Design, Modeling and Prototyping of a Pipe Inspection Robot

Abstract— **one of the most important requirements in repairing and maintaining of pipelines is the ability to monitor and evaluate the pipes interior. This work deals with the design and prototyping of an apparatus to traverse piping systems for inspection, cleaning and or examination of the piping systems. At first, the existing pipe crawlers are studied and compared. Furthermore a mechanism of a crawler is proposed and modeled and the robot tested in vertical elbowed pipes and pipes with obstacle inside. A pan and tilt camera and an ultrasonic sensor are mated on the robot. However, any kinds of tools and sensors may be mounted on robot.**

Index Terms— **In-pipe inspection, Nondestructive test, Robot mechanism**

I. INTRODUCTION

ONE of the most important requirements for repairing and maintaining of pipelines is the ability to monitor and evaluate the pipes' interior.

Such interest often exists where prior nondestructive testing has been identified to have caused internal corrosion problems and where a visual confirmation is desired before performing corrective actions and /or expending capitol costs. Visual inspection is also important where build-up of iron oxide, scale and / or foreign deposits are suspected of causing a loss of flow, and where nondestructive pipe thickness testing cannot provide the necessary diagnostic information. Furthermore, it is useful when the pipeline is out of reach as in underground pipelines.

Physically cutting out one or more small sample sections of the pipe is the most common method employed in such cases. However, attached to that method is the high cost of replacement and the associated downtime.

Due to the typical variations in corrosion rate or deposit buildup found between different pipe locations, it is questionable, as well as very risky, to extend the results from the analysis of one area alone to the whole pipe.

The present work relates to an apparatus known in the industry as a pipe crawler. Pipe crawlers are frequently used to deploy monitoring equipment including sensors and/or cameras to monitor the pipe integrity and to help diagnose needed repair or maintenance.

This work deals with the design and prototyping of an apparatus that traverses pipes for inspection, cleaning and or examination of the piping system.

Typically such devices include a testing probe, sensor, or camera carried by a support structure that travels through the piping system being inspected.

At first the existing pipe crawlers are studied and compared. Numerous devices have been developed and are being used to traverse piping systems [1,2].

While such pipe crawlers are advantageous in that they allow for the in-situ cleaning, examination, inspection of piping systems, they are not without their disadvantages. Many original locomotion concepts have been proposed to solve the numerous technical difficulties associated with the changes in pipe diameters, presence of vertical pipes, various elbow and "tee" joints and the energy supply.

The important drawback of most of existing pipe crawlers is that they cannot traverse vertical and curved pipes [3, 4 and 5].

Simple mechanisms that permit movement only in horizontal pipes and elbows inturn have the difficulty of producing necessary friction force to continue moving in far distances in the pipes. Since they need to provide sufficient motive force to pull extensive lengths of their power and signal cables. These difficulties have been solved in some ways in the past [6, 7 and 8].

In this paper, we propose a new mechanism for an apparatus that has the capability of traversing horizontal as well as vertical pipes. In addition the apparatus has been successfully demonstrated to have adapted to changing diameters, and passes over small obstacles in the interior surface of the pipes. Mechanism design for pipes of 10 to 20 inches in diameter.

Furthermore, the proposed pipe crawler can navigate through various elbow joints contained in most piping systems. The device was tested in vertical and elbowed pipes and also in pipes with obstacles inside. The results were in good agreement with the modeling and simulation results.

A pan and tilt camera and an ultrasonic sensor were mounted on the device *but it is also flexible enough so that other kind of tools can be mounted on it.*

II. MECHANISM DESCRIPTION

We will first consider a 6-bar planner mechanism; comprise linear and revolute joints (Figure 1).

As it is shown in the figure when link 2 moves, link 6 lifts. It has translational motion when it is lifted and remains parallel to the prior position. Because links 4 and 5 have equal length and are parallel so we have a parallel-crank mechanism with an adjusting screw. The mechanism has one DOF with assumption of fixed link 1 as the ground.

