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AN INNOVATIVE APPROACH TO AUTOMATED PIPE LABELING USING A ROBOTIC SYSTEM

A.H. Embong[1], S.B. Abdul Hamid[1], M.F. Nor Fathi[1]

[1] Department of Mechatronics Engineeing, International Islamic University Malaysia, Kuala Lumpur, Malaysia

Corresponding author:
syamsul_bahrin@iium.edu.my
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ABSTRACT

This paper introduces a novel robotic system designed to streamline and automate the traditional manual process of pipe labelling in industrial settings. The robot, equipped with a tailored design, an adjustable gripper, and bi-directional movement capabilities, can accommodate pipes of different sizes and shapes. Two printing technologies, stencil spray coating and flexographic printing, are integrated into the robot's print head, optimizing print quality. The system's functionality and efficiency were tested both in simulation and through a physical prototype. The robot demonstrated the ability to effectively clamp different pipe diameters and stencil at calculated distances by adjusting the servos' angle. The stencilling accuracy, evaluated against a hand stencil trained using the YOLOv3 algorithm, revealed an inverse relationship between stencilling accuracy and the distance between the stencil plate and pipe surface. Specifically, a 0.3 cm distance achieved an impressive 99% average accuracy. The system's innovation offers a significant improvement to industrial pipe labelling, providing a more efficient, accurate, and cost-effective alternative to conventional methods.

Keywords: *Outer Pipe Robot; Stencilling Robot; Printing Robot; Mechanism Design.*

1.0 INTRODUCTION

Pipes are integral components within industrial settings, facilitating the transportation of various substances including fluids, gases, and particulate matter, such as slurries, powders, and small, solid masses, to the requisite structures. Predominantly, steel pipes are employed due to their versatility, strength, and lightweight properties. Each pipe variant is utilized for specific applications, hence the necessity for clear differentiation and identification through labelling, which provides vital information regarding the pipe's length, size, and type [1]. Distinct codes and standards have been established for pipe marking, including those by the American Society of Mechanical Engineers (ASME), International Organization for Standardization (ISO), and American Society for Testing and Materials (ASTM) among others [2]. Pipe marking is essential, not only for safety management but also for facilitating efficient routine maintenance and expediting facility improvements.

Various techniques are employed within the industry for marking and stencilling steel pipes. These include thermal ink jet, continuous ink jet, dot matrix printing, flexographic printing, and stencil spraying [3]. The thermal ink jet method, for instance, leverages thermal energy to heat ink before applying it onto the pipe, resulting in a high degree of printing resolution and speed

[4]. In contrast, the continuous ink jet technique, which expels electrically charged ink droplets through an electric field, offers a greater print distance but at the expense of lower printing resolution [5]. The dot matrix printer, an affordable option using mechanical components, is less favourable due to its low printing speed and resolution [6], [7]. Flexographic printers, utilizing a letterpress technique with a roller, are less complex and yield a high printing resolution but are limited to specific words [8]. The stencil spray technique is a low-cost, low-complexity method that creates stencilled words on the pipe through paint spraying onto a stencil plate.

Given the manual operation and lack of durability of these devices in various locations, there is a palpable demand for a portable, automated solution. A robotic system capable of navigating and gripping the outer surface of pipes for marking purposes while moving autonomously is a promising innovation that addresses the industry's needs.

A plethora of scholarly inquiries have elucidated various mechanisms designed to securely grip pipes, such as clamp grippers and wheel-type grippers. Aracil et al. [9] have pioneered the development of an automated climbing robot designed to traverse the exterior of pipes. The project incorporates radial gripping, an innovative strategy that moves radially towards the pipe to stabilize the robot's movements. However, this gripping apparatus solely clamps the pipe, thus necessitating the use of gait techniques to mobilize the robot's body. This method requires an extensive degree of freedom and substantial power usage. This shortcoming can be ameliorated by implementing a wheel-type gripper that eliminates the need for gait techniques to mobilize the robot's body. In this respect, Lee [10] has devised a pipe inspection robot for nuclear power plants utilizing a wheel-type gripper to securely grip and manoeuvre along both straight and curved pipes. Three wheels are affixed to three linear actuators in a C-shaped structure to move radially towards the pipe, enabling the linear actuator to grip pipes of varying diameters. This form of gripping necessitates a high frictional force between the wheel and the pipe surface to ensure secure gripping without slippage.

