International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 1, No. 2, July 2012

Research Paper

DEFECT IDENTIFICATION IN PIPE LINES USING PIPE INSPECTION ROBOT

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Inspection robots are used in many fields of industry. One application is monitoring the inside of the pipes and channels, recognizing and solving problems through the interior of pipes or channels. Automated inspection of the inner surface of a pipe can be achieved by a mobile robot. Because pipelines are typically buried underground, they are in contact with the soil and subject to corrosion, where the steel pipe wall oxidizes, and effectively reducing wall thickness. Although it's less common, corrosion also can occur on the inside surface of the pipe and reduces the strength of the pipe. If crack goes undetected and becomes severe, the pipe can leak and, in rare cases, fail catastrophically. Extensive efforts are made to mitigate corrosion. Pipe inspection is necessary to locate defects due to corrosion and wear while the pipe is transporting fluids. This ability is necessary especially when one should inspect an underground pipe. In this work, Pipe Inspection Robot (PIR) with ability to move inside horizontal and vertical pipes has been designed and fabricated. The robot consists of a motor for driving and camera for monitoring.

Keywords: PIR, Inspection robot, Pipe inspection, Pipe defects, Mobile robot

INTRODUCTION

Robotics is one of the fastest growing engineering fields of today. Robots are designed to remove the human factor from labor intensive or dangerous work and also to act in inaccessible environment. The use of robots is more common today than ever before and it is no longer exclusively used by the heavy production industries. (Horodinca *et al.*, 2002).

The inspection of pipes may be relevant for improving security and efficiency in industrial plants. These specific operations as inspection, maintenance, cleaning etc. are expensive, thus the application of the robots appears to be one of the most attractive solutions. Pipelines which are tools for transporting oils, gases and other fluids such as chemicals, have been employed as major utilities in a number of countries for long time.

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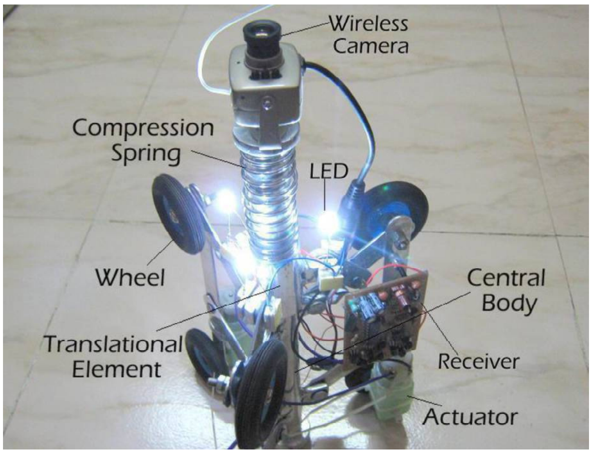
Recently, many troubles occur in pipelines, and most of them are caused by aging, corrosion, cracks, and mechanical damages from the third parties. Currently, the applications of robots for the maintenance of the pipeline utilities are considered as one of the most attractive solutions available (Mhramatsu *et al.*, 2000) Pipe Inspection Robot is shown in Figure 1.

Figure 1: Pipe Inspection Robot (PIR)



SELECTION OF MATERIALS

The materials used for this machine are light and rigid. Different materials can be used for different parts of the robot. For optimum use of power the materials used should be light and strong. Wood is light but it is subjected to wear if used for this machine. Metals are the ideal materials for the robot as most if the plastics cannot be as strong as metals. Material should be ductile, less brittleness, malleable, and high magnetic susceptibility.

Among the metals, aluminum is the material chosen for the linkages and the common rod, which is made as hollow for reduction in weight. However, other materials are chosen for the motor. The materials chosen for the motor should have high magnetic susceptibility and should be good conductor of electricity. The materials are copper and so on. But aluminum is chosen as the materials for the linkages and central body because of its much-desired properties.

Aluminum has lightweight and strength; it can be used in a variety of applications. Aluminum alloys with a wide range of properties are used in engineering structures. The strength and durability of aluminum alloys vary widely, not only because of the components of the specific alloy, but also because of heat treatments and manufacturing processes.

