DEVICE FOR MEASURING THE PAINTING THICKNESS AND CIRCUNFERENCIAL DEFORMATION ON 14" PIPELINES

Vitor Ferreira Romano, romano@mecanica.ufrj.br
Federal University of Rio de Janeiro - Poli/UFRJ
Mechanical Engineering Department – Robotics Laboratory
Cidade Universitária – CT, Bloco G-204
CEP 21945-970 Rio de Janeiro - RJ - Brazil

Cesar Gomes Ferreira, cesarlog@gmail.com
Digital Dinâmica Automação Ltda.

Luiz Eduardo da Silva Demenicis, demenicis@hotmail.com
Patriot Mechanical Handling Ltd.
West Yorkshire BD17 7DW, UK

Ney Robinson Salvi dos Reis, salvireis@petrobras.com.br
Petrobras/CENPES/PDP/Underwater Technology Dept.

Abstract. *This article presents the mechanical design aspects of a measuring device prototype (Tinta-P) designed to evaluate the internal operational condition on a 14" diameter pipeline for oil & derivates transportation. The scenario of application is a 28 km length and 40 years old pipeline located in the State of Bahia, from a marine terminal to a Petrochemical Complex. The pipeline operator made a contract with a company to provide an extended life procedure against coating and corrosion, using a technology based on internal deposition of a chemical inhibitor along the pipe. The Tinta-P prototype was developed to verify the right distribution of internal painting in a given section of the pipeline and its circumference deformation. Tinta-P prototype has radial and angular positioning control (R – θ directions), waterproof facilities (two meters H_2O) and auto-compensation mechanisms. The design phases of the three constructed prototypes are the main topics related to this paper.*

Keywords*: mechatronic design, measuring device, pipeline, robotics.*

1. INTRODUCTION

1.1. Operational site

In a marine terminal located in the State of Bahia (SICM, 2007) arrives at about 40 ships per month, mainly from offshore oil drilling platforms in the Sergipe-Alagoas Basin. Its installed facilities operate nearly 1,000,000 m^3 of crude oil and derivates per month. Most part of these products is transported by pipelines to a refinery and to a Petrochemical Complex located 28 km from the marine terminal. Both pipelines are under the soil and in many regions the nearby area is populated. This paper deals with the development of prototypes conceived to make internal inspections on the 28 km length pipeline from the marine terminal to the Petrochemical Complex.

1.2. Pipeline maintenance

Inspection of the inside surface of the pipe is necessary to verify the existence of anomalies like corrosion and crack. Other important information regards pipe structural deformations such as bending and ovality as the result of external forces caused by soil motion or increase of pressure due to human constructions.

Pipeline cleaning is a usual procedure to increase the capacity of product transportation, since organic deposits as paraffin in crude oil and inner surface irregularities due to corrosion inside the pipe can cause turbulence and consequently increase friction loss, reduce pipe bore and decrease capacity in the product flow.

2. INTERNAL INSPECTION TOOLS

2.1. Pigs

Pig is a cylinder-shaped electromechanical device designed for cleaning or inspection of the internal wall of a pipe with non destructive testing techniques (Baldez1 et all, 2001). The term pig is associated to a device that travels with the propelling force of the fluid being pumped (liquid) or compressed (gas) through the pipeline. Rubber seals on the pig make it act like a piston in the pipeline. Instrumented Pig uses transducers, electronics, and recording or output functions integral to the system. While traveling the onboard data acquisition system records the defect data, sensed by the transducers touching the internal surface of pipe wall. These data usually corresponds to defects sizing and location along the inspected pipe (Baldez1 et all, 2001).

Pig tools can be classified according to their operational tasks as metal loss tools: magnetic flux leakage and ultrasonic; crack detection tools: ultrasonic and transverse magnetic flux; elastic wave tools: ultrasound in two directions; geometrical tools: caliper (mechanical fingers or electromagnetic methods to detect dent or deformations); pipe deformation tool: caliper and gyroscopes provide pipe bend information; mapping tools: use of GPS (Da Silva et all, 2001).

