Design, analysis and development of pipeline inspection robot

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Abstract

Pipe line inspection is an important task where robotics could be applied extensively. Robotic pipeline inspection devices reported in literature are primarily of internal type, requiring special preparation of pipelines for their deployment and retrieval. In this context, robotic systems which can traverse along the external surface of the pipeline structure have the advantage of being able to do inspection without blocking the pipeline. In this paper we have done the design, analysis and development of an external pipeline inspection robot. The proposed system consists of a base with two arms on both sides. It has four wheels, two large hollow ones enclosing the complete base structure and two smaller ones at the end of each arm. For inspection, the system hugs the pipe along its outer periphery such that, only the wheels are in contact with the surface and then drives along the length of the pipeline. Approximate mathematical modelling of the system has been performed and its working has been analysed through an ADAMS-Matlab Co-simulation. Based on the results, a prototype has been manufactured, consisting of multiple digital servos for arm joints and dc motors for the wheels, along with on-board controllers and wireless camera. The system can be controlled through WiFi from a remote station. Field trials have shown that the robot is capable of inspecting pipelines with an outer diameter of about of 200 mm. The application potential of the system includes surface and exposed large diameter pipeline inspection in outdoor and industry.

Keywords: Pipeline inspection, mobile robot, modelling, simulation.

1 Introduction

Development of pipeline inspection systems is a major industrial domain where robotics is being used extensively. Since their inception in the nuclear, electric or gas power plants and distribution systems these robots have resulted in significant savings within a year or less of purchase [1]. Applications such as mandated inspection of nuclear power plants or petroleum pipelines are often hazardous to such an extent that they are seldom performed due to safety concerns of the inspecting personnels. Robotic inspection systems become inevitable solutions in such situations. They offer comprehensive

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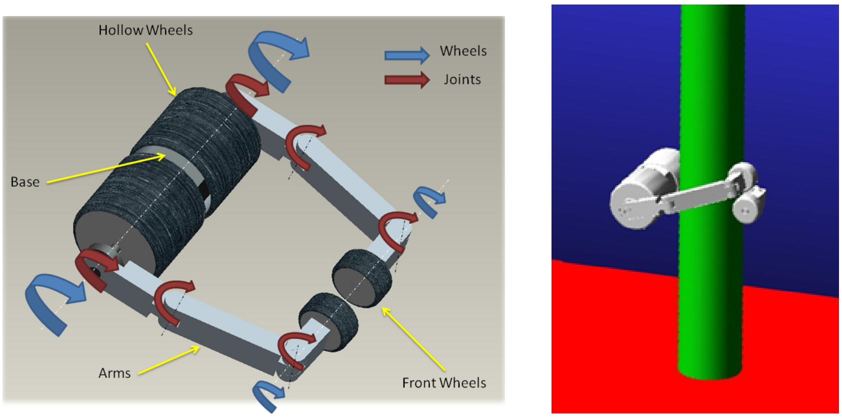


(a) Proposed design (b) Climbing methodology

Figure 1: Inspection robot

inspection, safety, flexibility and reliability; thereby helping to solve maintenance and operation problems economically [7].

Most of the systems developed till date are of internal inspection type. They use different methods for clamping and moving inside the pipeline system. The most common being magnetic wheels which gets attracted to the ferrous pipelines [2]. Other methods include using expandable mechanisms which are often fitted with large wheels or treads to provide sufficient grip on the interior of the pipeline [3]. Some robotic inspection systems use clamp and pull mechanism [4], which basically consists of a pair of grippers connected together by means of a linear actuator. Clamp and pull systems provide the most reliable means of locomotion, even though they are often more complex and slow when compared to other methods. Till date very few systems have been developed for external inspection of pipelines [5]. The major problem with internal type inspection systems is that, the pipeline service has to be stopped through out the duration of inspection. Moreover pipelines supplying oil or gas need special preparation before the robot can be inserted for inspection. Often wireless communication methods also face problems when the robot travels deep inside thick metallic pipes. Based on the literature survey it becomes clear that there is a need for external pipeline inspection robot which is capable of handling variations in diameter of the structure as well as climb along slight inclinations. They must be of clamping type with wheels for locomotion, so that they can inspect maximum length of the pipeline in a given time. On-board power supply and wireless communication needs to be provided to allow for flexibility of operation and freedom of movement. In this paper we have presented the design, analysis and development of such an inspection robot.

The rest of the paper has been organised as follows: Section 2 describes the proposed design and climbing methodologies. Section 3 describes the controller design followed by section 4 which presents the simulation results. Section 5 describes the prototype development. In the sixth section the experimental validation , results and observations have been presented.