Effect of Temperature:

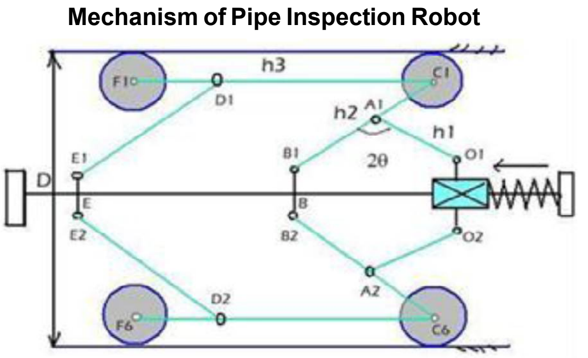
Another important property of aluminum alloys is their sensitivity to heat. Workshop procedures involving heating are complicated by the fact that aluminum, unlike steel, will melt without first glowing red. Aluminum alloys, like all structural alloys, are also subject to internal stresses following heating operations such as welding and casting. The problem with aluminum alloys in this regard is their low melting point, which make them more susceptible to distortions from thermally induced stress relief.

- The toughness, as measured by crack propagation energy, decreases as yield stress increases.
- At the same yield stress, the under aged structure has greater toughness than the over aged structure.

MECHANISM

The mechanism involved here is a four bar mechanism consisting of three revolute joints and one prismatic joint as depicted (Figure 2) (Paul E Sandin, 2003).

Figure 2: Mechanism of PIR



$H = 2r + 2d + 2h_2\cos\theta$

h_1 = 24 mm, h_2 = 56 mm, h_3 = 84mm (h_1 = OA, h_2 = BC = D, h_3 = CF)

Where *D*-Diameter of the pipe in mm,

d-Distance between EE' in mm.

h_1, h_2, h_3 are the length of the links in mm.

r-Radius of the wheel.

For uniform Diameter, assume $\theta = 45°$

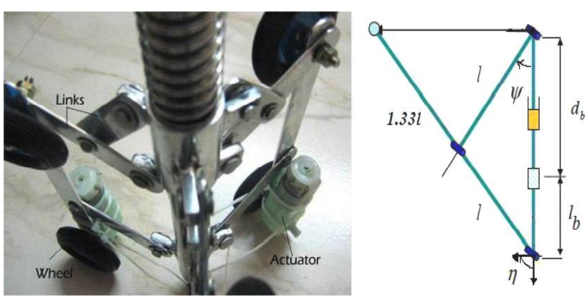
$D = 2*25 + 2*22.5 + 2*56*\cos 45°$

$D = 174.195$ mm

Kinematics of Mechanism

The linkage structure can be represented as (Figure 3). This is a four-bar mechanism consisting of three revolute joins and one prismatic as depicted. Thus, the motion of all revolute joints can be described in terms of the displacement d_b (Jadran and Roth, 2006).

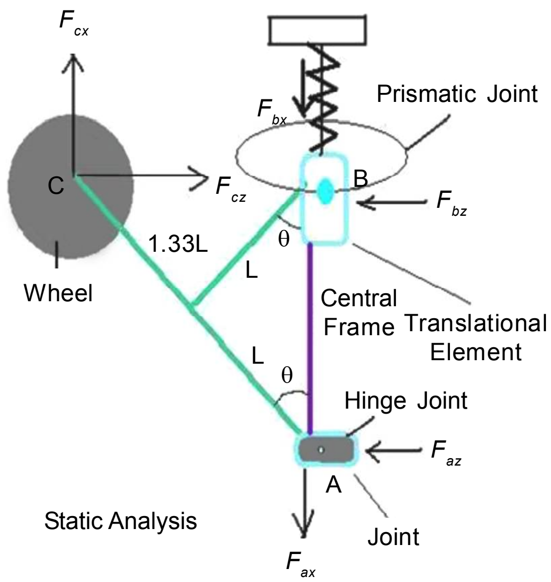
Figure 3: Linkages of PIR



Static Analysis

In order to decide the actuator size, it is necessary to perform the static analysis. Assume that in (Figure 4), F_{cx} and F_{cz} denote the reaction force and the traction force exerted on the four-bar by the driving wheel, respectively. Now applying the virtual work principle to the free-body diagram of (Figure 4) gives:

Figure 4: Static Analysis



$$\delta W = F_{cz}\,\delta z - F_{bx}\,\delta x = 0$$

where F_{bx} is a spring force.