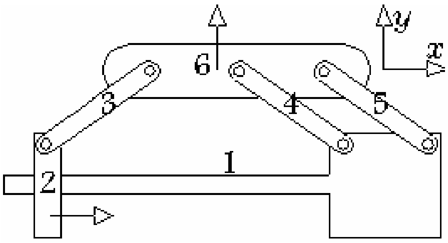

Fig. 1 . A 6-bar planner mechanism

In order to obtain equivalent plan mechanism for our robot we have developed a new and improved mechanism on the basis of the one shown in Fig.1. New links have been added namely 3',3",4',4",5',5" and 6',6" as seen in Figure 2.

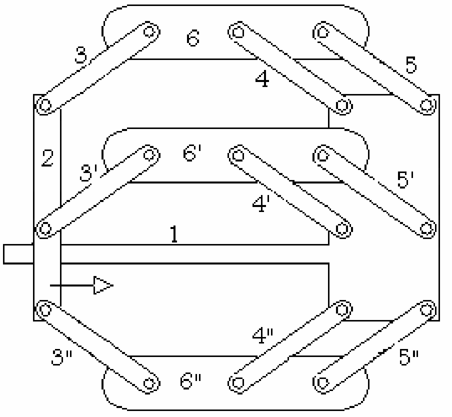

Fig. 2 . Equivalent planner mechanism for robot

If the links are deployed in a tripod format around the axis parallel to the links (6,6',6"), this will result in a spatial mechanism.

Now, if we consider that a device with the above mechanism is deployed in a pipe in a way that links (6,6',6") be parallel to the pipe axis, then assuming the slider link(2) is the driver, the driven links (6,6',6") have translational motion parallel to the pipe axis and are pushed to the internal surface of the pipe. This arrangement thus corresponds to one DOF due to below calculation.

Furthermore, if links (6,6',6") are able to drive independently as a transporter of mechanism then the device will move within the pipe. To calculate the DOF we use the equation:

$$DOF = 3\times(n-1) - 2\times f_1 - f_2 \qquad (1)$$

In spatial mechanism we have n= 14, f1=19 & f2= 0 so the DOF is : DOF =1

If the links(3,3',3") are further improved by introducing links (7,7',7") as shown in Figure 3 then, by using equation 1 by n=17, f1=22 and f2 =0 we have: DOF= 4

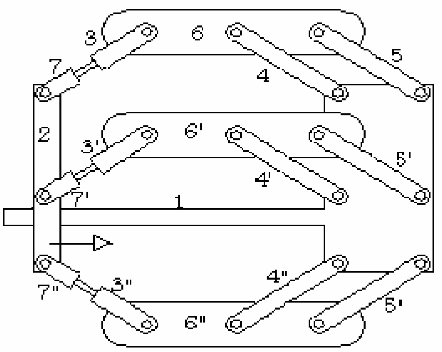

Fig. 3 . Improvement of the equivalent planner mechanism

This improvement gives more flexibility to the robot which will be later discussed in this paper.

Let us call links (6,6',6") as a “tracked unit” and links (3,3',3",4,4',4",5,5',5") as the “arm” and the links (1,2) as the “chassis”.

Figure 4 shows the robot assembled with the above mechanism.

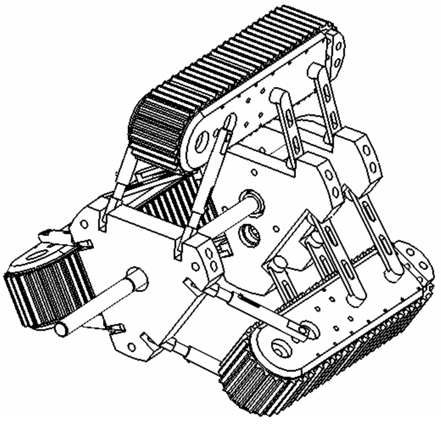

Fig. 4 . Assembly of final mechanism

As shown in the Figure we have double arms parallel to each other in each position such that one has no effect on the other in computing the DOF of the mechanism. It only increases the structural stability of the device.