2.2. Special tools

Pigs are very useful for pipeline cleaning and inspection, but are not able to make interventions or activities that require large consumption of electrical and mechanical power in specific positions, as occur in welding and ovality deformation repair in a circular pipe. Pigs cannot also be used in situations where the fluid has low velocity since the friction forces against the pipe wall can be higher than the propelling force of the fluid-pig interaction.

The development of special devices and tools for internal pipe intervention are necessary to execute those activities that a Pig is not able to do. In general they are teleoperated units formed by modules (locomotion or traction, data processing, instrumentation, power supply and so on) connected to an external operational base by an umbilical cable.

3. PROTOTYPE DESIGN CONCEPTS

3.1. Project scenario

In 2002 the pipeline operator made a contract with a company to provide an extended life procedure against coating and corrosion, using a technology based on internal deposition of a chemical inhibitor along the pipe. The scenario of application was a 14” diameter pipeline with 28 km length and 40 years old located in the State of Bahia, from a marine terminal to a Petrochemical Complex.

The first activity performed by the company was a “Pre-Inspection Preparation” of the internal surface using some cleaning Pigs. Then, an instrumented Pig with appropriate tool was used to paint the pipe inner surface with the chemical inhibitor.

In order to evaluate the contracted service, the pipeline operator asked for the development of a special instrumented device able to verify if the distribution of chemical inhibitor product in a given point of the pipe section was attending international standards and to quantify its circumference deformation. This device here denominated Tinta-P should be connected to a traction module and support an external pressure of two meters of water column. The measurements should be made with no flow at the pipeline.

Two prototypes were constructed and tested before the final conception of Tinta-P.

3.2. Design general aspects

The general design aspects needed for the project are:

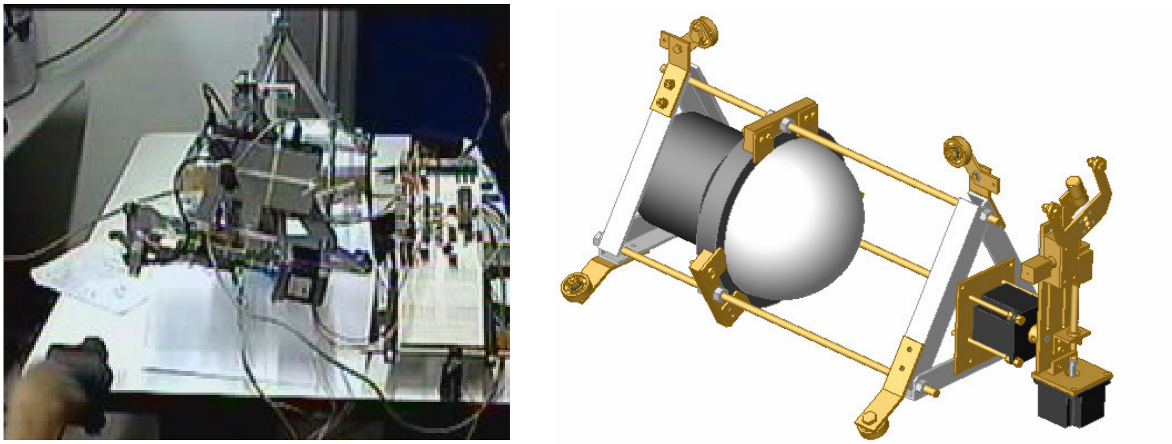
- Use of a commercial ultra-sound transducer to measure paint thickness (Mitutoyo).
- Capability of moving in curved pipes (curvature radius of 10 x diameter).
- Protection facilities to onboard camera and electronic hardware.
- Mechanism to guarantee the alignment of the prototype axis relative to the pipe axis.
- Weightless parts.
- Easy procedures for mounting and dismounting of parts.
- Commercial component for fast maintenance.
- Compact design.