This is because only F_{cz} and F_{bx} conduct work. The corresponding coordinates of these forces relative to the coordinate located at the A hinge are expressed as:

$$z = 2.33l\sin\theta,\ x = 2.33l\cos\theta$$

$$\delta W = F_{cz}\ \delta(2.33l \sin\theta) - F_{bx}\ \delta(-2.33l \cos\theta)$$

$$= F_{cz}{*}2.333l \cos\theta\delta\theta - F_{bx}{*}2.33l \sin\theta\delta\theta. = 0$$

Rearranging gives

$$F_{bx} = F_{cz}{*}\cos\theta/\sin\theta$$

Thus, the spring force at the prismatic joint B is related to the normal force F_{cz} by

$$F_{bx} = F_{cz}{*}\tan\theta$$

And the total weight W of the robot is the sum of the six traction forces exerted on the belt. Thus, each traction force F_{cx} is one six of the whole weight of the robot structure. Thus, the size of the actuator enclosed in the wheel is calculated by

$$\tau = F_{cx}{*}R = WR/6$$

Where R is the radius of the wheel. From the above static analysis, it is also known that the large weight of the robot does not influence the foldable motion of the linkage.

The spring stiffness is found to be 0.9 N/mm and the spring force is found to be 4.5. Thus we came to the conclusion that the actuator should have atleast 3 kg torque. So, we used 3 actuators with 1.5 kg torque (total 4.5 kg torque). It is safe to use an actuator with more torque than the required torque.

DESIGN

Helical Spring (Figure 5)

Inner dia – 20 mm

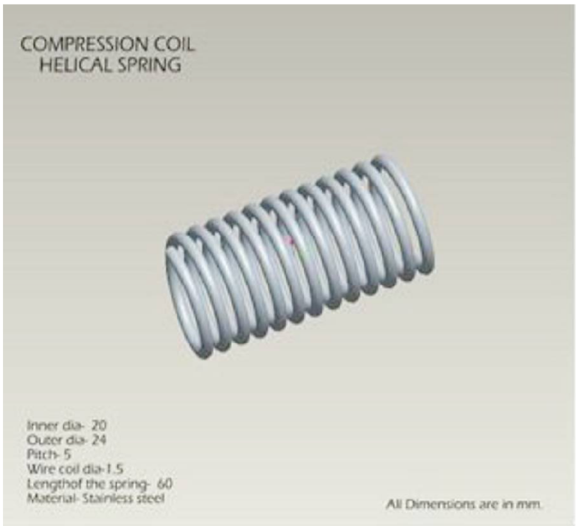
Outer dia – 24 mm

Pitch – 5 mm

Length of the spring – 60 mm

Material – Stainless steel

Figure 5: Helical Spring



Translational Element (Figure 6)

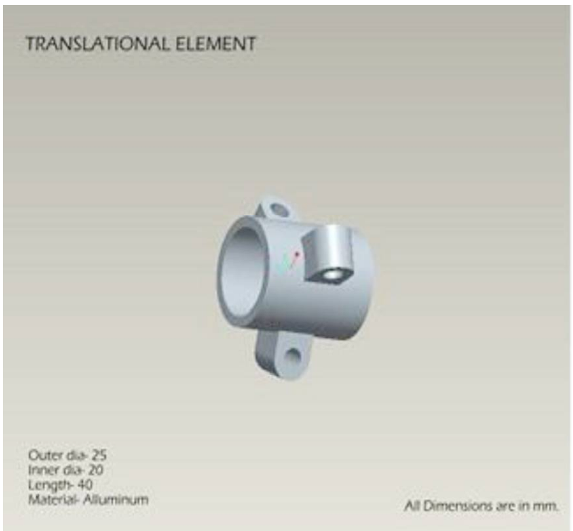
Inner diameter – 20 mm

Outer diameter – 25 mm

Length of the element – 40 mm

Material – Aluminum

Figure 6: Translational Element



Wheel

Dia – 50 mm

Distance Between the Extreme Drilled Holes (Figure 7)

