d_0 is a central point at which the diameter of the spray pattern is established, on the XY test platform this was chosen to be a target surface to nutation centre distance of 21.0 cm. The second point d_1 is ahead of the central position closer to the target surface, on the test platform this was chosen to be a distance of 11.0 cm. Lastly, the third point d_2, which is behind the central position and further away from the target surface, was chosen to be a distance of 31.0 cm. At each of these key positions, the laser module was activated momentarily in order to create a circular laser trail on the target surface. The diameter of the laser trail was then physically measured and recorded. The results of conducting this test with a fixed nozzle nutation can be seen in Figure 12.

As can be seen with the three circular spray patterns shown in Figure 12, the prototype does not generate a perfect circular spray pattern. Due to the slightly distorted shape of the circular spraying patterns, a vertical and horizontal measurement were taken of each spray pattern to obtain the mean circular diameter of each pattern. The recorded measurements and calculated mean circular diameters of the resulting spray patterns shown in Figure 12 are presented in Table 1. Additionally, as seen in Figure 12, the circular spraying patterns do not posses smooth curves, this is due to the low resolution of the stepper motors used to create the proof-of-concept prototype. Stepper motors were chosen for the prototype's construction due to physical design constraints. The result, however, could be improved if DC servo motors were used in place of the stepper motors in future prototypes.

Table 1. Measured Spray Pattern Diameters for Fixed Nutation Circular Spray at Target Surface Distances: d_0, d_1 and d_2

Dist. (cm)	Horizontal Dia. (cm)	Vertical Dia. (cm)	Avg. Dia. (cm)	%Diff.
d_1: 11.00	7.80	8.0	7.90	−35.0
d_0: 21.00	12.30	12.0	12.15	N/A
d_2: 31.00	18.00	17.5	17.75	+46.1

As can clearly be seen in Figure 12 and Table 1, as the shotcrete tool was advanced from a target distance d_0 to target distance d_1, the average diameter of the circular spray pattern reduced from 12.15 cm to 7.90 cm, an approximate 35.0% decrease in average diameter. Additionally, as the shotcrete tool was moved backward from target distance d_0 to target distance d_2, the circular spray pattern increased from an average diameter of 12.15 cm to an average diameter of 17.75 cm, an approximate 46.1% increase in average diameter. The shrinkage and growth of the circular spray pattern diameter as demonstrated in the fixed nutation magnitude test is what the robotic shotcrete spraying tool is intended to counteract and control. The test was conducted again with the active nutation control algorithm utilized in the prototype's control. Table 2 details the results of the physical measurements.

Table 2. Measured Spray Pattern Diameters for a Circular Spray Pattern With Autonomous Nutation Control at Various Target Surface Distances

Dist. (cm)	Horizontal Dia. (cm)	Vertical Dia. (cm)	Avg. Dia. (cm)	% Err.
d_1: 11.00	13.20	13.00	13.10	2.74
13.50	13.20	13.00	13.10	2.75
16.00	13.40	13.00	13.20	3.53
18.50	13.50	13.00	13.25	2.93
d_0: 21.00	13.00	12.50	12.75	N/A
23.50	13.40	12.70	13.05	2.35
26.00	13.50	13.10	13.30	4.31
28.50	13.20	12.90	13.05	2.35
d_2: 31.00	12.9	12.7	12.80	0.39

From the results presented in Table 2, it can be seen that the prototype robotic shotcrete spraying tool and its autonomous nutation control algorithm were able to successfully maintain the approximate average diameter of the circular spray pattern on the target surface at the various target surface distances, while demonstrating little variation in average measured pattern diameter. The percent error values listed in Table 2 for each target distance position were calculated by comparing the respective average measured spray pattern diameters at each position to the average measured spray pattern diameter of 12.75 cm established at the initial target distance d_0. The average percent error as calculated from the percent error values presented in Table 2 was determined to be 2.79%. The low average percent error of the physically measured results empirically shows that the prototype robotic shotcrete spraying tool and its open-loop control algorithm were able to successfully control the diameter of a projected circular spray pattern on the target surface by adjusting nozzle nutation in response to changes in target distance.