3.3. First prototype

The first prototype (Fig. 1) was developed to test a solution based on a two degrees-of-freedom (d.o.f.) mechanism and step motors (1.8^{o} resolution). This device was characterized by:

- No pressure protection.
- No waterproof protection.
- Actuators:
  - ✓ 1 step motor for angular motion (transducer orientation).
  - ✓ 1 step motor for radial motion (transducer positioning).
- Radial motion: screw mechanism with a limit switch.

- Angular motion: direct drive.
- Safety return electro-mechanism actuated in case of energy fault (solenoid).
- Alignment mechanism.
- Programmed motion for data acquisition procedures.



(a) (b)

Figure 1. First prototype. (a) Performance Tests. (b) CAD model.

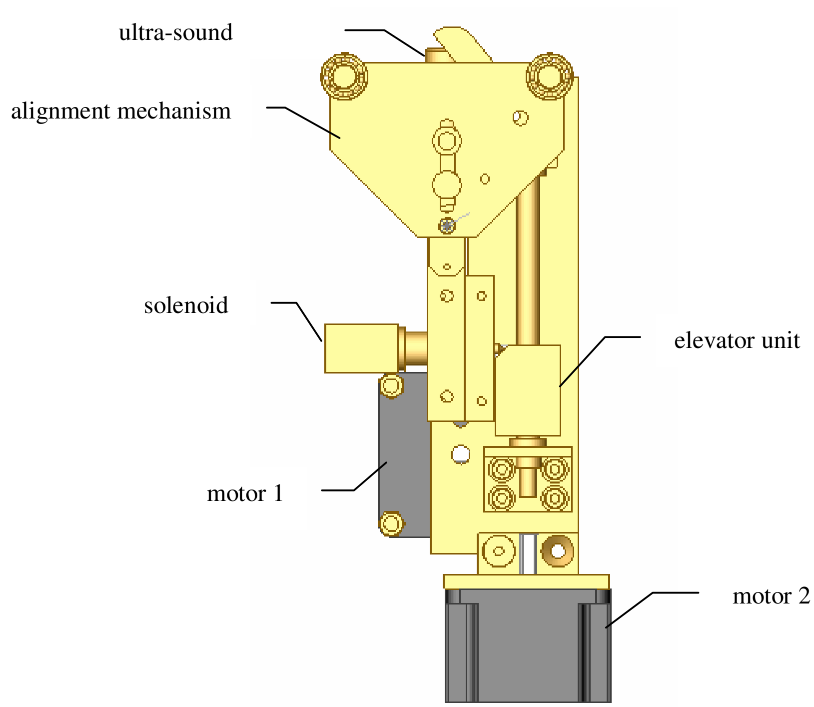


Figure 2. First prototype: mechanism main parts.

The first prototype mechanism worked properly but undesired vibrations occurred in the radial motion. Another critical part was the small amplitude of the alignment mechanism, reducing the system capability to move in curved pipes.

3.4. Second prototype

The main improvements made on the second prototype (Fig. 3) are related to the modified alignment system, ensuring more amplitude and rigidity to the system, and the adjustments on the motion mechanism to reduce vibration.

Figure 3. Second prototype.

The performance of this prototype was acceptable for the measuring of the specified parameters. After some tests the design team started the development of the final prototype.

4. TINTA-P PROTOTYPE

This final version prototype is characterized by the following improvements (Fig. 4 and 5):

- Radial and angular positioning control (R – θ directions).
- Teleoperated or robotic operation modes.
- Waterproof (2 meters H_2O) and explosion-proof container unit.
- Auto-compensated alignment system.
- Radial motion unit: pneumatic actuator and 2 d.o.f. mechanism.
- Angular motion: DC motor and planetary gear reduction.
- Pendulum transducer system to keep horizontal reference.