Link 1 – 24 mm

Link2 – 56 mm

Link3 – 84 mm

Thickness – 3 mm

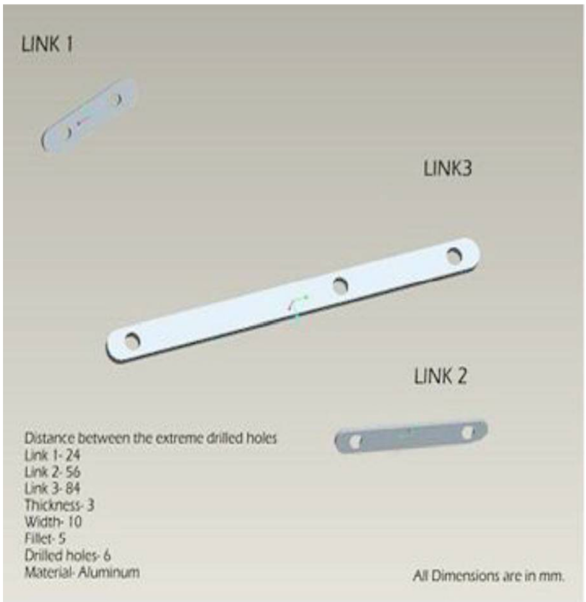
Fillet – 5 mm

Width – 10 mm

Drilled holes – 6 mm

Material – Aluminum

Figure 7: Distance Between the Extreme Links



Central Element (Figure 8)

Hollow

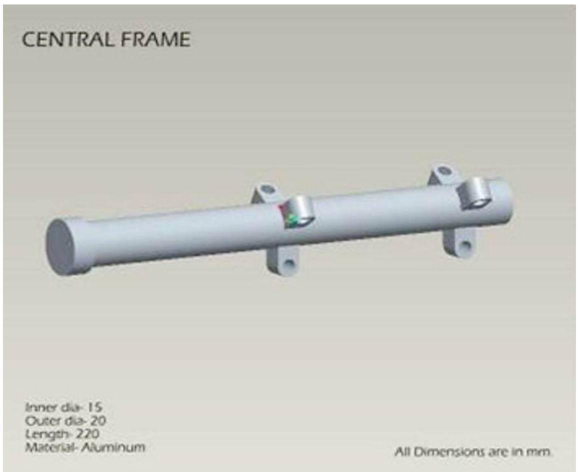
Inner dia – 15 mm

Outer dia – 20 mm

Length – 220 mm

Material – Al

Figure 8: Central Element



EXPERIMENTATION

The main part of the fabrication of the pipe inspection robot involves drilling and shearing operations. The drilling is done for making holes for insertion of the rivets. The linkages are linked to one another using rivets. In a single 4 bar linkage each of the four links are connected by a rivet. Three linkages are connected to the central body at 120 degrees using rivets.

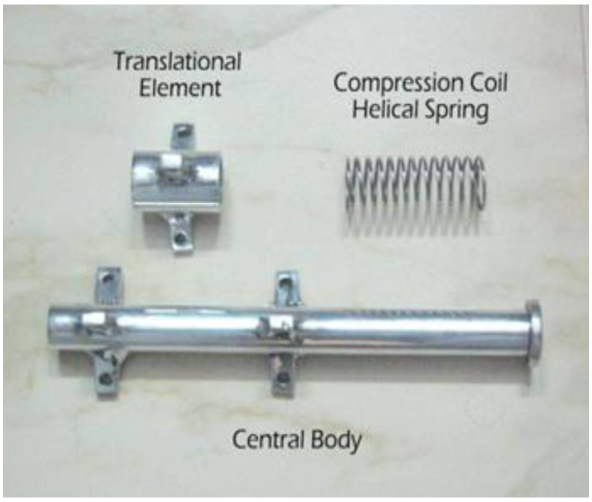
Thus, drilling operation is needed for facilitating holes for the insertion of these rivets. The rivet diameter used here is 5 mm. Thus, the hole drilled must be 5 mm or higher. But, the drilled hole for the central body at its centre would be 15 mm for insertion of pencil batteries. The actual linkages are cut from an aluminum sheet. The thickness of the aluminum sheet is around 3 mm. The single aluminum is cut into rectangular sheets of required length and breadth. This is done using a shearing machine. Welding also needs to be done to attach the joints which hold the links by a rivet. Welding process used was the brazing process.

COMPONENTS OF PI ROBOT

Central Frame

Central body is the frame of the robot (Figure 9). It supports all other components and holds batteries at the centre of the body. The joints are brazed on the central frame at 120 degrees. The central body is drilled and its ends are threaded internally for the insertion of pencil batteries and closing with externally threaded caps. Wireless camera is fixed at one end of the frame.

