Motion Control Analysis of a Spherical Robot as a Surveillance Robot

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Abstract. A robot is designed to be a helping tool for the human to work in the dirty, dull and dangerous environment, such as underwater, underground and disaster area. The most suitable type of robot for surveillance is a spherical robot. This type of robot has the ball-shaped, therefore minimize the contact to the ground, reduce friction, and energy consumption. All the components are shielded inside a shell; therefore it is possible to make this robot to be waterproof. One of the applications of this spherical robot is an industrial piping surveillance robot. The robot considered in this study is semi-autonomous where a user moves the robot through user interface installed in an android. The user can control the robot by examining the monitor. The input analysis of how the signal can move the robot is discussed in this paper. To prove the effectiveness of the proposed method, the robot is moved in an experimental setting including a pipe-like tunnel to test it. The robot moved and controlled smoothly, and it can maintain the position of the camera (robot head) always up to ensure the clear vision for the user.

Keywords: Industrial inspection, motion control, spherical robot, surveillance.

1. Introduction
The robot is intended as a helping tool for a human to work in the dirty, dull, and dangerous area. The definition of dirty, dull, and dangerous can be extended to the places that are not easy to reach by human such as underwater, air-surveillance, undergrounds, and disaster areas. The most suitable type of robot for surveillance is mobile robots that can fly, slide, roll, etc. reaching far and difficult places. The need for surveillance is increasing due to its wide range of application scenarios [1]-[4].

Urban search and rescue, industrial inspection, and military purpose require a surveillance robot. One of those industrial inspections is piping inspection, before or after its installation. Piping is also one of the places easier to reach by a robot rather than deploying human due to its size and position such as an underground, installed pipe. Piping surveillance robot does not have to be a sophisticated robot, a simple robot equipped with inexpensive sensors is sufficient, such as a vision, gas, or proximity sensor. Granosik 2006 designed a serpentine robot for industrial inspection due to its flexible motion capability including climbing steps [2]. Ahrary 2008 discussed the application of mobile robot for sewer system named Kantaro [3].

Any robots can conduct an initial piping inspection before installation, however, after installation or during scheduled maintenance inspection, the environment inside the pipe might not be suitable for some robots, for example, water might still flowing inside the pipe. Therefore the application of waterproof and flexible robot is necessary.
The spherical robot is the type of mobile robot that has high motion flexibility and can be designed to be waterproof. Crossley 2006 reviewed the design of the spherical rolling robot [5]. A spherical robot is a ball-shaped robot having all the drive mechanism and control inside a spherical shell. Therefore, the driving system has to transfer the power to the outer shell. The spherical robot is a holonomy robot that able to move in omnidirectional [6]. This type of robot relies on internal weight balancing and mass distribution to achieve smooth motion. Chase 2012 reviewed the mechanical driving principles of the spherical robot [7]. The spherical robot can be equipped with many types of sensor such as vision [8], proximity [9], and navigation sensors [10]. The installation of sensors makes its design to be more challenging to ensure the positioning of the camera and other sensors to stay on the designed place during robot rolling motion, for example, the installed camera is always in up position to ensure the clear visibility of an inspected environment [11][12]. Due to its stochastic motion behavior, it is quite challenging to make a spherical robot utterly autonomous during the industrial inspection [13]-[20].

This paper proposes a design and application of a spherical robot as an industrial surveillance robot. This robot is designed as the extended eye for a human to check the condition of the piping system or other places that are difficult to check by human due to the location. The robot considered in this study is semi-autonomous where a user moves the robot through user interface installed in an android. The user can control the robot by examining the monitor. The input analysis of how the signal can move the robot is discussed in this paper. Experimental application in a similar environment proves the effectiveness of the proposed method.

2. Spherical Robot Design
Among the many types of mobile robots, the spherical robot has some benefits. It has only a single contact to the ground therefore minimal friction occurs and reduces the energy required for locomotion. Its shape makes it possible to move in a tight space such as pipe, and since it can be completely shielded, it can be designed to be water or gas proof.

![Figure 1. Schematic diagram of the spherical robot.](image)

The spherical robot is designed with the principle of pendulum system to ensure the ballast inside the shell always climbs up during its locomotion. Figure 1 shows the schematic diagram of the spherical robot design consists of vision and robot system. The vision system consists of a camera and laptop or PC for monitoring. Robot system consists of android to give input and control in moving the robot through Bluetooth HC-05 module. Input from Android processed by a microcontroller (Arduino Nano)
to move DC Motor Driver and DC Motor. PWM input from Android controls the velocity of DC motor through Bluetooth HC-05.

