Development of a Novel Autonomous Robot for Navigation and Inspect in Oil Wells

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Abstract: This paper proposes a novel robotic system that is able to move along the outside of the oil pipelines used in Electric Submersible Pumps (ESP) and Progressive Cavity Pumps (PCP) applications. This novel design, called RETOV, proposes a light weight structure robot that can be equipped with sensors to measure environmental variables avoiding damage in pumps and wells. In this paper, the main considerations and methodology of design and implementation are discussed. Finally, the first experimental results that show RETOV moving in vertical pipelines are analyzed.

Keywords: autonomous robot, navigation, inspection, maintenance.

1. INTRODUCTION

As a result of the increasing interest on climbing robots around the world, different types of climbing robots were developed for climbing over flat or curved surfaces.

Research topics on the pipe climbing robots that can move along the walls or pipes in many environments, including buildings and large ships are the most reported in the literature. These kinds of robots stick to the desired surfaces and move up or down using electromagnets (M. Eich and T. Vögele (2011), W.K. Chung et al. (2011), T. Yukawa et al. (2006)). Robots for climbing inside pipes or ducts were also developed (Y Kwon et al. (2011), F.Y. Xu et al. (2011), C. Choi et al. (2010)) and the mobility of pipeline wheeled robots are also studied in (J. Park et al. (2009, 2011), M.P. Le et al. (2010)).

In the petroleum industry there are some robotics devices to take measures of process variables inside of pipeline called Pipeline Inspection Gauges (PIG). These kinds of robots travel inside the pipe through the fluid (T. Guibin et al. (1965), Z.Hu and E. Appleton (2005), W. Liu et al. (2011)).

One of the most important equipment used in the oil extraction are the pumps. Submersible pumps are divided into two types:

- Surface pumps (PCP) where the motor is in the surface and the pump is inside the well (Fig.1a), and;
- Electro-submersible pumps (ESP) where the motor and pump are inside the well (Fig.1b).

These technologies have two critical issues, the first is the extreme condition under these equipment operate (high temperatures, high pressure, acid attack, etc.) and the second is the delicate balance that exists between the productions levels and the integrity of the well (extract more oil than the well can produce, could result in damages).

From Fig.1, it can be seen that a typical oil installation has a deep well made with reinforced concrete, usually called casing, and a straight pipeline is inside of it. Due to the length of the internal tube, some connectors must be used to link the pieces of pipelines.

It is important to remark that inside of well, the environmental conditions lead to reduce useful life of the instruments and equipment (around three months). However, if internals well variables like pressure, temperature, flow of oil or oil level are not known, the maintenance tasks cannot be performing in a good way. Furthermore, the maintenance tasks in ESP and PCP systems can be made more frequently to keep them in good conditions. Therefore the maintenance tasks are expensive, tedious and dangerous.

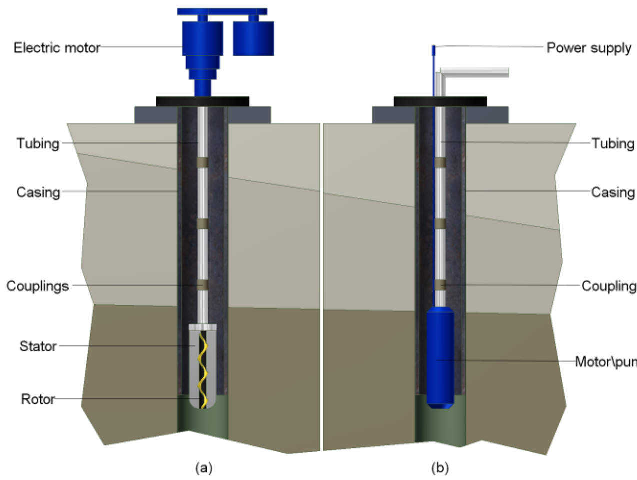

Fig. 1. (a) Progressive cavity pump (PCP); (b) Electrical submersible pump (ESP)

This paper presents a novel design of a sliding robot to perform inspection and maintenance tasks in any kind of straight pipelines. Particularly, this development is carried out like an optimal solution to measurement problems and maintenance tasks in the oil industry.