Figure 9: Major Components



Translational Element

Translational Element (Figure 9) is the movable part in the robot which slides along the central body for repositioning in case of pipe diameter variation. This element is drilled at the centre for the translating along the central body. This will restrict the links to some extreme angles beyond which it could not be translated. The extreme angles are found to be 15 degrees and 60 degrees. The joints are brazed on the translational element at 120 degrees for the links to be fixed onto it.

Compression Spring

A spring is an elastic object used to store mechanical Energy. Spring used here is made out of hardened steel. Compression spring (Figure 9) is mainly used to exert tension. The purpose of spring is as follows:

- The force that the minirobot mechanism exercises on the pipe walls is generated with the help of an extensible spring.
- The helical spring disposed on the central axis assures the repositioning of the structure, in the case of the pipe diameters' variation.

Links

Each resistant body in a machine which moves relative to another resistant body is called Kinematic link or element. A resistant body is which do not go under deformation while transmitting the force. Links (Figure 10) are the major part of the robot which translates motion. Links are connected to form a linkage. The mechanism involved here is a 4 bar mechanism which has 3 revolute pairs and 1 single prismatic pairs as depicted. Links holds the receiver, switch, and 9v battery for the camera. Also it supports the actuator.

Figure 10: Links

Actuators

Actuators are the drive for the robot (Figure 11). Since we have chosen aluminum material for fabrication, the weight is comparatively less. So the motor should have 2 kg torque to travel inside the pipe. We used 3 motors which has 1 kg torque to make the robot in motion. The supply for the motor is 6v which is from the central body. The 3 motors are placed at 120 degrees and are supported on the links by a tag.

Figure 11: Actuator

Batteries

Batteries give supply for a motor and wireless camera. Motor and radio frequency gets 6v supply from the central body and wireless camera gets supply from a 9v battery. And 3v batteries for transmitter which has two toggle switch. One is for motor forward and reverse control and the other one is for glowing LED's.

Wireless Camera

Wireless communication is the transfer of information over a distance without the use of electrical conductors or "wires". The distances involved may be short or long (Figure 12).

Figure 12: Wireless Camera

Wireless cameras have a channel also. The receiver has channels to tune in and then you get the picture. The wireless camera picture is sent by the transmitter the receiver collects this signal and outputs it to your TV or in a desktop by a TV tuner card. Camera is fixed at the one end of the frame and the robot is meant for inspection inside a pipe which could be monitored in a desktop. Camera transmits signal to the receiver which receives the signal and is connected to the monitor to view the inner side of the pipe.

MACHINING PROCESS

Conventional machining is one of the most important material removal methods. The three principal machining processes are classified as turning, drilling and milling.

Machinability Ratings

- Aluminum – Good to excellent
- Brass – Good to excellent
- Cast Iron – Fair to good

There are various drilling tools or drilling machines available. The drilling machine used was the radial drilling machine.

Radial Arm Drill Machine

The biggest radial arm drill presses are able to drill holes as large as four inches (101.6 mm) in diameter. But for this project only holes of 5 mm and 6 mm were needed. The drilling was done on the aluminum sheets for the required dimensions and then the finished component was filed and reverses drilled using a larger drill bit for a good finish.

Boring Operation

The boring process can be carried out on a lathe for smaller operations, but for larger production pieces a special boring mill (work piece rotation around a vertical axis) or a horizontal boring machine (rotation around horizontal axis) are used. A tapered hole can also be made by swiveling the head.

Gas Welding

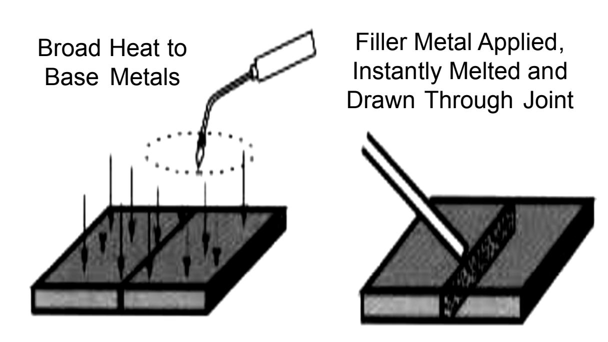
The most common gas welding process is oxyfuel welding, also known as oxyacetylene welding. It is still widely used for welding pipes and tubes, as well as repair work. Oxy fuel equipment is versatile, lending itself not only to some sorts of iron or steel welding but also to brazing, braze-welding, metal heating (for bending and forming), and also oxyfuel cutting.