**Figure 2a.** The whole view of the spherical robot

**Figure 2b.** The design structure

Figure 2 shows the spherical robot design considered in this study that is divided into two parts, the head, and body. Figure 2a shows the whole body and figure 2b shows the inside shell view. An IP camera is attached to the head, and the camera is connected to the user interface using WIFI wireless communication. The user interface used to control this spherical robot is an android. At the body part, Arduino Nano, DC motor driver L293 D, and Bluetooth HC-05 are attached.

**Figure 3.** Modeling of a spherical robot in figure 2

Based on the modeling shown in figure 3, the motion analysis of the spherical robot considered in this study is given by

\[ T = J \frac{d^2 \phi}{dt^2} \]  \hspace{1cm} (1)

where \( T \) is the torque, \( J \) is the moment of inertia, and \( \phi \) is the rotation angle.

The motion analysis in eq. 1 can be extended to

\[ rmg \sin \theta = I_{ball} \omega \]  \hspace{1cm} (2)
where \( m \) is the mass of the robot, \( r \) is the distance between the center of gravity of the ball and spherical robot, \( \theta \) is the tilting angle, \( I_{ball} \) is the moment of inertia, \( g \) is the gravitational force, \( \omega \) is the angular velocity and \( v \) is the translational velocity.

The locomotion of the spherical robot considered in this study is by assuming the turning radius only depends on the roll angle of the robot without taking account of the gyro effect of the rotation body. It means the gyro effect does not hold the direction of the rotating shaft.

3. Result and Discussion

The height of spherical robot in this study is 10 cm, the diameter is 15 cm, and the weight is 2kg. The robot is designed by using components with specification as follow:

a. Power supply,
   6800 mAh power bank supplies the robot with input power 3.7 V\(_{DC}\).

b. Arduino Nano
   The controller installed in Arduino Nano is AT Mega 328 with operational voltage 5 V and input power 7 – 12 V, 13 pins of digital I/O 13 Pin Analog I/O 6 pin, \( I_{DC} \) per pin I/O 40 mA, flash memory 32 KB with 0.5 KB for bootloader, SRAM 2 KB, EEPROM 1 KB, Clock speed 16 MHz, and weight 5 gram.

c. Driver DC motor IC L293D
   \( V_{in} \) min 4.5, \( V_{in} \) max, 36 V, 16 pins, four output channels, 600 mA, max 1.2 A \( I_{output} \) per channel and applied to 2 DC Motors.

d. DC motor
   12 output voltage, rotation speed 110-450 rpm, wheel diameter 65mm, maximum torque 800gf, and maximum and minimum current is 70mA (250mA MAX)

e. IP Camera
   IP Camera IR Led black, with infrared, night vision and real-time video capture, 5V voltage input, 2.4G 802.11n Antenna Wireless, can be accessed by Android, iPhone, and Microsoft, format video AVI, M-JPEG video coding, 15fps±1fps video frame rate, 1/3" color CMOS sensor, and 4:3 image ratio.

Arduino is the primary controller to move the robot through the PWM signal that activates the motor driver. The designed program moves the robot based on user command of forward, reverse, turn right, and left. A user moves the robot using a user interface installed in an android that connected to the IP camera. Therefore, the user can see what the robot “sees,” and still be able to control the robot without being able to see the robot, i.e., robot position is inside a pipe.

The analysis of how the signal sends by Bluetooth in moving the robot is given in figure 3. Figure 3a to 3d show the Tx signal from a user interface in moving the spherical robot. The analysis of how the controller interprets the Tx input signal is given as follow:

- Figure 3a. shows Tx digital signal “01010011 01010100110” transferred by Bluetooth HC-05. The signal is converted to be decimal “83” in microcontroller program, and decimal “83” in ASCII code is “S.” Therefore, “83” is set for variable “S” means STOP. Variable “S” indicates that all the inputs from Arduino is “0” therefore no voltage flow to the right and left motors. Therefore, the robot is in the “STOP” position.

- Figure 3b. shows Tx digital signal “01000110 01010001100” transferred by Bluetooth HC-05. The signal is converted to be decimal “70” in microcontroller program, and decimal “70” in ASCII code is “F.” Therefore, “70” is set for variable “F” means FORWARD. Variable “F” indicates that input 2 and 3 from Arduino are “1”, therefore both right and left motor will be powered and the robot moves FORWARD.