Fig.2 shows a photograph of the first developed prototype. Because of the novel mechanical design, this robot can move between the casing and the oil tube. One of the most powerful advantages of this closed structure is its light weight and also its capacity to adapt around any pipeline diameters because of its modular components.

Moreover, the RETOV robot can navigate along the tube with three types of different movements: circular, straight and spiral. Using suitable combinations of them, the robot can avoid obstacles or change the direction of movement through its wheels.

The mechanical structure was also designed to hold the most important sensors needed for a good maintenance of the oil installations.

This article is organized as follow. Section 2 describes the most important aspects taken into account in the mechanical design of the robot. Also the hardware used in the first developed prototype is presented. Section 3 shows a kinematics model under screw theory and some simulations results that allows to validate the model. Experimental results are detailed in Section 4 and; finally, conclusions and futures advances are presented.

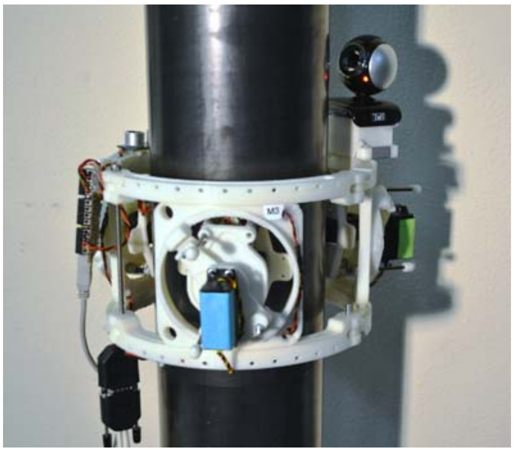

Fig. 2. Functional prototype of RETOV

2. DEVELOPMENT OF THE FIRST PROTOTYPE

2.1 Design Considerations

There are many restrictions to be taken into account in the mechanical design of this robot. Undoubtedly, the distance between tubing and casing (Fig.1) is the meaningful. In (M. Urdaneta et al. (2012)) a complete analysis about all design considerations must be found. Table 1 summarizes the most common distances between the oil pipeline (tubing) and the walls of the well (casing). This space is irregular and the robot must move in-between. Therefore, the developed robot must be designed to change the movement direction toward the maximum free space.

Table 1. Annular distance between tubing and casing*

ØTUBING [mm]	Ø CASING [mm]	ANULAR [mm]
88.9 (3-1/2")	139.7 (5-1/2")	25.4
88.9 (3-1/2")	177.8 (7")	44.5
114.3 (4-1/2")	244.5 (9-5/8")	65.1
139.7 (5-1/2")	244.5 (9-5/8")	52.4

*Data provided by FIELD BCP-VEN

Based on Table 1, the minimum space between tubing and casing can be determined in 25.4 mm. Therefore, no collision between robot and tubing-casing shapes is warranted when the maximum robot diameter is equal or less than 279.4 mm.

2.2 Mechanical Hardware

The RETOV prototype is made by two articulated rings that fix three drive wheel systems uniformly distributed along the circumference of the tubing (120º spaced, in order to have optimal force conditions).

Each drive wheel system is charged to orientate and rotate a polypropylene wheel by actuating the servo and micro motors respectively. Also a suspension formed by four compression-springs was installed in this drive system to allow obstacles avoidance like weld beads or pipe couplings. Fig.3 shows a 3D mechanical model of this novel prototype realized in Autodesk Inventor Pro® 2012.

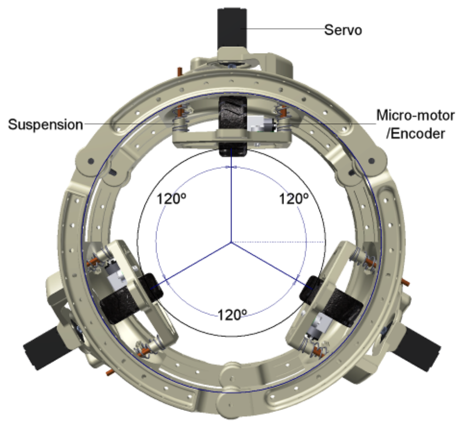

Fig. 3. 3D mechanical model of RETOV (top view)

This prototype is able to change its movement direction describing three different types of motion. Pure rotational and translational motion can be obtained independently when all three drive wheel systems are horizontally and vertically oriented respectively (servomotor at 0º and 90º respectively). Pitch variable helical movements are also possible when the same acute orientation angle is defined for all the three wheel systems.