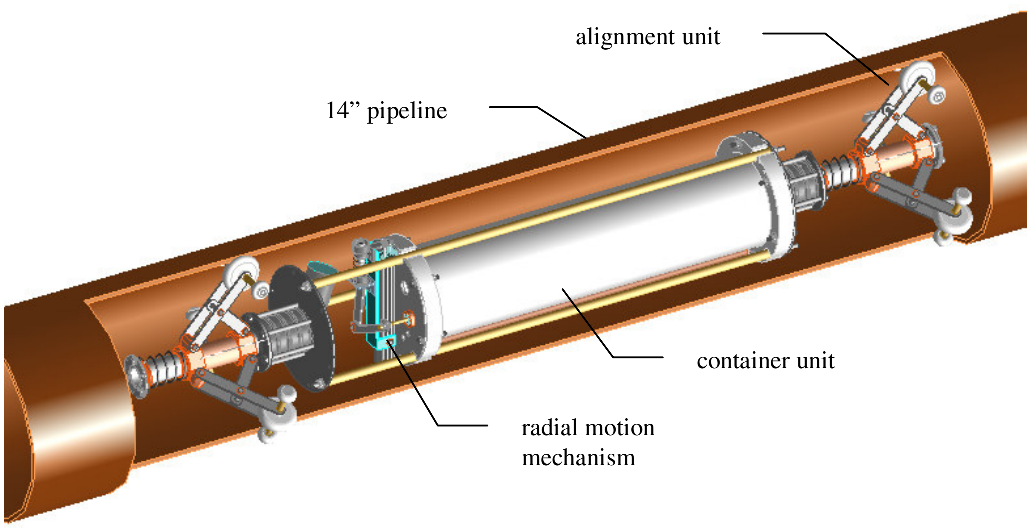


Figure 4. Tinta-P prototype and pipeline CAD model.

4.1. Structural unit

The structural unit provides the necessary rigidity, alignment and protection to all system units. It has stainless steel components and is formed by two circular shape flanges rigidly interconnected by three structural bars in pretension with screws.

The structure is also responsible for container unit protection against external forces/moments due to pipeline interaction.

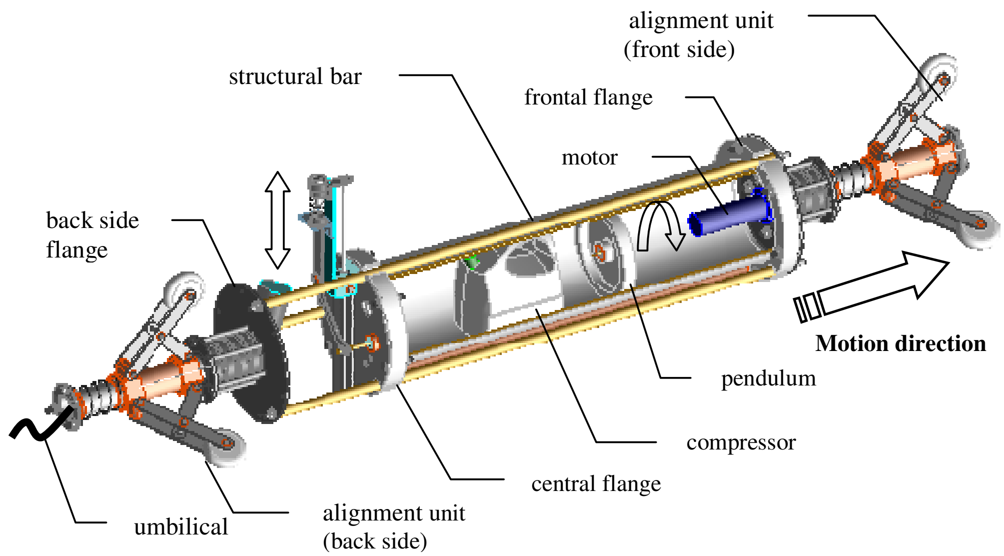


Figure 5. Details of Tinta-P components.