This paper presents a robotic prototype capable of automatically stencilling and manoeuvring on pipes. The optimal stencil technique and pipe gripping technique have been selected for integration into a singular robotic system. The proposed stencil technique is stencil spray, a method that demands less operational complexity compared to other techniques. Moreover, the content of the print is prioritized over the quality of the print, making this printing technique a reliable choice for pipe stencilling. The stencil spray will be integrated into the robot alongside a wheel-type gripper equipped with a servo. Six servos are employed to grip the pipe, enabling the robot to accommodate various pipe diameters. Subsequently, the printed text on the pipe is evaluated to ascertain the percentage of similarity accuracy relative to manual stencilling, providing empirical verification.

2.0 METHODOLOGY

2.1 Identification and requirement of the design

In collaboration with our industrial counterpart, we have determined a series of fundamental requirements necessary for a robot designed to execute pipe stencilling across various pipe dimensions:

i. A robust mainframe is necessary to uphold the robot's body structure during the stencil application on the pipe, ensuring the stability and precision of the operation.
ii. A versatile gripper must be incorporated, capable of securely grabbing the exterior surface of the pipes, irrespective of their diameter, to facilitate efficient movement and operation.
iii. The inclusion of a sturdy and balanced chassis is obligatory to provide foundational support to the robot. This aids in maintaining stability when the robot is in motion or applying stencil on the pipe's surface.

iv. The integration of a print head, capable of linear movement, is crucial to perform accurate stencil application on the pipe. This functionality ensures seamless and precision-based stencilling.

2.2 Conceptual Design of Automatic Pipe Stenciling

Upon evaluating the requisite components for pipe stencilling and gripping, several designs were contemplated for the construction of the robot, as depicted in fig 1(a) to through fig 1(d). The design selected incorporated a hexagonal mainframe composed of two distinct sections, constructed from Polyvinyl Chloride (PVC) pipes, and a paint spray employed as the printing head. The finalized assembled robotic design, illustrated in Figure 1(e), encompasses six servomechanisms tailored to grip pipes of varying diameters by adjusting the servo's angle. Each servomechanism is equipped with linkages and wheels for enhanced mobility. The two upper servos employ a pair of Direct Current (DC) motors to facilitate the robot's linear movement along the pipe. The printing head utilized in this design adopts a stencil spray technique, whereby spray paint is applied to a stencil plate to generate a word pattern on the pipe. This pattern is determined by the spacing within the stencil plate, ensuring a precise and uniform application.

(a) (b) (c) (e) (f)

Figure 1: Construction of the robot showing different components (a) Main Frame (b) Gripper (c) Chassis (d) Printing Head (e) Fully Assembled

2.3 Component Selection based on Conceptual Design

Drawing from the established design layout, it is feasible to discern and incorporate the necessary electrical, mechanical, and control components. These elements are integral constituents of the overall design, each playing a pivotal role in ensuring the functionality and efficiency of the robot.

2.3.1 Stepper Motor Selection

The acceleration torque, T_a needed to move the print head on the belt drive actuator can be calculated using mass of the load, radius of the roller and acceleration and is shown by Eq. (1).

$$T_a = m_1 g r_1 + m_1 r_1^2 a + m_b r_1^2 a \quad (1)$$

Where; m_1 is the mass of the print head, m_b is the mass of the belt, r_1 the radius of the pulley and a is the angular acceleration.

2.3.2 Motor Selection for the Wheels

The torque, *T* needed for the motor to rotate the robot wheels on the pipe can be calculated using Eq. (2). To avoid slipping, the minimum friction force, $f_{friction}$ should be equal to the weight of the robot which can be calculated using Eq. (3).

$$T = rf \quad (2)$$

$$f_{friction} = \mu P = mg \quad (3)$$

Where; r is radius of the wheel, μ is the frictional coefficient of the robot wheel, P is the normal force from the pipe, m is the mass of the robot and g is the acceleration of gravity at 9.81 ms^{-2}.