Computing the DOF of the mechanism is by using n=17 and f1=22 and with the assumption of keeping the link (1) as the ground. So when the fixer 1 becomes freely movable we have an extra link and by using n=18 & f1=22 we have: DOF=7.

Figure 5 shows the mechanism device when only one of the tracked units is assembled.

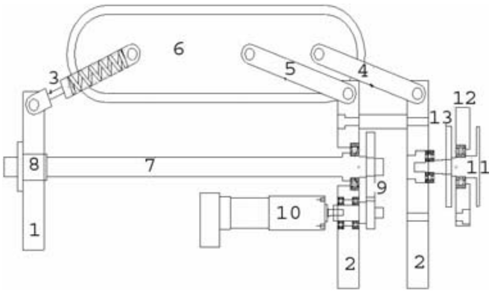

Fig. 5 . Mechanism device, assembled with one of the tracked units

The various parts of the device are listed below:

1. Rear chassis (rear fixer platform)
2. Front chassis (front fixer platform)
3. Rear springed arm
4,5. Front arms
6. Tracked unit
7. Adjusting screw
8. Nut of adjusting screw that is placed in 1
9. Gearbox (power transmission from driver motor to the adjusting screw)
10. Driver motor of screw
11. Main shaft of camera and sensor mechanism
12. Fixer platform of camera and sensor mechanism
13. Pulley

The robot can traverse horizontal and vertical pipes of 10 to 15 inches in diameter and in horizontal pipes it can crawl up to 30 inches. The Robot can also adapt itself to the pipe size as a result of turning the adjusting screw that expands or contracts the linkage pair thereby rising or lowering the tracked units. As explained previously each tracked unit has independent motion caused by a separate dc driver motor. Moreover, each unit is completely independent of the other, providing the system with excellent steering and maneuvering capability. Each motor transfers its power through a right angle gearbox to the driver pulley. Then the pulley's movement transfers to the belt by friction and the friction between the track and the inner surface of the pipe causes the whole system to move forward. A significant achievement in this part of the work was that the motor, the pulley and the gearbox were placed in the minimum possible space. As the space in each tracked unit was mainly filled by the driver motor, so an optimized motor must be chosen that has minimum size with respect to its power. Needed power is estimated due to the most critical situation which is ascending the vertical pipe so the motor power is taken with respect to a safety factor.

The tracked unit and its part are shown in Figure 6.

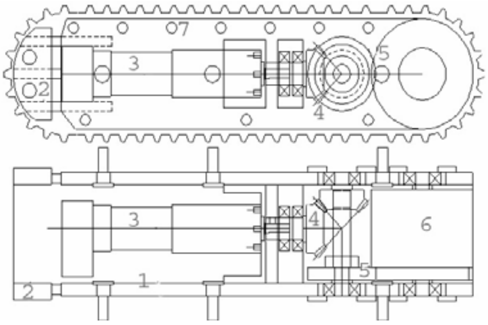

Fig. 6 . Tracked unit and its part

The various parts are listed below:

1. Side wall of tracked unit
2. Side wall of take up pulley mechanism
3. Driver motor
4. Right angle gearbox comprising bevel gear
5. Power transfer gearbox between bevel gear and pulley
6. Driver pulley of belt
7. Caring and return idler roller

III. DESIGN OF MECHANISM

The first limitation in design of the crawler is the pipe diameter. The proposed mechanism is expected to work in pipes with diameter over 10 inches. In other words the robot must be small enough to traverse through these pipes.

On the other hand, for the selection of the mechanism of the robot such that each tracked unit has its own independent movement, there is limitation of space.

The smallest dc driver motor which has the capability to work in such a condition can fit in a unit that is 6*6*25 cm in dimension. Therefore as a first step for the design, a 25 cm diameter circle was drawn and three squares of 6*6 cm each were inscribed in this circle.

The remaining space could be used for accommodating the chassis and arms.

The most critical condition occurs when the robot is ascending a vertical pipe as there should be adequate friction between the track and the inner surface of the pipe that must be provided to support the robot and the supply wire weight. Also in a horizontal pipe, friction is needed for movement and for pulling the supply wire.