4.2. Container unit

The container unit is located inside the structure and has cylinder components made in PVC. Its main functions are: isolation from external pressure and humidity (waterproof for 2 meters of H_2O) of the onboard components, such as electronics – motor, encoders, data acquisition and control circuits, communication circuit - and pneumatic system – compressor, directional valves, air pressure reservoir -, and explosion-proof capability

The onboard components can be easily accessed due to container unit modular concept, as presented in Fig. 6.

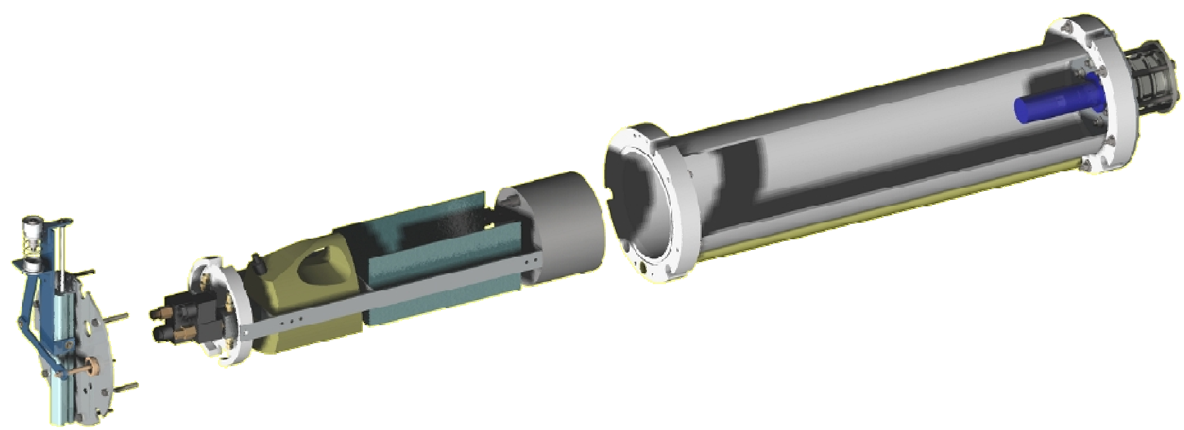


Figure 6. Details of the Tinta-P container unit and onboard components.

4.3. Transducer unit

Tinta-P was designed to measure in a given transverse section of the pipeline inner surface, the coordinates of selected points referenced to pipeline symmetry axis and their associated chemical inhibitor thickness. The database of sampled points represents the section mapping situation in terms of geometrical parameters: radial deformations due to external pressure from soil interaction and distribution of the internal painting.

A commercial ultra-sound calibrated transducer (Mitutoyo, 2000) was used to evaluate the chemical inhibitor thickness. The transducer operates in the 10 MHz to 50 MHz frequency range, giving a ±5 µm resolution.

This transducer is located in a linear platform that moves in connection with a piston rod, in a very slow velocity.

When the piston rod moves upward and touches the pipe inner surface, the transducer achieves its proper position, orientation and contact force due to adjustment of a spring located in the extended extremity of a two d.o.f. arm.

The data acquisition is made after the mechanical stabilization of the arm positioning.