- Figure 3c. shows Tx digital signal “01000010 01010000100” transferred by Bluetooth HC-05. The signal is converted to be decimal “66” in microcontroller program, and decimal “66” in ASCII code is “B.” Therefore, “66” is set for variable “B” means FORWARD. Variable “B” indicates that input 1 and 4 from Arduino are “1”, therefore both right and left motor will be powered and the robot moves BACKWARD.
• Figure 3d. shows Tx digital signal “01010010  01010100100” transferred by Bluetooth HC-05. The signal is converted to be decimal “82” in microcontroller program, and decimal “82” in ASCII code is “R.” Therefore, “82” is set for variable “R” means turn RIGHT. Variable “R” indicates that input 3 from Arduino is “1” and input 2 is “0”, therefore right motor will be powered, left motor will be off, and robot turns RIGHT.

• Figure 3d. shows Tx digital signal “01001100  01010011000” transferred by Bluetooth HC-05. The signal is converted to be decimal “76” in microcontroller program, and decimal “76” in ASCII code is “L”. Therefore, “76” is set for variable “L” means turn LEFT. Variable “L” indicates that input 3 from Arduino is “0” and input 2 is “1”, therefore right motor will be off, left motor will be powered, and robot turns LEFT.

The summary of TX signal analysis and voltage measurement results are shown in table 1, to show that the robot is effectively controlled from a user interface.

![Figure 3a. Tx signal when the robot is stop](image1)

![Figure 3b. Tx signal when the robot is forward](image2)

![Figure 3c. Tx signal when the robot is reverse](image3)

![Figure 3d. Tx signal when the robot turns right](image4)

![Figure 3e. Tx signal when the robot turns left](image5)

Figure 3. Tx signal analysis of robot motion relative to user signal using android interface
Table 1. Voltage measurement in spherical robot

| Bluetooth Input | Arduino Nano Microcontroller | DC Motor Driver L293D Input (Volt) | Motor 1 Input (Volt) | Motor 2 Input (Volt) | Robot Motion |
|-----------------|------------------------------|-----------------------------------|---------------------|---------------------|--------------|
| Pin 5, Pin 6, Pin 9, Pin 10, Pin 15 | Pin 2, Pin 7, Pin 10 | Input 1 | Input 2 | Input 3 | Input 4 |
| F 0 | 1 | 1 | 0 | 0 | 5 | 5 | 0 | 0.4 | 7.4 | 7 | 0.4 | Forward |
| B 1 | 0 | 0 | 1 | 5 | 0 | 0 | 5 | 6.8 | 0.4 | 0.4 | 7 | Reverse |
| R 1 | 0 | 1 | 0 | 5 | 0 | 5 | 0 | 6.9 | 0.2 | 6.8 | 0.2 | Turn Right |
| L 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 | 0.4 | 6.8 | 0.2 | 6.9 | Turn Left |
| S 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Stop |

Figure 4. Spherical robot in an experimental setup

To show the effectiveness of the proposed method, the spherical robot is moved in an experimental setup as shown in figure 4. The experimental setup consists of an area with a pipe-like tunnel to test robot motion and vision. The robot moves smoothly, and the robot vision is shown in figure 5. Figure 5 shows that the robot can maintain the position of the camera (robot head) always up.

Figure 5a. Robot vision outside pipe-like
Figure 5b. Robot vision before entering pipe-like
Figure 5. Robot vision
4. Conclusion
A spherical robot is an ideal type of mobile robot to be deployed as a surveillance robot in industry, such as for checking the piping system. Due to its shape, the robot contact to the ground is only at one point, therefore minimize the friction occurs during its locomotion and can reduce power consumption. All the robot components are situated inside a shell. Therefore it is possible to make the robot to be a waterproof robot and deployed in the wet area. This paper shows a spherical robot designed to be an industrial surveillance robot. The considered robot is a semi-autonomous robot that is moved by a user through a user interface installed in an android. This paper shows the input signal analysis of how to move the robot, and to prove the effectiveness of the proposed method, the robot is moved in an experimental setting including a pipe-like tunnel to test it. The robot moved and controlled smoothly, and it can maintain the position of the camera (robot head) always up to ensure the clear vision for the user.

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