The estimated weight for the robot and the supply wire is 150 N. The friction force between each track and the pipe must be close to 50 N.

If the coefficient of friction between the tracks belt and pipe is μ, then the normal force is calculated as:

$$N = \frac{Mg}{3\times\mu} \qquad (2)$$

Then using this normal force and applying some simplification such as taking equal force in the front arms the stress in each part can be calculated.

IV. DESIGN OF REAR ARMS

Flexibility and nonrigidity of the robot inside the pipe is increased by special design of the rear arms that is comprised of a cylinder and a piston, containing a spring inside and every arm has three independent one DOF joint.

The inner surface of the pipe may contain deposits, seam and particles and the robot must be able to pass over them. Also the robot can navigate through elbow joints because of the presence of spring joints that are discussed below:

The front arms are parallel-crank and the track is always parallel to the pipe axis. In Fig.7 performance of the device when passing over an obstacle of height h is illustrated.

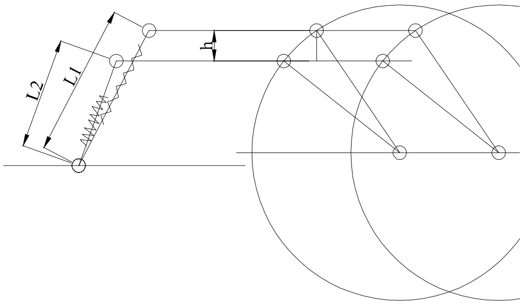

Fig. 7 . Mechanism flexibility concept

Assume h is the obstacle height on the inner surface of the pipe as shown in Figure 7.

For the robot to pass over this obstacle, it needs to cause deflection of ΔL in the rear arm springs.

Passing over an obstacle of 5 mm in height in pipes of 25 and 35 cm in diameter is shown in Figure 8. As is expected the deflection of the springs while passing over a fixed obstacle is in direct ratio with the pipe diameter.

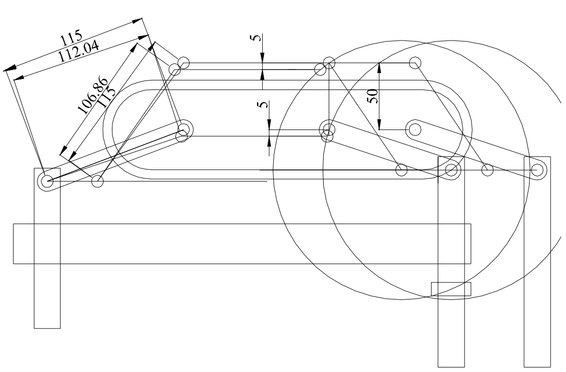

Fig. 8 Passing over an obstacle of 5 mm in height in pipes of 25 and 35 cm in diameter

So in a pipe that is 35 cm in diameter, the deflection becomes critical.

One embodiment of the robot while navigating through a standard elbow is illustrated in Fig. 9. In this figure the length of each tracked unit is considered to be d.

The point is that in the outer curve within the pipe wall the tracked unit has two points of connection and in the inner curve the track has one point of connection that makes the distance between the tracks decrease as it is illustrate in Figure 9.

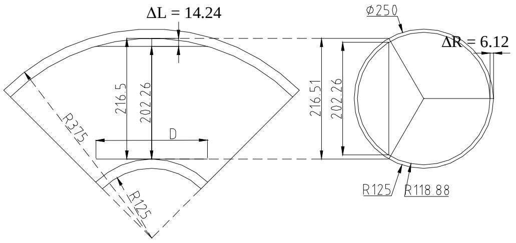

Fig. 9 . Elbow passing concept

ΔL is converted to ΔR geometrically as illustrated in Figure 9.

This means that each tracked unit must either negotiate with an obstacle of height ΔR or should move in the pipe with reduced diameter while traversing an elbow.

The most critical elbow is a standard short-radius elbow which is 25 cm in diameter such that ΔR becomes equal to 6 mm from Figure 8.

