Towards robotic non-destructive inspection of industrial pipelines

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Abstract

In this paper, the development of a novel omni-directional inspection robot is presented, which is capable of delivering NDT sensors to surfaces on straight pipe, pipe bends and branch connections, overcoming the limitation that a test area over a pipe bend or past a branch or other obstruction raise. The lightweight crawler is attached on the outside of the pipe to the thin metal strip that holds the insulation in place without deforming the insulation through the application of a force controlled clamping mechanism while performing longitudinal, circumferential and arbitrary movements. In order to be able to cope with a range of pipe, materials and coverings, to allow for future modifications and to be able to incorporate a wide range of NDT inspection equipment, a modular approach was considered for the design of the mobile robot. Either two different inspection sensors may be mechanically incorporated into the chassis of the crawler and deployed at the same time or just a double-sided acting sensor (e.g. X-Ray).

Keywords: mobile robotics, omni-directional robot, external-pipe crawler, automated inspection, NDT scanner.

1 Introduction

Over 10 million kilometers of pipelines in Europe carry hazardous fluids (1,2). These pipelines are subjected to corrosion by the environment and contents. Other defects in pipes are caused by mechanical fatigue. The inspection of a great majority of the pipes is mandatory to ascertain their structural integrity as failure to inspect can result in leakage of hazardous material into the environment and even explosion. Up to 90\% of these pipelines are inaccessible for inspection by current methods (1) because these are covered with coatings, such as paint and insulation. Pipeline spills of hazardous fluids into the environment outnumber all other source, e.g., tanker spills in oceans, combined. In Europe, up to 4 million gallons of oil are leaked into the environment per year (3-9). In Brussels, European Union officials have urged member governments to begin applying new inspection rules and technology to stem this pollution (10).

In recent years, many mechanised inspection techniques, sensors and systems for finding defects and corrosion in pipe have been developed. On the other hand, current inspection methods have major drawbacks because these are based on the following regime: “intelligent pigs” that travel along with the fluid inside the pipe, which, except in transmission lines, is rarely possible because “pig traps” are not present to insert the “pig” and retrieve it. For pipelines covered with coatings, inspections involve removing the coatings, inspecting the pipeline under the coating and then reinstating the coating. These inspection methods add extra costs to the inspection process. Thus, development of mechanised inspection techniques, sensors and systems for finding defects and corrosion in pipe that is inaccessible to the operator, covered with coatings, such as thick paint or insulation, without the need to “dig up” or remove coatings out, is the sine qua non of nowadays non-destructive inspection.

Today, there are no commercially available current inspection techniques that can accurately detect significant corrosion or other types of defects in pipework under thick coatings. Another limitation is
that current inspection techniques can only be applied manually by highly trained operators. Recent PANI trials (11), carried out to assess the effectiveness of manual inspections have shown that operators detect only 50% of defects. Commercial scanners have been developed for scanning pipe girth welds and lengths of straight pipe with inspection sensors (12). These are primarily ultrasonic sensors and the scanning is in simple X-Y routines. These scanners either move around the pipe on tracks or along the pipe on magnetic wheels. However these cannot work on curved surfaces around pipe bends and in the vicinity of valves, branches and other features in the pipe. Unluckily, these are areas where corrosion is most likely to occur.

2 Design Scheme

The design concept of the robotic pipe crawler encompasses the following features: longitudinal and circumferential motion and scans of pipe surface, manipulation of pipe bends, elbows, pipe supports and other obstructions, mechanical incorporation and deployment of a wide variety of NDT sensors, modular construction and easily scalable chassis, lightweight, holding on the thin metal band around insulation of pipe without deforming it, limited height and compact so as to cope with restricted access between pipes, execution of inspection routines in arduous on-site conditions and cost-effective design.

In Fig. 1 the final design and the main subsystems of the crawler are presented. The major brake-thought was to optimise the integration of drives and power transmission components, the structural framing, sensors, and the omni-wheels in quite tight space. Additionally an opening at the frame (see Fig. 1) is necessary in order that a stationary obstacle, such as pipe supports, branches, etc., can be avoided. A second function of this opening is to allow for easy and quick placement of the scanner on and off the pipe.

One may also notice that various neat-lines are drawn, inside which the mobile system is to be limited, so that manipulation of curved pipe segments is possible. These lines are drawn with respect to the external dimensions of scanner’s components that lie around and above the pipe and the values from Fig. 2 that represent the bounding dimensions of the chassis to facilitate the crawler travelling along pipe bends. In particular, Fig. 2 demonstrates the effective bounding dimensions of the chassis...
for three different curvatures of a pipe bend. All the points below these curves correspond to a specific set of dimensions, i.e., length and width of the mobile vehicle, which ensure that the system is able to crawl along the curved pipe without bumping into it. Typical values for the curvature of a pipe bend are 1-3.5 times the standard diameter of pipe.

![Fig. 2. Bounding dimensions of chassis in order to overcome a pipe bend.](image)

The outside diameter of the pipe is considered to be from 270 to 285 mm, which is analyzed as follows: 6” inch inner pipe diameter, 50 mm thick insulation and 2 mm thick cladding. By picking up the dimensions of the chassis and arranging the placement of various components of the system on the crawler accordingly, i.e., after consulting the nomograph of Fig. 2, successful manipulation of curved pipe is intrinsically obtained by design. In Fig. 3 a well executed turn of the developed robotic crawler around a 285 mm outer diameter pipe bend is simulated.