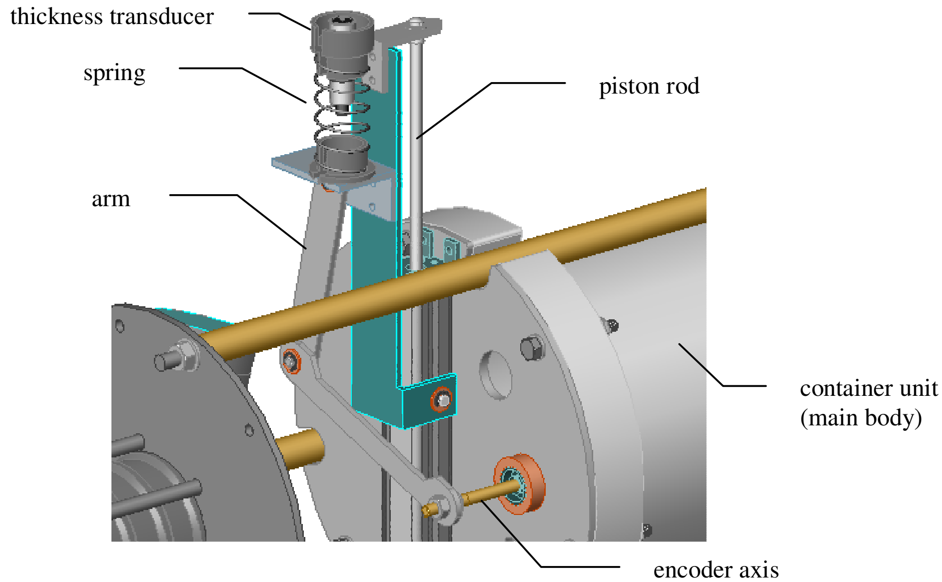


Figure 7. Details of the Tinta-P container unit and onboard components.

4.4. Alignment Unit

The auto-compensated alignment system is formed by back side and front side units (Fig. 5). Each one contains a tripod mechanism with wheels actuated by a rigid spring.

This system tends to keep the geometrical axis of the Tinta-P concentrically to the theoretical symmetry axis of the pipeline, in the vicinity of the region of analysis.

5. MOTION ESPECIFICATION

In order to sample representative points located in the internal circumference of the pipeline wall, Tinta-P is able to move in the radial and angular directions. These motions are executed automatically.

5.1. Radial motion

The radial motion is obtained with the displacement of a piston rod associated to a pneumatic cylinder. This motion is necessary to move the ultra-sound transducer nearby the measurement point.

A planar two d.o.f. arm measuring system with revolute joints is used to quantify the radial displacements referred to the geometrical axis of the Tinta-P.

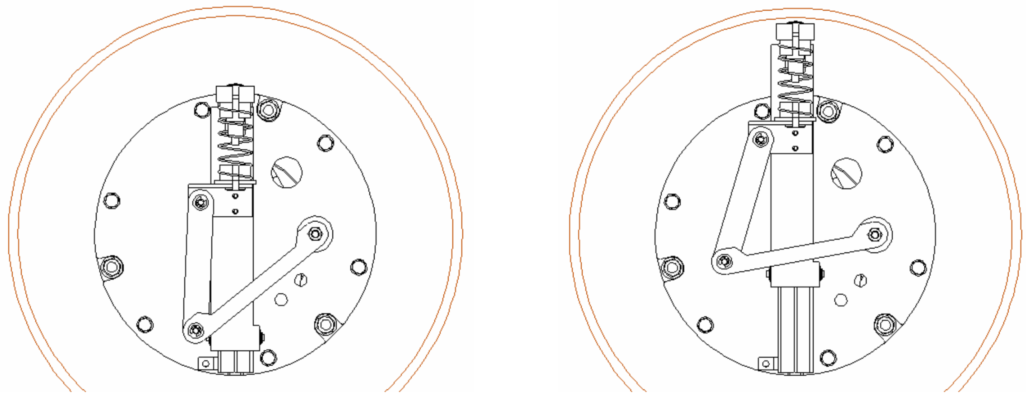
One of its extremities is connected to the piston rod and the other to an encoder (Fig. 7). When the piston rod moves, induces the movement of the arm and consequently the angular displacement of the encoder.

5.1.1. Kinematics model

A Denavit-Hartenberg parameterization (Sciavicco and Siciliano, 2001) was used to establish the analytical relation of the arm positioning and encoder angular displacement. The limit configurations of the radial motion are described in Fig. 8.

The direct kinematics model can be expressed by a homogeneous transformation matrix, which indicates the rotation and position of the transducer location relative to the system reference coordinate frame, concentric to the encoder axis.

Denavit-Hartenberg parameters are used to obtain the homogeneous transformation matrix. For the modeled planar arm with two degrees-of-freedom (Fig. 8), links 1 and 2, corresponding to lengths l_1 and l_2 and angles θ_1 and θ_2 respectively. These parameters are indicated in Tab. 1.