2 Proposed system

The conceptual design and basic mathematical analysis of the robot has been presented previously in [6]. The design as shown in Fig. (1(a)), consists of a base with two arms on both sides. Each of the arms is designed to have three DOF by means of three rotary joints. The battery and associated electronic circuitry are housed in the base. This base is then fully enclosed by two hollow cylindrical wheels that are driven separately. Two smaller wheels attached at the end of each arm. For climbing or moving along a pipeline the two arms on the system will encircle the structure such that the front and back wheel maintain proper contact with the surface. Then the system as a whole can be driven along the length of the pipeline while the arms adjust for variations in the diameter of the structure or other surface irregularities, as shown in Fig. (1(b)). In this paper we will analyse the ability of the proposed design to climb on pipelines without any branches or bends.

3 Controller Design

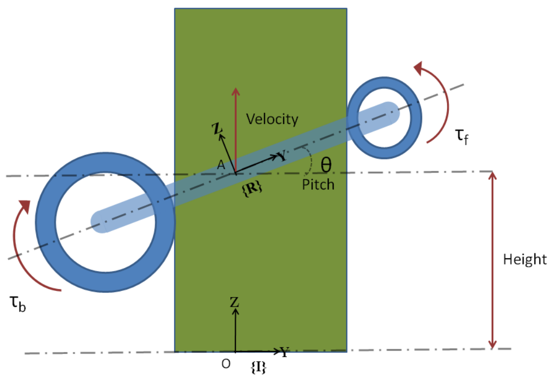


Figure 2: Controller inputs and outputs

The basic requirement of the robot is to climb up to a desired height and maintain the same with minimum deviations. This can be achieved using a simple PID controller. The control law will be written for the combined force to be applied using all the four wheels. All four wheels together make up three contact points in total as per the assumption that both the back wheels together make a single contact. The controller design is described in Fig. 3.

The control law is given by:

$$F = K_p e + K_i \int edt + K_d \frac{de}{dt} + mg \quad (1)$$

Where:

K_p, K_i and K_d are the proportional, integral and derivative constants.
e is the error given by:
e = desired height - current height
and $\frac{de}{dt}$ = - current velocity, since desired velocity = 0
m is the mass of the system and g is the gravitational constant.

The control law is written under the assumption that both the back wheels are driven by the same torque τ_b and the both the front wheels by τ_f. Once the amount of force to be exerted has been decided by the controller the amount of torque to be exerted by each wheel can be obtained as per the following equations:

$$\begin{aligned} \tau_{fh} &= \frac{F}{4} R_f \\ \tau_{bh} &= \frac{F}{4} R_b \end{aligned} \quad (2)$$

Where:

τ_{fh} and τ_{bh} are the torque to be applied on the front and back wheels respectively.
R_f and R_b are the radius of the front and back wheels.

The above controller will ensure that the system climbs up to the desired height, but the robot could also rotate about the X-axis as shown in the Fig. (3). Initially when the system clamps on to the pipeline the orientation may be level, but while climbing, due to slipping or surface irregularities the orientation of the robot may change. In order to maintain the orientation stable through out the operation of the system a second controller is to be employed. This controller will monitor the pitch angle θ and make adjustments on the wheel torques so that the system holds the desired orientation.
A simple P controller is designed for the above purpose. The control law for the same can be given as follows:

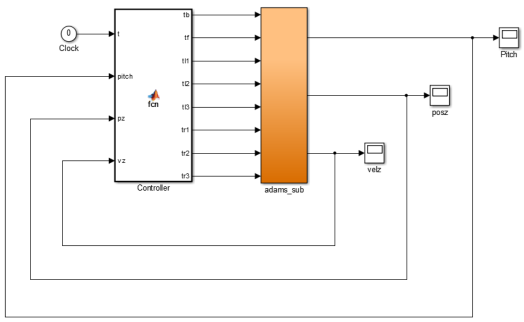
$$\begin{aligned} P_f &= \quad K e_p \\ P_b &= -K e_p \end{aligned} \quad (3)$$

Where:

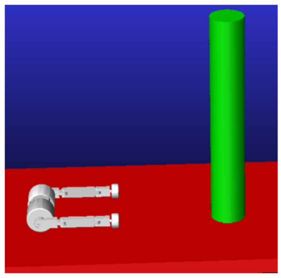
P_f and P_b are the pitch correction for the front and back wheels respectively.
K is the proportionality constant.
e_p is the error in pitch, given by: $e_p = \theta_d - \theta$
θ_d is the desired pitch angle (usually 0^o).
θ is the current pitch angle.