The equipment is relatively inexpensive and simple, generally employing the combustion of acetylene in oxygen to produce a welding flame temperature of about 3100 °C.

Brazing

Brazing is the joining of metals through the use of heat and a filler metal—one whose melting temperature is above 840 °F (450 °C) but below the melting point of the metals being joined (Figure 13).

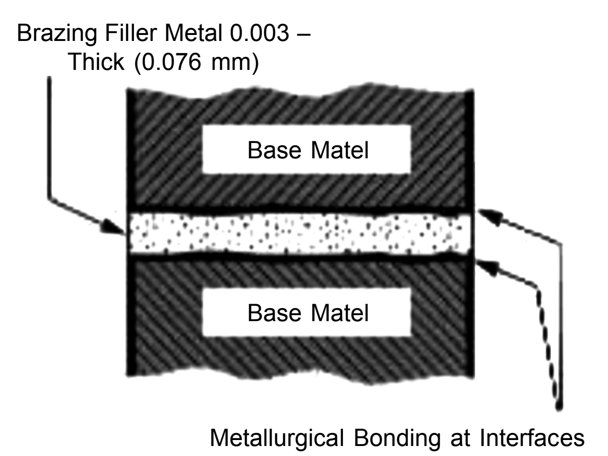
Figure 13: Principle of Brazing



A brazed joint is made in a completely different way from a welded joint. The first big difference is n temperature. Brazing doesn't melt the base metals. So, brazing temperatures are invariably lower than the melting points of the base metals. If brazing doesn't fuse the base metals, how does it join them? It joins them by creating a metallurgical bond between the filler metal and the surfaces of the two metals being joined (Figure 14).

Surface Grinding Operation is used to produce a smooth finish on flat surfaces.

Figure 14: Bonding at Interfaces



Surface Finishing

Polishing and buffing (Figure 15) are finishing processes for smoothing a work piece's surface using an abrasive and a work wheel. Polishing is a more aggressive process while buffing is less harsh, which leads to a smoother, brighter finish.

Figure 15: Links Before and After Buffing

WIRELESS COMMUNICATION

Radio Frequency

Radio Frequency (RF) radiation is a subset of electromagnetic radiation with a wavelength of 100 km to 1mm, which is a frequency of 3 KHz to 300 GHz, respectively. This range of electromagnetic radiation constitutes the radio spectrum and corresponds to the frequency of alternating current electrical signals used to produce and detect radio waves. RF can refer to electromagnetic oscillations in either electrical circuits or radiation through air and space. Like other subsets of electromagnetic radiation, RF travels at the speed of light.

Antenna

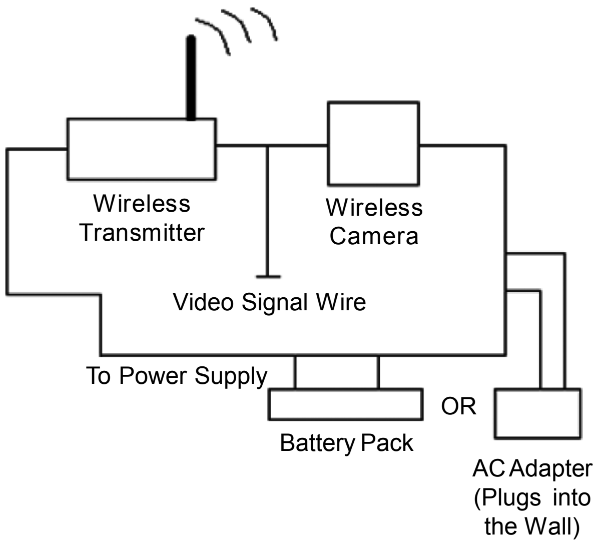
An antenna (or aerial) is a transducer designed to transmit or receive electromagnetic waves. In other words, antennas convert electromagnetic waves into electrical currents and vice versa.