In other words each tracked unit must pass over an obstacle of 6 mm in height that the deflection of rear arm springs will be derived. While adapting the robot with the pipe size, the power screw must be actuated and expand device pushing the tracked units to the inner surface of the pipe. The power screw must actuate till the normal force is provided for achieving the necessary friction between the belt and the pipe wall.

It can be derived statistically that for a particular normal force on the tracks the force in rear arm is greater in a pipe which is 25 cm in diameter rather than 35 cm in diameter. Thus the critical threshold size is 25 cm in diameter.

The force in rear arm causes a deflection in the springs. This deflection plus deflection caused by the navigating elbow is the maximum required deflection. This is the main criteria for designing the springs.

The proposed robot has a spring in the rear arm with a maximum deflection of 14 mm which has been already described in the paper and from some calculations with respect to a safety factor.

These springs are squared and Ground ends with the stiffness of $280\, {}^{N}\!/_{cm}$ and outside diameter of 10cm.

When the tracked unit hit an obstacle, the length of rear arms reduce and the track pass over that obstacle, remaining parallel to the pipe axis. The tracked unit remains parallel because of parallel- crank mechanism. It can be one of the problems in ascending and descending vertical pipes. Suppose the track hits an obstacle during ascending or descending a vertical pipe, then, the deflection of the rear arm spring cause the contact between the track and the pipe wall is separated and the contact remains only in the obstacle point. Thus the contact surface reduces and the needed friction force can not be accommodated. As a result, traversing vertical pipes will encounter with difficulty. Using flexible or movable caring idler ruler solves the problem because the only point that the tracked unit deflect is the obstacle point and the remaining surface of the track stays in contact with the pipe. But the flexibility and movability of the carrying idler ruler have their own complexity which must be considered in future works.

It must be mentioned that the rear spring arms are not only useful in negotiating obstacle but also help the robot to pass elbows. However, if the flexible idler roller is used instead for passing over obstacle the system wouldn't have enough flexibility in moving through an elbow.

V. MODELING AND SIMULATION

All the parts and pieces are modeled with a mechanical Engineering software tool, Visual Nastram. After completing the modeling and design, then the parts are drawn in detail for prototyping.

All parts are assembled in their right position (Fig. 4).

Robot motion inside the pipe is modeled with the Visual Nastram software (Figure 10).

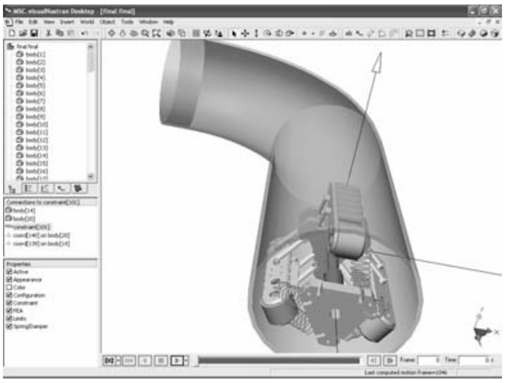

Fig. 9 . Modeling the mechanism with the Visual Nastram software

The Robot model is simulated in different situations taking into consideration both vertical as well as elbowed pipes.

Good performance of model certain the designing. This modeling has some advantages. As an example deflection of the spring in the rear arms of the robotic model are compared with the results we obtained by designing the robot. Spring deflection of the two rear arms while traversing a horizontal and elbowed pipe during 1.5 seconds is shown in Figure 11 and 12. The arms are located at 120° of each other.

Stress in the third arm, in symmetric position on third part of triangle, is shown in Figure 13.