![Fig. 3. Simulated turn of the crawler represented by a bounding box.](image)
As seen in Fig. 1, three sets of omni-directional wheels are symmetrically placed at 120°. The first set of wheels is responsible for the longitudinal movement of the crawler. Three rows of twin omni-wheels are evenly distributed along the total length of the crawler. The main axes of rotation lie in a direction perpendicular to the symmetry axis of pipe, while the rotation axes of the rollers, of which each omni-wheel consists, are parallel to the pipe so that the circumferential movement of the crawler is not restrained. A second assembly of a twin omni-wheel set and a DC servo motor drives the scanner around the periphery of the pipe.

The last set of wheels consists of two passive, free-rotating omni-wheels and completes the locomotion scheme. This is part of the clamping mechanism, which exerts a controllable force to the pipe. A precision servo drive, a ball-screw and two linear sliders comprise the clamping subsystem. Strain gauges are placed in appropriate location on the scanner and measure variation in strain of the aluminum chassis due to clamping and therefore provide a feedback for the magnitude of the clamping force. This feedback closes the control loop with the torque-controlled DC servo motor. A static analysis of the system, after a constant clamping force has been applied, is presented in Fig. 4.

![Fig. 4. Reaction forces on the chassis after clamping onto pipe.](image)

The center of mass of the scanner lies inside the outline of the pipe. Ideally, it should coincide with the center of pipe. This deviation causes a moment due to gravitational force to be exerted on the system and tends to rotate the crawler clockwise or anticlockwise according to the orientation of the system with respect to horizontal each time. Thus, for an unbalanced chassis, the circumferential drive should always provide an amount of torque to the omni-wheels so that the crawler is not uncontrollably rotating around the pipe under the gravitational load.
In order to avoid a constantly working motor and because the chassis is not yet passively balanced a suitable combination for the material of the rollers and the magnitude of clamping force should be selected and would lead to a static system. The rollers of omni-wheels are usually made of nylon or polyurethane. Nylon exhibits low sliding and rolling friction coefficients on steel, whereas rollers made of polyurethane provide better grab. The latter were finally selected for the crawler. With a minimum clamping force that was estimated after exhaustive trials and omni-wheels with polyurethane rollers the static friction that is generated is adequate so that the crawler always stays onto the pipe without slipping even when the motors are not providing any torque.

Changes in the magnitude of the reaction forces versus the orientation of the crawler with respect to horizontal are presented in Fig. 5. The reaction force on the passive wheels is constant and in fact equals the clamping force. This force determines the reaction on the driving wheels that changes with respect to the orientation of the scanner. The reaction force on each wheel is the vertical force that the wheel “sees”. This force multiplied by the static friction coefficient gives the frictional force that is generated on that wheel. Practically, this force is the maximum force that the motor may “pass” on the wheel. Motor torques that result to greater forces than those presented in Fig. 5 cause spinning of wheels instead of rolling, which is completely undesirable. This effect can be eliminated by applying even greater clamping force, but its magnitude is limited by the deformation limit of the thin metal band that covers the insulation and the insulation itself.

![Fig. 5. Static analysis of the crawler after clamping onto pipe.](image-url)
come the rolling friction of the wheels, which is developed due to the clamping force that may reach up to 25 Kg and the rolling of the polyurethane rollers on the metal outer side of pipe. At last, the drive motors should have enough torque to overcome the metal stripes that hold the cladding around the insulation and are 2 mm thick. Summation of all these, taking into account a safety factor of 20% and 6 cm diam omni-wheels, results to a required torque of 12 Nm, much the same for both the longitudinal and circumferential drive. A smaller DC servo motor of 6 Nm drives the ball screw mechanism of the clamping mechanism, while the maximum linear and rotational velocity of the robotic crawler is 150 mm/s and 5 rad/s, respectively.

**Fig. 6. CAD model and a photo of the crawler and the control set-up.**

**Fig. 7. Photos of the crawler manipulating a pipe bend and a support.**

### 3 Conclusion - Future Work

Development of an omni-directional mobile robot was presented. The robotic crawler is capable of delivering NDT sensors to the external surfaces on straight pipe, pipe bends and branch connections, overcoming the limitation that a test area over a pipe bend or past a branch or other obstruction raise. The lightweight scanner is attached on the outside of the pipe to the thin metal band that holds the in-
sulation in place without deforming the insulation through the agency of a force controlled clamping mechanism and performs both longitudinal and circumferential movements. A modular approach was considered for the design of the chassis in order to be able to cope with a range of pipe, materials and coverings, to allow for future modifications and to be able to incorporate a wide range of inspection sensors. Either a double-sided acting sensor or two different inspection sensors may be mechanically incorporated and deployed at the same time.

Future work will primarily include optimization of the current design of the crawler aiming at further reduction of its size and weight but without sacrificing the rigidity of the chassis. A perfectly balanced system, which in turn will lead to smaller DC servo motors, will be obtained either by systematic placement of various subsystems and components on the periphery of the chassis or by putting counterbalancing weights in appropriate locations on the chassis. The proper placement of the counterbalancing masses will result from exhaustive simulation on the CAD model of the crawler. Design and manufacture of custom-made omni-wheels exclusively for use with the proposed clawer is also included in the scope of future work. Finally, a sophisticated control scheme for special, uncommon and fully automated inspection routines will be developed.

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