(a) (b)

Figure 8. Arm measuring system. (a) retracted configuration. (b) extended configuration.

Table 1. Denavit-Hartenberg parameters.

Link	α_i	a_i	d_i	θ_i
1	0	l_1	0	θ_1
2	0	l_2	0	θ_2

The resulting homogeneous transformation matrix is presented in Eq. (1).

$$ {}^{0}T_2 = {}^{0}T_1 \cdot {}^{1}T_2 = \begin{bmatrix} C_{12} & -S_{12} & 0 & l_1 C_1 + l_2 C_{12} \\ S_{12} & C_{12} & 0 & l_1 S_1 + l_2 S_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

$$ where: \quad C_{12} = Cos(\theta_1 + \theta_2) \quad e \quad S_{12} = Sen(\theta_1 + \theta_2) $$

5.1.2. Uncertainty analysis

The Cartesian coordinate (x , y) of the contact point at the pipeline is given by the first two terms of the 4th column in the homogeneous transformation matrix, equation 1. Both values are function of the parameters l_1, l_2, θ_1 and θ_2.

The positioning deviation of a point (x, y) depends on the uncertainties related to these parameters. For example, the positioning deviation of coordinate x is calculated according to the Eq. (2) (Holman, J.P., 1989).

$$ w_x = \left[\left(\frac{\partial x}{\partial l_1} \cdot \Delta l_1 \right)^2 + \left(\frac{\partial x}{\partial l_2} \cdot \Delta l_2 \right)^2 + \left(\frac{\partial x}{\partial \theta_1} \cdot \Delta \theta_1 \right)^2 + \left(\frac{\partial x}{\partial \theta_2} \cdot \Delta \theta_2 \right)^2 \right]^{1/2} \tag{2} $$

where W_x is the uncertainty of x. A similar equation can be used to y coordinate to achieve W_y.

The value of an absolute error for the point is here defined as Eq. (3).

$$ W = \sqrt{(w_x)^2 + (w_y)^2} \tag{3} $$

The angular uncertainty is related to the encoder resolution. The encoder (incremental type) moves with link 1 (θ_1 angle) and has a resolution of 512 points/revolution. This value can be multiplied four times by the algorithm that makes the digital conversion from the transducers. Then, the angular uncertainties $\Delta\theta_1$ and $\Delta\theta_2$ are considered to be $2\pi/2048 \approx 0.003$ rad.

The calculated uncertainty W is about 0.2 mm.

5.2. Angular motion

A DC motor and planetary gearhead module furnishes the torque to move the main body units, relative to the alignment units, that remain fixed to the pipeline. The motion is settled to be at low velocity and will only occur whenever the arm is at retracted configuration.

A similar incremental encoder as the one used to measure radial displacements is integrated to a pendulum, giving the value of the relative angular motion (Fig. 7).

The calculated angular resolution is also considered as $2\pi/2048 \approx 0.003$ rad.

6. TESTS

6.1. Laboratory Set Up

The prototypes were mounted and calibrated at the Laboratory facilities.

To validate the performance of the equipments, test facilities such as 2 meters length linear and curved 14” pipelines were installed at the Lab.

A “last minute” design modification on the alignment units of the 3rd prototype was necessary to permit the system to move along a visiting hole located at the upper part of the pipe. This consisted in the addition of wheels at the tripod mechanism. It should be noted that a visiting hole exists at each 200 m of pipeline length.

The constructed prototype and a data mapping of a pipe section are presented in Figures 9 and 10.

6.2. On Site Tests

While the 3rd prototype was under tests at the Laboratory, the 2nd prototype was sent to Bahia, in order to measure a pipeline sample submitted to the internal painting.

This 2nd prototype measured data proved that the distribution of chemical inhibitor product in a tested pipeline section was not according to pipeline operator standards.