2.3.2 Servo Selection

In this project, a servo is used to grip the steel pipe. The torque of the servo is important to make sure the robot can grip the pipe firmly. The equation for torque, τ can be calculated using Eq. (4).

$$\tau = rF \tag{4}$$

Where; r is the length from the servo motor to the DC motor that is connected using servo motor holder.

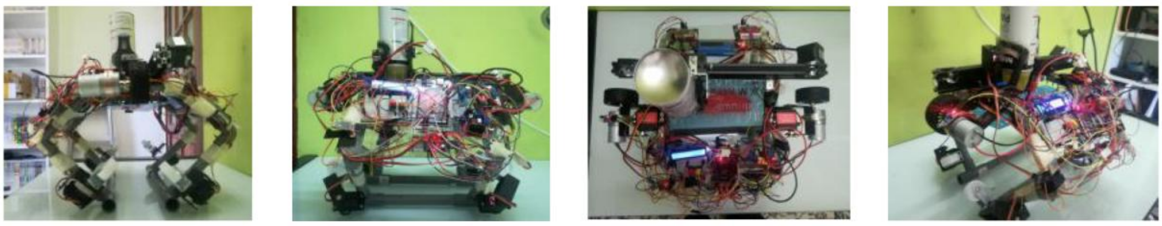
2.4 Construction of Prototype

2.4.1 Electrical Design

The robotic system leveraged an Arduino Mega microcontroller for regulating its electrical components, including six servo motors, a stepper motor, two DC motors, and various sensors. A PCA9685 driver was used to operate the servos through the SCL and SDA pins connected to the Arduino. Two 12V batteries powered the robot's electrical parts, with strategic placement on both sides for stability. One battery powered the DC motors while the other energized the 12V stepper motor and the PCA9685 servo driver module. An LM2596 voltage regulator reduced the 12V to 6V to power the servo driver module. The DC motors and stepper motor were managed by MD30B and L928N motor drivers, respectively.

2.4.2 Mechanical Design

Fig 2 presents a detailed depiction of the robot prototype's design. The utilization of PVC pipe as the primary material for the robot's body or chassis has been strategically employed to reduce the overall weight of the apparatus, thereby increasing its efficiency. This structure comprises two significant frameworks that form the foundational structure, further enhancing the robustness and stability of the robot.



Front View Side View Top View Isometric View

Figure 2: Multiple view of robot prototype (a) Front view, (b) Side view, (c) Top view, (d) Isometric view

2.5 Mechanical Design

The robotic system is bifurcated into two primary components: the gripping subsystem and the stencilling subsystem. The gripping subsystem is primarily manipulated by a servo, which engages in rotational motion to secure the pipe. The servo's torque generates a normal force from the robot's wheel to the surface of the pipe, effectively establishing a firm grip without risking slippage. The servos are designed to operate within a range of 0° to 90°, thereby ensuring that the pipe can be securely gripped in this angular spectrum. The robot's axial movement is facilitated by driving wheels, which are interconnected to all six servos. As the robot traverses along the pipe, it performs the stencilling action. A DC motor is employed to instigate the wheel's rotation, which subsequently dictates the word spacing on the pipe. The wheel's rotation is calibrated to align with the word spacing of the text to be printed by the printing head. The stencilling subsystem encompasses the movement of the printing head in a linear fashion along the pipe. An aerosol paint, affixed to the aluminium profile, serves as the printing head. A stepper motor, synchronized with a timing belt, propels the carrier containing the aerosol paint to spray through the stencil plate onto the pipe. The stroke of the printing head is contingent on the length of the aluminium profile. Fig 3 represents a simulation of the robot's operation, as modelled in Solidworks.

Figure 3: Solidwork simulation of the robot

2.6 Operating Sequence and Control Sequence

The robotic system is designed to function autonomously, employing an Arduino Mega to execute the movement and stencilling operations on the pipe. Prior to initiating the automatic operations, the user is required to provide specific information and input parameters to ensure the robot performs according to the desired specifications. The parameters to be selected include the size of the pipe to be stencilled, the distance between the stencil plate and the pipe surface, and the spacing length of the words to be stencilled. Fig 4 illustrates the graphical user interface, which allows the user to define the robot's operational parameters before it begins the autonomous stencilling process. The application establishes communication with the Arduino system via Bluetooth.