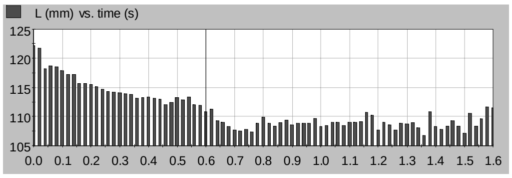

Fig. 11 . Spring deflection of one rear arm

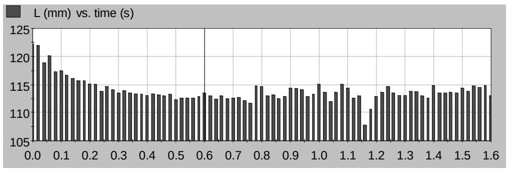

Fig. 12 . Spring deflection of another rear arm

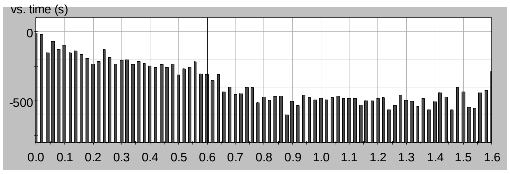

Fig. 13 . Stress in the arm, in symmetric position on third part of triangle

In the first 0.6 seconds the robot moved through the horizontal pipe and in the remaining 0.9 seconds the robot navigates the elbow.

As seen in Figures the largest deflection is on arms 3 and the least deflection is on arm 2. Deflection of arm 3 is compared with the results we obtained by designing the device.

Due to the stiffness of spring ($k = 280 \, {}^{N}\!/_{cm}$) deflection can be derived from figure 13.

The Rear arm length is 113 mm while traversing a horizontal pipe which is reduced to 105 mm while navigating the elbow so the deflection is about 8 mm that has agreement with our design values.

It must be mentioned that the pipe diameter used in this model is 25cm.

VI. THE ROBOT PROTOTYPE AND TEST

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 15.4 kg. The body of the robot was fabricated mostly from aluminum and steel. The Robot was driven by four dc motors. Each track has an independent dc motor and the power screw was driven with the forth dc motor.

The camera and the ultrasonic sensor were driven by a tree dc motor.

Figure 14 shows the fabricated prototype.

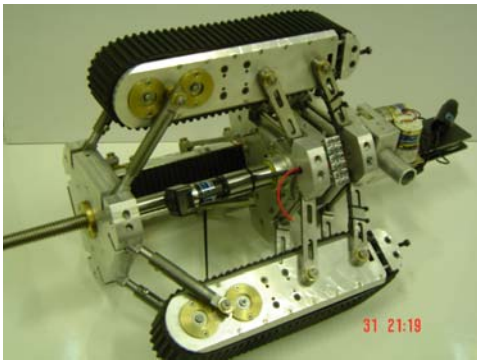

Fig. 14 . Fabricated prototype

The Robot was tested under different conditions inside of pipes having different diameters.

Due to the pipe diameter, the adjusting power screw first reduces the robot size by contracting the tracked units to enter the pipe and then adjusts the robot size with the pipe diameter by expanding the tracked units. The driver motor actuates till the track pushes into the pipe wall and the driver motor of the tracked units acted and the robot started to move through pipes with different diameters.

VII. CONCLUSION

A Robot that offers significant improvements, compared with similar ones is proposed. It has wide industrial usage where pipe inspection under various conditions becomes an issue which includes traversing through vertical pipes, elbows and long horizontal pipelines.

Presence of obstacles within the pipelines is a difficult issue. In the proposed mechanism the problem is solved by spring rear arms and increasing the flexibility of the mechanism.

The robot is designed to be able to traverse elbowed and vertical pipes. This is done in the proposed mechanism with the help of rear spring arms. Thus the rear spring arms are not only useful in negotiating obstacle but also help the robot to pass elbows.

An adjusting power screw is proposed to adapt the robot with the interior pipe diameter. Furthermore, the adjusting power screw by contracting tracked units can be useful in passing through an elbow.

A camera monitors the elbow and the operator contracts the tracked units by driving the power screw motor.

Empirically during testing, the track unit’s driver motor demands extra current through passing the elbow and the robot was not successful in it compared with the simulation results due to the fact that there was no limitation of power consumption in the simulation model. It should be mentioned that by the aid of adjusting screw and contracting the tracks, the robot could pass elbow successfully. Also, by decreasing the rear arm spring stiffness, the robot could pass the elbow with less difficulty.

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ACKNOWLEDGMENT

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