RETOV parts were made by a Dimension Elite® 3D printer in ABS plastic. The parts of this robot are lightweight by construction but rigid by design. To accomplish the design considerations, the robot ring diameters were fixed in 220 mm and the length between two rings in 134 mm. RETOV prototype was designed to freely move over the pipe and to avoid pipeline obstacles with a height less than 8mm. The height of obstacles which the robot can handle depends on the size of the diameter of wheels used in this robot.

Table 2. Physical characteristics

Weight	1 kg
Load Capacity	0.5 kg
Maximum Size	110 x 135 mm (cylindrical r x h)
Materials	ABS plastic (first prototype)

Based on Table 2, some of the most important characteristics of the system are a total weight of 1 kg and a maximum payload capacity of 0.5 kg. Materials used in the parts of the robot depends on the application, for the first RETOV prototype ABS plastic was used for its lightweight and construction facility. Some aluminium alloys could be used for hard environments.

This mechanical architecture allows a set of different kinds of sensors and its electronics if it is necessary. The ABS plastic rings are fabricated with a circular hole-pattern to allow the modular assembly of its components.

2.3 Control and Inspection Hardware

Control hardware manages the information concerning the status of the robot. The rotation and orientation of each wheel are actuated by micro-motors and servomotors respectively. Micro-motors are driven by a shield card (Ardurobotronica) which is commanded by an Arduino UNO® that controls its H-bridges. Servomotors receive a PWM signal directly from Arduino UNO®. Both cards are connected to an User-PC via USB port.

Three permanent-magnet electric micro-motors (Pololu®) with high torque planetary gearboxes (298:1), which generate a torque of 6.5 kg/cm at 6V and speed of 100 rpm were used to move the attached polypropylene wheels with high traction used on radio control cars. The motors have a quadrature encoder which are connected to the motor controller and can be used for position or velocity feedback.

Three Hitec® HS-645MG servomotors drive the orientation of the RETOV wheels. This motor can switch motion with three possibilities: 0º for rotation around the tubing, 90º for translational displacement, and pitch variable helical displacement of the robot when the angle varies between 0º and 90º degrees.

Robot position along the vertical axis (Z-displacement) is measured by a Parallax® PING sonar. The robot orientation angle (ϴ-orientation) is measured by a quadrature encoder coupling in the micro-motor shaft. An Inertial Measurement Unit (IMU) was installed to verify the real orientation in a case of wheel slipping. The connectivity of all these components is showed in Fig.4.

The inspection hardware acquires information related to the environmental conditions inside the oil well. Different types of variables as temperature, humidity, pressure and others can be sampled by sensors mounted on the structure of RETOV. According to this statement, a cordless digital camera was installed on the robot to show the conditions of the tubing surface in the user interface.

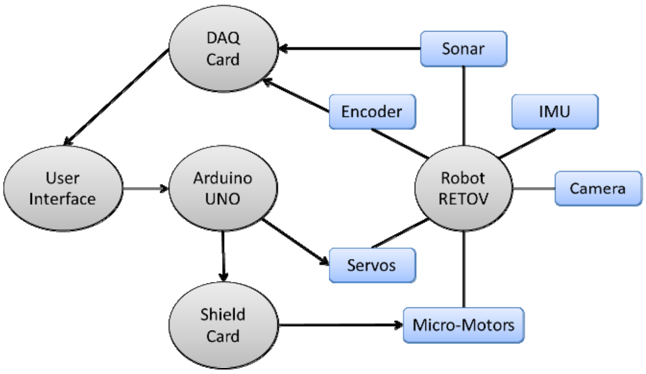

Fig. 4. Control and sensing architecture

A real deployed view of the robot is shown in Fig.5 with the mechanical structure equipped with all the embedded sensors installed on RETOV for this work.