THE WIRELESS CAMERA

Transmitter

The power is provided by battery and/or transformer/adapter. The complete (Figure 16) wiring for the wireless camera and transmitter end follows:

Figure 16: Wireless Camera Transmitter Block Diagram 1

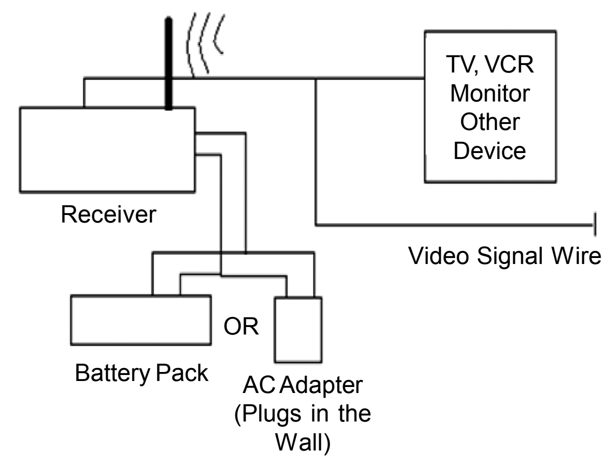


As in Figure 16, the camera sees an image, sends it to the transmitter, and the transmitter sends the signal out to the air. The receiver picks up the signal and outputs it to a TV/Monitor/Digital Video recorder.

Receiver

After the wireless camera and transmitters have provided the wireless video signal the receiver collects this signal and routes it the Monitor, TV, VCR or alternative recording or viewing device as shown in Figure 17. The receiver accepts the wireless transmitters signal and then out puts it to your TV, VCR, Monitor or Other Recording Device. The receiver needs only power and a Device to view and or record the Signal/Video.

Figure 17: Wireless Camera Receiver Block Diagram 2



PI ROBOT TEST RESULT

Following the design and modeling of the proposed mechanism a prototype unit was built. The prototype was built for a robot with the weight of 2.7 kg. The body of the robot was fabricated mostly from aluminum. The Robot was driven by three dc motors. PIC robot tested successfully for movement in horizontal and vertical pipes. The robot has a good mobility and ability to pass over small obstacles. The important thing is the amount of force between robot tracked units and pipe wall. Even in horizontal moving, attachment of the up tracked unit in addition to bottom ones, improve the movement of robot. Because in this state 3 motors participate in robot move although friction is more. In addition to this, the robot is more stable and distribution of load on different actuators is more similar. Monitoring the pipe inside was suitable and the control of different actuators was effectively possible. The model of PIR is drawn with the help of mechanical engineering software tool, Pro ENGINEER Which shown in (Figure 18) and PIR while inspection in various stages are shown in (Figure 19).