Based on Eq. (2) and (3), the final control input to the front and back wheels can be given by:

$$\begin{aligned} \tau_f &= \tau_{fh} + P_f \\ \tau_b &= \tau_{bh} + P_b \end{aligned} \quad (4)$$



(a) Simulink controller



(b) ADAMS model

Figure 3: Co-simulation

4 Simulation

In order to verify the feasibility of the proposed design simulations need to be carried out on the robot. This would also enable us to verify the reliability of the control strategies that was discussed above. A simplified model of the robot was prepared in ADAMS and the feedback controller was designed in Simulink. Finally a co-simulation was setup between the two. The Simulink controller decides upon the joint angles for each arm and the torques to be applied on each wheel and dictates it to ADAMS during the simulation. ADAMS in turn reports back the instantaneous height and orientation of the robot to Simulink.

The density of the ADAMS model was adjusted so that the total weight of the system comes around 7 Kg. For the simulation, the system was made to climb upon a cylindrical structure with a constant diameter of 200mm. The coefficient of friction between the wheels and the cylindrical surface was kept constant at 0.6. A torque of 4 Nm was set at each of the arm joints. All the above values were set based on the calculations as mentioned in [6].

The Simulink controller monitors the height, climbing velocity and pitch angle as given by ADAMS. In the beginning of the simulation, the Simulink block dictates the desired joint angles for each of the arm to the ADAMS module. Once the system clamps on to the cylindrical structure the feedback controller provides the torque values to be applied on the front and back wheels so as to climb to the desired height while maintaining the desired orientation. During the simulation, the system was made to climb to a height of 1m, while maintaining a pitch angle of 0^o.

The simulation results are shown in Fig. 4. The plots clearly reveals that the system is able to climb up to the desired height of 1m in 15 seconds, with an average climbing speed of 10 cm per second. It is also shows that the system is able to hold the desired height reliably. The plot of pitch angle with respect to time shows that even though initially the pitch angle varies from zero as the system clamps on, the controller brings it back to stable orientation within 15 seconds. In summary the results verify the effectiveness of the proposed climbing strategy as well as designed control strategy.

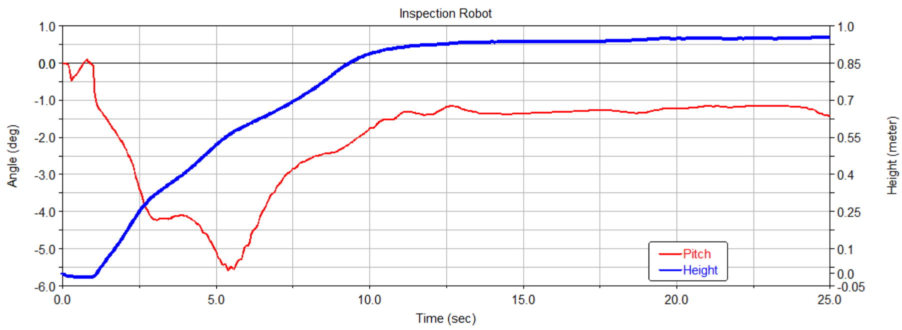
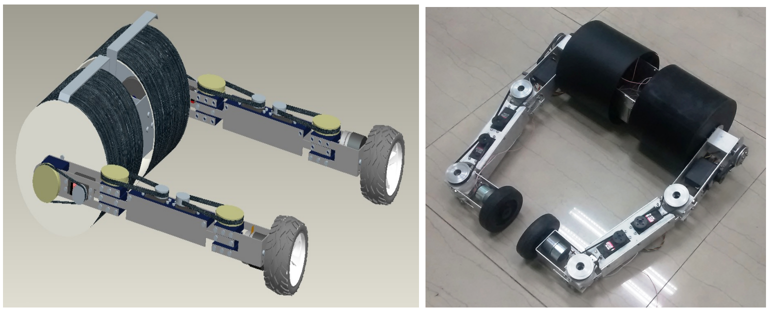


Figure 4: Simulation results

5 Prototype development



(a) CAD model (b) Final assembly

Figure 5: Prototype

For the prototype development, a detailed design was done in Pro Engineer as shown in Fig. (5(a)). For the arm joints, servo motors are used. DC gear motors are used to drive the front and back wheels. In order to measure the climbing height and velocity, ultrasonic range sensor is used. In addition, a 9 DOF Razor inertial measurement unit is mounted on the base of the robot, which measures the orientation of the robot in real-time and gives the readings to the on board processor. The complete electronic system used in the robot is shown in Fig. (6). A single board computer, the BeagleBone Black is used as the on board processing unit. An AVR AT Mega 328 micro-controller is used for controlling the servo motors. The SBC is connected to the base station through WiFi, allowing the system to be controlled remotely via joystick input. The on board camera can be used for remote monitoring purposes. The completed prototype is shown in Fig. (5(b)). The system has all overall width of 500mm, length of 575mm and height of 180mm and weighs nearly 8Kg.