From Fig.5, it can be observed that the robot is completely modular; that is a new segment can be easily added and then the structure can slide by pipelines with higher diameters.

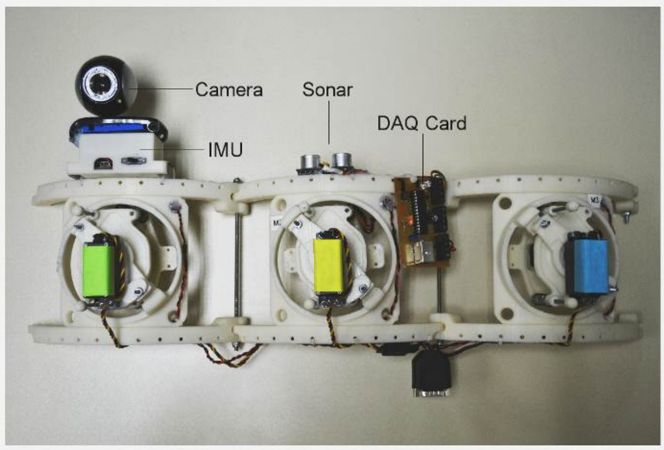

Fig. 5. Deployed view of modular RETOV

3. KINEMATICS MODEL

The basic movements of the robot are rotation and translation along the same axis. These movements can be described perfectly by the screw theory, initially developed by Sir Robert S. Ball.

The kinematics model assumes constant angular velocity in the three wheels at all time. It also assumes that there is no wheel slip with respect to the tubing. It is possible to anticipate the approximate trajectory of the robot along the pipe by using the kinematics model. Therefore, wheel revolutions can be estimated base on the final location of the robot.

A screw can be defined with eight parameters which are a unit vector, a position vector, a rotated angle and a displacement along the axis. Below are the equations that describe the motion of the robot:

$$s = [s_x, s_y, s_z] \tag{1}$$

$$s_o = [s_{ox}, s_{oy}, s_{oz}] \tag{2}$$

$$\theta = \frac{d}{R\tan\varphi} \tag{3}$$

Where:

s: unit vector along the direction of the screw axis.

s_o: position vector of a point on the screw axis.

θ: rotation angle about the pipe.

d: translational distance along the pipe.

φ: wheel angle.

R: radius of the pipe.

Using the formula of Rodrigues (L.W. Tsai (1999)) for a spatial displacement of a rigid body, a homogeneous transformation can be obtained as:

$$^{A}\hat{p} = A\,^{B}\hat{p} \tag{4}$$

Where:

$^{A}\hat{p}$: a vector with the calculated location.

A : is a 4x4 transformation matrix.

$^{B}\hat{p}$: a vector with the desired position.

To obtain the inclination that the robot must perform about the pipe, the follow equation is calculated:

$$\varphi = \arctan\left(\frac{d}{\theta R}\right) \qquad 0 \le \varphi \le \frac{\pi}{2} \tag{5}$$

Replacing the screw parameters in (4), the transformation matrix results in:

$$A = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

3.1 Kinematics Model Validation by Simulation

A MATLAB® program has been performed to implement the kinematics model. Then for a given Z-displacement and the number of turns around the tubing, it calculates the wheel orientation angle to develop the desired manoeuvre.

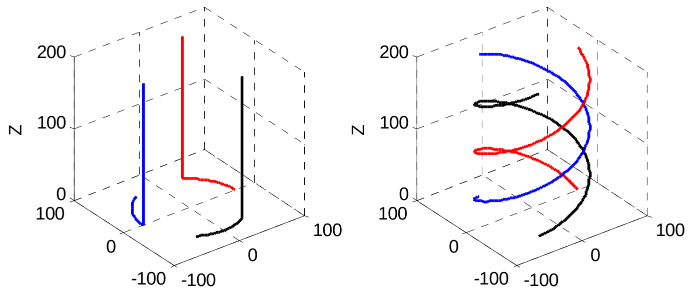

Fig. 6. Kinematics model validation results from different types of movements

Fig.6 (left) shows two basic movements that this prototype can execute independently (pure rotation and translation). Fig.6 (right) shows a pitch-variable helical movement by combining rotation and translation movements. Avoiding obstacles is possible combining these kinds of movements. Fig.7 shows a 3D model graph for better understanding of one particular wheel displacement.