Based on these results the pipeline operator was able to apply a punishment to the contracted company and redefine the service.

(a) (b)

Figure 9. (a) Prototype at the Lab. (b) Testes in a curved 14” pipe.

7. CONCLUSIONS

The mechanical characteristics of the second and third prototypes were able to measure the internal distribution of chemical inhibitor product in a 14” pipeline section and its circumference deformation.

Although the concept of the 3rd prototype was more sophisticated then the 2nd one, the on site measuring tests with the 2nd prototype was enough to evaluate the pipeline conditions, according to the pipeline operator standards.

The successful performance of the equipment helped the pipeline operator to redefine the service and new conditions were established.

Tinta-P may be used as an instrumented module unit connected to other specialist modules to perform tasks such as pipeline internal welding and overall inspection. These modules must be intercalated to traction modules to provide mobility.

For future developments the authors suggest a new concept based on hydraulic actuators, so that a high pressure could be applied to the equipment and measurements be made with the presence of fluid flow at the pipeline.

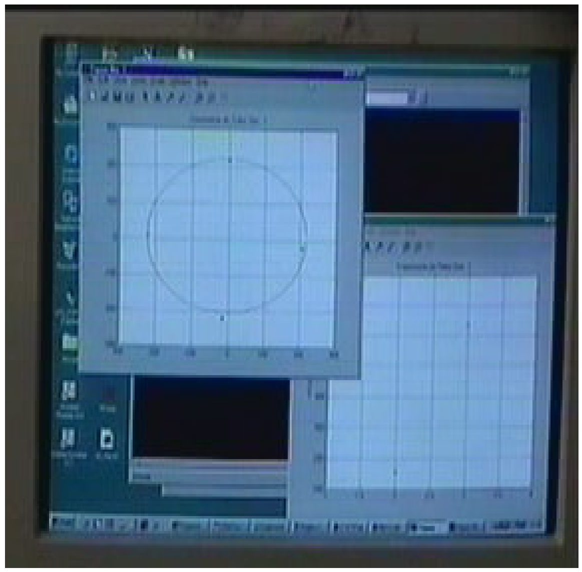


Figure 10. Mapping of a pipeline section.

8. ACKNOLEDGEMENTS

The authors thank prof. Liu Hsu for his participation as Project Coordinator.

This project was mainly financed with FINEP/CT-Petro 1 funds. Partial funds were also obtained with CNPq.

9. REFERENCES

Baldez1 M., Pereira, J.A., Janvrot, I.V., Camerini C.S., “Inspeções com Pigs Geométricos: Principais Resultados de Campo” (in portuguese), 3rd Seminar on Pipeline, CD version, Brazilian Petroleum and Gas Institute – IBP, Rio de Janeiro, Brazil, November, 2001

Beitz, W. and Küttner K.-H., Editors, “Dubbel Handbook of Mechanical Engineering”, Springer-Verlag, U.K., 1994.

Da Silva, J. A. Pereira and Pinho, A. F. “Ferramenta para Inspeção Geométrica de Dutos de 3 pol.” (in portuguese), 3rd Seminar on Pipeline, CD version, Brazilian Petroleum and Gas Institute – IBP, Rio de Janeiro, Brazil, November 2001.

Dorf, R.C., Bishop. R. H., “Modern Control Systems” (in Portuguese), Ed. LTC, pp. 93-127, 2001.

Holman, J.P., “Experimental Methods for Engineers”, McGraw-Hill Int. Edition, USA, 549 p., 1989.

Mitutoyo – Products catalogue, Japan, 2000.

Reis, N.R.S., “Get Inside Robot to Impel and Normal Operation – G.I.R.I.N.O.”, 1999.

Sciavicco, L. and Siciliano, B., Modeling and Control of Robot Manipulators. UK, Springer-Verlag, 2001.

http://www.bahiainvest.com.br/ing/index.asp, BahiaInvest Portal's, State Secretariat of Industry, Commerce, and Mining (SICM), 2007.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.