Figure 4: Graphical User Interface (GUI) for Automatic Stencil for Steel Pipe in Android OS.

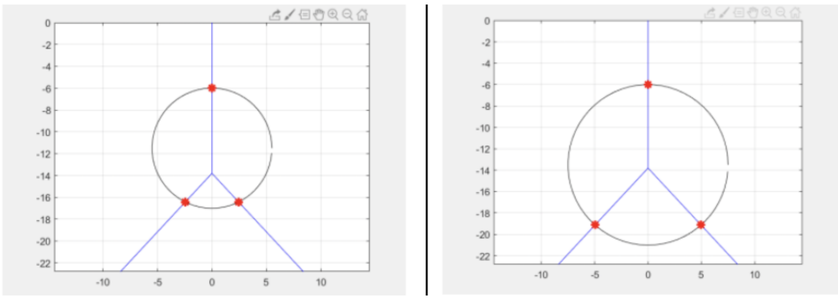
When seeking to securely grip the pipe, two salient parameters must be evaluated: the diameter of the pipe and the distance between the stencil plate and the pipe surface. Initially, the servo's rotation is contingent on the pipe's diameter. The servos, attached on both sides of the robot's mainframe, should rotate at a specific angle in accordance with the pipe's diameter to be gripped. Three servos are mounted on each side of the mainframe: one positioned at the top and two at the bottom. The GUI is designed as to be as intuitive as possible.

To ensure a firm grip on the pipe, the servos operate synchronously, rotating at identical angles. This is applicable when the distance between the stencil plate and the pipe surface is not factored in, allowing the robot to grip the pipe at the centre of the mainframe. Nonetheless, the distance between the stencil plate and the pipe surface remains a constant that cannot be altered. In order to adapt to varying pipe sizes and distances between the stencil plate and the pipe surface, a MATLAB code has been developed. This code computes the angle for the three servos on the robot's mainframe, namely servo1 (top servo), servo2 (bottom-left servo), and servo3 (bottom-right servo), based on the pipe's diameter and distance. Fig 5 illustrates a plotted diagram of the circle (representing the pipe) and lines originating from each servo, displayed in blue, based on two different pipe diameters at a distance of 1 cm. The point of intersection between the circle and the line is indicated by a red dot. The length of the blue line to the intersection point is computed, and the servo's angle can then be determined based on this length in accordance with Eq. (5).

$$Angle\ of\ servo, \theta = sin^{-1}\frac{H-r}{L} \tag{5}$$

where; H is the length of the blue line to the intersection point, r is the radius of the robot wheel and L = length of the servo link.

Drawing upon the calculations derived from Eq. (5), the angular orientation of each servo was computed and documented. These calculations were conducted for both 11 cm and 15 cm diameters, and for a variety of distances - specifically 0.3 cm, 1 cm, 1.5 cm, and 2 cm - for each respective diameter.



(a) (b)

Figure 5: Simulated Plotted Diagram of Pipe and Servo Connections (a) Diameter 11 cm Distance 1 cm (b) Diameter 15 cm Distance 1 cm

The positioning of the robotic system along the pipeline significantly influences the distribution of the stencilled words. The regulation of this spacing necessitates the computation of the wheel rotation duration, which is directly related to the desired displacement or the interval between successive stencilled words. This correlation is mathematically expressed and determined via Eq. (6)

$$Time, t = \frac{S_d}{d\pi\omega} \tag{6}$$

where; S_d is the spacing distance, d is the diameter of the wheel at 0.068 m and ω is the rotational speed of the DC motor at 20 ms^{-1}. Substituting Eq. (6) with the following spacing distance, S_d of 0.05 m, 0.10 m and 0.15 m gives the different time needed to rotate the wheel as shown in Table 1.

Table 1: Time take to rotate wheel for different spacing distance.