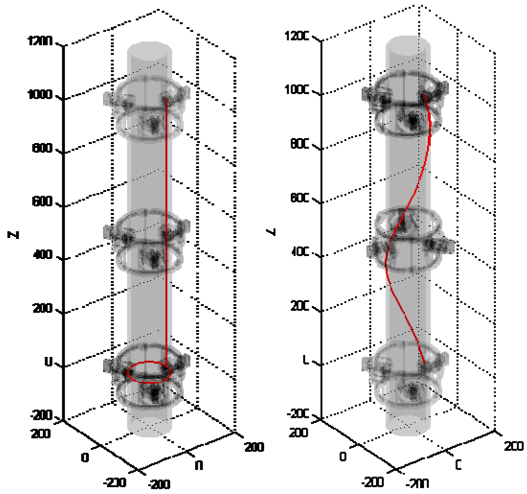

Fig. 7. Left: rotation and translation movements. Right: helical movement

4. EXPERIMENTAL RESULTS

4.1 User Interface

To perform experimental tests, a Graphical User Interface (GUI) was developed. This application has been done under LabView® 2010.

The aim of the GUI is to get the information given by measurement system and to process it.

The GUI structure consists in five main parts, which are a 3D View, a Cam View, Environment graph, Control elements and Indicator elements. Fig.8 shows a screenshot of the GUI and its components are described below.

3D View permits to observe the route before launching the robot into the pipe and also allows to visualize the instantaneous estimated location in the pipe. CamView shows at each moment images from the environment through a cordless camera what is happening inside the well. Environment graph shows a selected variable like temperature, pressure or humidity. Control elements are buttons and sliding bars that provide interaction between operator and robot, permitting to select the type of movement (translation, rotation, helical) change speed, angle of orientation, moving direction of RETOV and start-stop execution. Finally, Indicator elements allows the operator to know about the status of the robot.

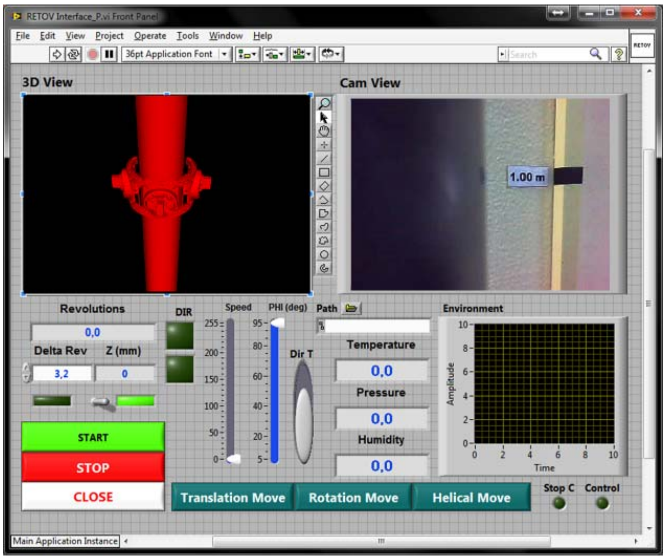

Fig. 8. Screenshot from the GUI application

4.2 Motion Test

Some tests were made to show the capabilities of RETOV to develop two basic types of movement stated before and also demonstrate that the combination of these basic motion can generate a more general helical movement. The following conditions were assumed: constant velocity for all the three wheels, maximum Z-displacement and ϴ-orientation were established in a meter and 360º respectively. Moreover, slipping phenomena were not taken into account because it exists a high rolling resistance due to the polypropylene deformable wheels.