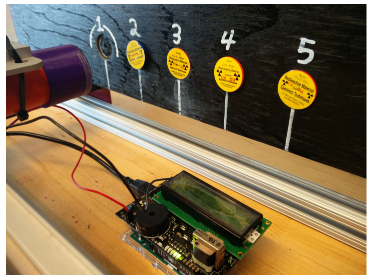

Fig. 13. Survey Experiment Radiation Profile Configuration: 1: Empty, 2: Cesium-137, 3: Cobalt-60, 4: Manganese-54, 5: Sodium-22

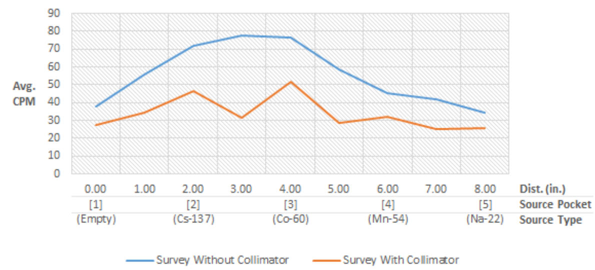

Fig. 14. Survey Experiment Results - Average CPM Readings Collimator Attached VS Detached

4.2. Radiation Tool Experimental Testing and Results

For testing the prototype radiation detection tool, a separate target surface comprised of a plywood surface with a series of equally spaced mounting pockets for radioactive disk sources was used (see Figure 13). The pockets allow disk sources to be embedded into the test surface at known locations. The source mounting pockets were spaced exactly 2.0" (50.80 mm) apart on centre and were labeled as Positions 1 - 5. The spacing of the source pockets was chosen based upon the dimensions of the radiation detection tool's detection region as described by Figure 10. According to Figure 10, with the collimator attached the detection tool should only be able to clearly detect sources within a 1.50" (38.1 mm) diameter circle on the target surface when a distance of 1.50" (38.1 mm) is maintained between the collimator and target surface. By placing the source pockets on 2.0" (50.8 mm) centres and using 1.0" (25.4 mm) measurement increments across the survey surface, the detector with the collimator attached is limited to viewing either no sources at all when measuring between pockets or only one source at a time when measuring at each pocket. This planned physical limitation allowed the function of the collimator to be isolated and evaluated.

A survey experiment was set up to test the performance of the radiation detection tool's collimator and circumferential shielding body when surveying sources of varying gamma energy and relative activity levels in close proximity. Four gamma sources were chosen from a source kit in order to create a unique radiation profile on the target surface. Figure 13 shows the sources selected and their configuration on the target surface for the experiment. The radiation profile depicted in Figure 13 was surveyed twice, once with the collimator attached, and once without. The resulting averaged counter per minute (CPM) readings from the collimator attached and detached surveys are presented in Figure 14 as an overlay line plot.

Analysis of the survey plots presented in Figure 14 show that there is a very apparent difference between the survey conducted with and without the collimator attached to the radiation detection tool. It can be seen that with the collimator attached to the radiation detection tool, the distinct peaks associated with the presence of a disk source can be clearly identified along the plot of the survey. This is particularly noticeable between Source Pockets 2 and 3. As expected, the CPM reading peaked when the detector was directly over the sources in Pockets 2 and 3 and then dipped down when measuring between the pockets at the 3.00" (76.2 mm) mark along the survey path. When the survey taken without the collimator attached was analyzed, it can be seen that the survey plot indicates the presence of one large radiation source located around the 3.00" (76.2 mm) mark along the survey path. When compared, it can be seen that though the survey conducted without the collimator attached does provide some indication of the location of the sources, their individual specific locations cannot be as easily discerned as in the survey taken with the collimator attached.

5. CONCLUSIONS

A proof-of-concept prototype robotic end-effector system for autonomous robotic shotcrete application and radiation surveying in underground uranium mining environments was developed. The system comprises two major sub-systems: 1) a robotic shotcrete spraying tool that is capable of autonomously maintaining and adjusting its circular spray pattern diameter on target surfaces in response to changes in target surface distance; and 2) a GM tube based radiation detection tool that uses lead shielding and a single hole collimator in combination with precise robotic positioning in order to capture localized radiation measurements of surfaces within radiation rich environments. Experimental testing showed the effectiveness of both sub-systems. For the first sub-system, the prototype tool empirically verified its ability to maintain circular spray pattern diameters at various target distances and demonstrated its application potential. For the second sub-system, the prototype tool demonstrated its ability to create radiation survey profiles that distinctly characterized the radiological profile of test target surfaces embedded with various radioactive sources.

ACKNOWLEDGEMENTS

This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and Cameco Corporation. Professor Roger Boudreau, Université de Moncton, is thanked for doing the French translation of the paper title and abstract.

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