No.	**Spacing Distance, S_d**	**Time to rotate wheel, *t***
1	0.05 cm	0.702 s
2	0.10 cm	1.404 s
3	0.15 cm	2.106 s

3.0 RESULTS AND DISCUSSION

3.1 Spacing of Stencil Work on Pipe

In accordance with the suggested design framework, the robotic mechanism is intended to traverse the length of the pipe for the purpose of imprinting stencil designs. The extent of this movement is directly dependent on the desired word spacing. However, owing to the comparatively diminutive size and length of the pipe, the robot's stability becomes a challenge. This instability can also be attributed to the servo mechanisms employed, which are unable to securely grip the pipe due to insufficient torque, thus increasing the risk of the robot losing its grip. Because of these limitations, the experimental design for testing stencil word spacing was adjusted from manoeuvring the robot in relation to the pipe, to repositioning the pipe relative to the robot. Three distinct word spacings (0.05 m, 0.1 m and 0.15 m) were calculated through adjustments to the DC motor's rotation speed. The outcomes of these three different spacings are depicted in Fig. 6.

(a) (b) (c)

Figure 6: Stencilled print for 3 different spacing (a) 0.05 m (b) 0.1 m (c) 0.15 m

3.2 Determining the Best Distance for Stencilling

In anticipation of the real-world application of the automatic stencilling robot, critical parameters, such as the optimal distance for stencilling, must be established. To delineate this optimal distance, a series of experiments were conducted in which the robot stencilled on a pipe at varying distances between the stencil plate and the pipe surface. This experimental design replicated the conditions under which the word 'mno' was manually stencilled and trained via Google Colab, thus maintaining consistency in the testing environment. The parameters held constant throughout these trials included the distance from the stencil plate to the paint spray, fixed at 3 cm, and the spacing between stencilled words, maintained at 5 cm. Fig 7 illustrates the stencilling outcomes at distances of 2 cm, 1.5 cm, 1.0 cm, and 0.3 cm between the stencil plate and pipe surface. Subsequently, each stencil produced by the robot was evaluated in PyCharm, with the accuracy percentage calculated in relation to the manual stencil. This comparative analysis allowed for a comprehensive evaluation of the robot's performance at various stencilling distances. Table 3 encapsulates the accuracy percentages for each tested distance, providing an empirical basis to determine the optimal distance for automatic stencilling.

(a) (b) (c) (d)

Figure 7: Stencilled print for 3 different distances (a) 2 cm (b) 1.5 cm (c) 1 cm (d) 0.3 cm

Table 2: Percentage Accuracy for different Images at different distances

Image Number	**Distance**				
	2 cm	**1.5 cm**	**1 cm**	**0.3 cm**	**2 cm**
1	81	81	98	99	81
1	71	98	99	99	71
2	69	61	99	99	69
3	88	87	88	99	88
4	88	88	94	99	88
5	**79.4**	**83**	**95.6**	**99**	**79.4**
Average	81	81	98	99	81

The data extrapolated from Table 3 reveals that the minimum mean percentage of similarity accuracy amounts to 79.4% when the distance between the stencil plate and the pipe surface is maintained at 2 cm. The average percentage of similarity accuracy demonstrates an inversely proportional relationship with the aforementioned distance, i.e., as the distance decreases, the average percentage accuracy increases. Notably, at a distance of 0.3 cm, the average similarity accuracy soared to approximately 99%, closely mirroring the manual stencilling precision. However, the potential for further enhancing the accuracy of these calculations exists. This can be achieved by supplementing the dataset with a larger number of images to facilitate more comprehensive training via Google Colab and YOLOv3.

4.0 CONCLUSION

In a bid to enhance efficiency, a robotic system was developed to automate the pipe stencilling process, replacing traditional manual methods. The robot, designed through Solidworks, comprises a mainframe, adjustable gripper, chassis, and print head, eliminating the need for oil paper templates. It can move bi-directionally along the pipe using six servos, six wheels, and two DC motors. Adjustability of these servos accommodates varying pipe diameters. A unique Matlab code determined servo angles based on the pipe's diameter and stencil plate-pipe surface distance. The robot's capability was tested by comparing its outputs to manually stencilled words, with the accuracy measured in percentages. Image datasets from hand-stencilled words trained using YOLOv3 algorithm were used for this evaluation. The robot performed stencilling at different distances from the pipe, with a 0.3 cm distance yielding the highest average accuracy (99%). This suggests the closer the stencil plate is to the pipe surface, the higher the accuracy of the robot's output resembles hand-stencilled results.

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CONFLICT OF INTEREST

Competing interests: No relevant disclosures.

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