Three phases of navigation were performed. In the first phase, the robot described a pure rotation of 360º around the tubing. The second phase consisted in a pure counter-gravity translation of a meter. Finally a combined motion was described by doing a complete counter clockwise revolution and descending a meter at the same time. The data logged at the three phases of motion are showed in Fig.9.

Theoretical odometry values were calculated for the three phases of movements by using the robot kinematics shown in Section 3 and programmed in MATLAB®. Practical odometry values were registered for each test in order to compare them with the theoretical ones. This information is listed in the Table 3.

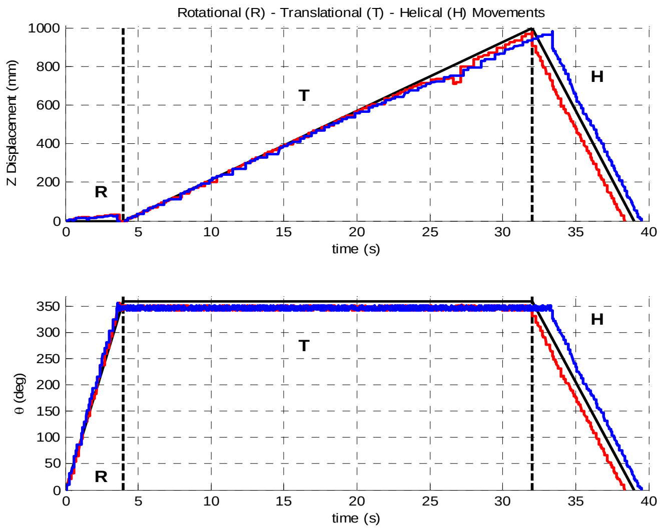

Fig. 9. Z-displacement and ϴ-orientation of RETOV during three types of motion along the tubing (black: theoretical motion; red and blue: some experimental results)

Table 3. Odometry results

Odometry	Type of Movement		
	Rotation	***Translation***	***Helical***
Theorethical	3.32 rev (360.0º)	7.58 rev (1.0 m)	8.28 rev (360.0º in 1.0 m)
Experimental	3.30 rev (357.4º)	8.30 rev (1.1 m)	7.10 rev (328.9º in 0.9 m)

Clockwise rotational movement is well tracked by the robot because rolling resistance is favourable in this situation. Counter-gravity translational movement shows a slight difference between theoretical and practical odometry values due to the reduction in the rolling resistance produces some slipping in the robot wheels. Helical descending movement presents a combination of rotational and translational wheel slipping characteristics.

The drive wheel suspension system pressed the polypropylene wheel over the tubing during the movements developed on this experiment. This pressure generated a frictional force that avoided wheel slipping. At the same time, wheel suspension adapted to unknown coaxiality of the pipe along the followed path. A snapshot sequence of a rotational movement shows the robot performance in Fig.10.

Fig. 10. Snapshot sequence of RETOV during a rotational movement

5. CONCLUSIONS

This paper presented the first developed prototype of RETOV. This robot is a patented novel design (C. García et al. (2012)) for performing inspection and maintenance tasks in any kind of straight pipe. However this prototype is an optimal solution for service tasks in oil industry.

Because the robot can navigate between two pipes, inspection and maintenance tasks can be performed in both interior and exterior tubes. Then, just one robot can repair or inspect both tubes at the same time.

The mechanical structure allows to get all the measurement system on-board then the most critical variables in an oil well can be observed in real time. Furthermore, the mechanical design is completely modular, that is the diameter of the robot can be increased by adding new modules, then pipelines with different dimensions can be inspected by this robot.

The robot can slide on the tube because a drive wheel systems that allow to perform three different type of movements. A suitable combination of them turn the robotic structure good for avoiding obstacles or reaching some objective point very fast.

The kinematics model was developed and validated by simulation first and then confirmed by experimental results.

Finally, the designed climbing robot can move, carry and measure the environment variables in the well. The potential applications of this robot are the inspection, exploration, and maintenance of the oil pipeline. Future work will primarily focused in design a robot capable of moving along horizontal, vertical and curved piping and avoiding various kinds of obstacles.

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