Figure 18: Pro-E Modeling of PIR

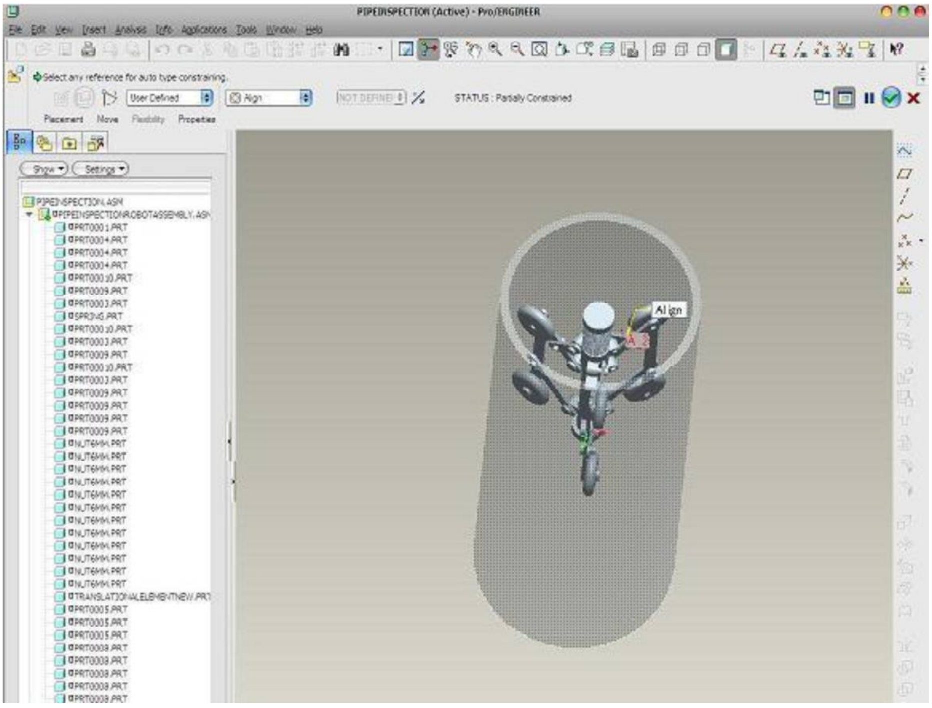
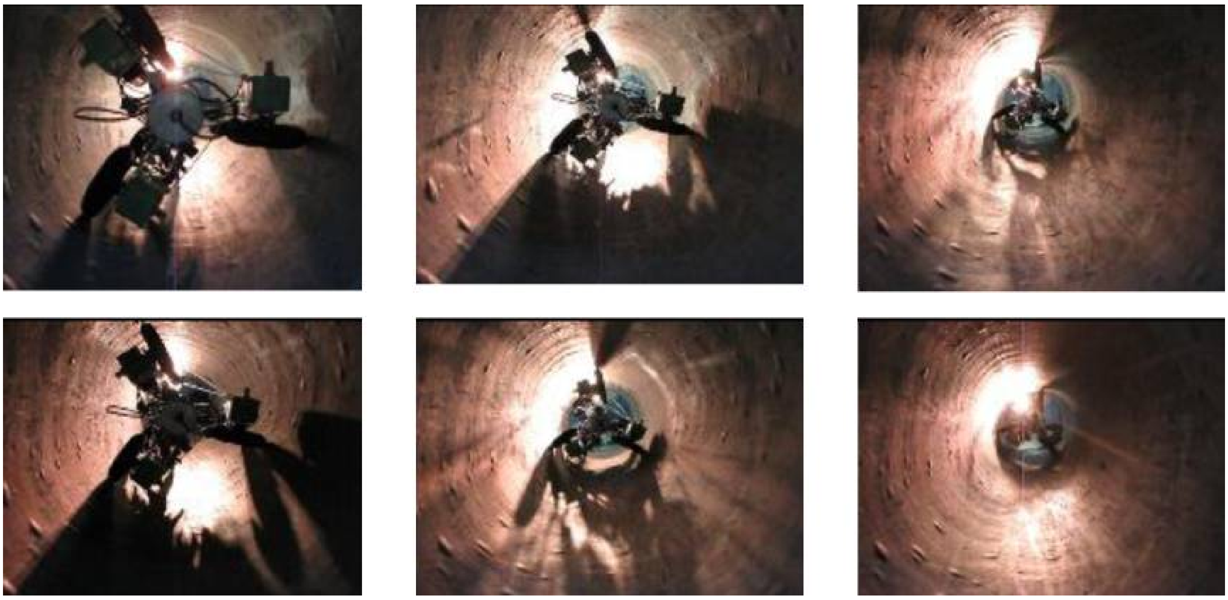


Figure 19: Stages in Locating Defects Inside the Pipe



CONCLUSION

A very important design goal of the robotic systems is the adaptability to the inner diameters of the pipes. So, we had proposed a new design in inspecting pipelines. The major advantage is that it could be used in case of pipe diameter variation with the simple mechanism. We developed a pipe inspection robot that can be applied to 140- 180mm pipeline. The kinematics of mechanism and actuator sizing of this robot have been investigated. A real prototype was developed to test the feasibility of this robot for inspection of in-house pipelines. We used a PCB board that can operate DC motor. Good conceptive and element design could manage all the problems. The types of inspection tasks are very different. A modular design was considered for PIC that can be easily adapted to new environments with small changes. Presence of obstacles within the pipelines is a difficult issue. In the proposed mechanism the problem is solved by a spring actuation and increasing the flexibility of the mechanism. The propulsion of the robot has been successfully conducted using only three motors, a radical simplification over existing efforts. The robot is designed to be able to traverse horizontal and vertical pipes. We had experimented our project and we got the test results. Several types of modules for pipe inspection minirobot have been presented. Many of the design goals of the Pipe inspection robot have been completely fulfilled.

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