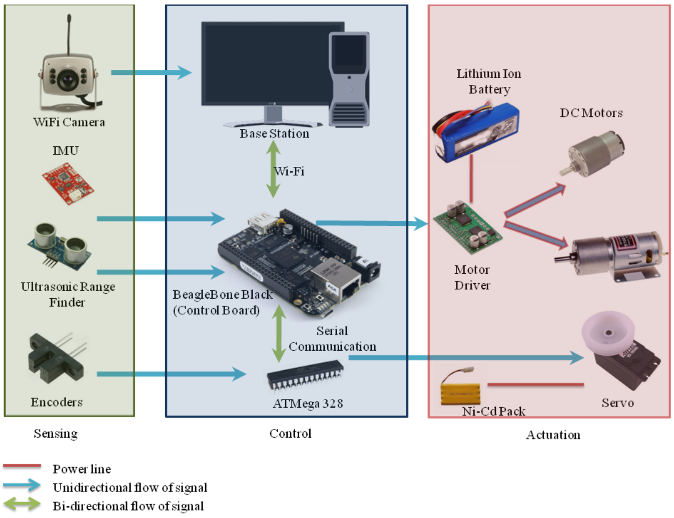
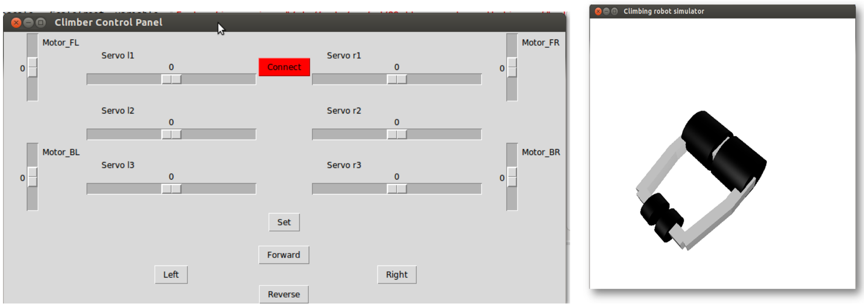


Figure 6: System architecture



(a) User interface (b) Simulator

Figure 7: Control software

A control software was written in python for driving the robot remotely. The software essentially consists of two modules running on separate threads:

1. A GUI which allows the user to manually set the speeds of each of the drive motors and the angles of each of the arm joints. The GUI as shown in Fig. (7(a)) was made using Tkinter.

2. A 3D simulator showing the current configuration of the robot. The simulation was updated in real time so as to show the configurations attained by the arms while the servo joints were moved. The simulator as shown in Fig. (7(b)) was built using Vpython.

Figure 8: Experimental validation

6 Validation

For experimental validation, the system was made to climb on a pipeline of 200mm diameter. The system was controlled from base station over WiFi using the control software. The system was driven between the start and end points multiple times while the inclination of the pipeline was slowly increased, starting from . For each trial, the time taken for climbing, the distance climbed by the system and the inclination of the pipeline was noted. The angle of inclination was increased till the system started slipping.

Table 1: Results of experimental validation

Inclination of pipeline (in degrees)	*Climbing Velocity (in cm/s)*
4.0	6.5
5.5	5.8
8.0	4.75
12.0	3.41
15.0	2.40
18.0	1.60
20.0	1.20
25.0	0.0

The results of the experiment are tabulated in table 1. Fig. (8)shows the prototype on a horizontal pipeline. During the experiment it was seen that at 25^0 the driving gears on the back wheels started slipping under the load acting on the motor. This is the result of misalignment in the gear assembly and can be corrected by ensuring proper mounting of the motors and the gears.

7 Conclusion

This paper proposed to address the problem of using robotic systems for external inspection of pipelines. A novel mechanical design and climbing strategy was proposed for pipeline inspection. This was followed by controller design and validation using a Co-simulation between ADAMS and Matlab. The results verified the feasibility of the proposed design and climbing strategies. Based on the design, a prototype was developed that could be controlled remotely over WiFi. Finally experimental trials were conducted on a 200mm diameter pipeline. The system achieved reasonably good climbing speeds on horizontal and inclined pipelines (up to an angle of 25^0). For inclination greater than 25^0 the base wheel transmission system was slipping due to misalignment and excessive load.

The developed prototype did verify the practicality of the proposed design. As of now the system is manually controlled. The joint angles and the wheel velocities are set manually. With proper sensor suite and software the system can be made to climb autonomously to a desired height. This could make it easier to use future versions of the system for various applications like surveillance, inspection and maintenance.

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