www.ndt.net - 3rd MENDT - Middle East Nondestructive Testing Conference & Exhibition - 27-30 Nov 2005 Bahrain, Manama

Robotic NDE: A New Solution for In-line Pipe Inspection

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Introduction

Failure of energy pipes and tubular equipment in energy plants tend to be catastrophic, resulting in costly property damage, loss of business continuity and even fatalities. There is an ever-growing global awareness of this issue. Pipe failures have caused several governments to take conducive actions in mandating inspection requirements. For example, due to recent failures, the US government has been increasing pipeline inspection and safety requirements, presenting new challenges to operators and inspection service companies. In the North Sea, the Norwegian government mandates that all Coiled Tubing strings be inspected before every job.

Small-diameter pipes and tubes are abundant in critical energy applications, such as oilfield coiled tubing, coiled line pipe, liquid and gas pipelines, boilers, and heat exchangers in refineries and a variety of large plants. Integrity threats to these pipes include third-party damage, external and internal corrosion and pipeline cracking. With Pipe integrity at the top of the agenda, owners and operators of these systems are cautious regarding their reliability and safety to avoid leaks and catastrophic failures.

Currently, there are two categories of commercially available solutions, either internal or external inspection. However, these solutions have limitations. The external inspection devices are not always practical since they cannot reach embedded tubes and subsurface pipelines. The internal inspection devices are either tethered, which limits the reach inside of the pipe to be inspected, or non-autonomous having specific operational requirements (e.g. a medium, differential pressure, launchers, etc). These restrictions leave many pipe operators in constant search for new and improved inspection tools. A complete solution is yet to be put forward, reinforcing the emerging need for robotic NDE systems.

Robotic NDE for Energy Pipes

Robotic NDE for pipes is a procedure utilizing a robotic device in which nondestructive evaluation, including testing and data interpretation, is performed without human intervention. Clearly, the pipe inspection can either be performed externally or internally (in-line inspection). Robotic in-line inspection, the focus of this paper, is driven by the growing need to inspect a wide range of energy piping systems that are inaccessible to external inspection.

So why go robotic? An inspection device in operation is either controlled by human beings (non-robotic) or by a computer system executing a control algorithm (robotic). Human control implies either direct access to the device and thus to all pipe sections being inspected during the inspection (the case of tethered probes), or non-autonomous mode of operation according to a preset, canned scenario (the case of smart pigs driven by differential pressure of the medium inside the pipeline). Given the abundance of non-piggeable energy pipes (i.e., with no launchers, lack of medium with differential pressure, etc.) with intricate topologies (i.e., inaccessible sections to tethered probes), there is a need for a robotic inspection solution.

Having established the need for a robotic in-line inspection system, let’s define the primary objective of such a system by listing its fundamental requirements. They are:

1. the ability to traverse the entire pipe in a reasonable time (without getting stuck)
2. the ability to inspect the pipe with the expected accuracy and spatial granularity
3. the ability to safely transmit the inspection data to the outside world for reporting

We turn now to the challenges encountered while addressing these requirements for robotic in-line inspection of very long small diameter pipes.

Challenges Facing Robotic In-line Inspection

A variety of resource limitations represent major constraints in the design of a robotic in-line inspection device for very long small-diameter pipes. These constraints are mainly due to operating in a confined physical space (the small diameter) for a long time (the length of the pipe) with limited on-board resources. Having to depend solely on on-board resources will be established later in the paper once we establish the necessity of tether free operation.

Pipe Geometry and its Design Implications

Pipe topology and geometry must be assessed thoroughly to ensure the success of the robotic in-line inspection device. Many pipe configurations in the various applications in the Energy and Power industries present major design difficulties. These configurations involve:

- very long continuous pipe sections
- small inside diameters down to sub-inch diameters as found in heat exchangers
- inside diameter (cross section) variations —These variations could be a pipe feature by design, such as the valves found in pipelines and the bottlenecks and pipe widening found in certain plant tubular equipment (e.g., boilers). They may also be the result of undesired transformations due to harsh operational conditions, such as uneven wall thinning and "ovality" that can develop in coiled tubing strings
- sharp angles as severe as 1-D 90° elbows and 1-D 180° U shaped pipe sections, as found in furnace tubes

Very Long Pipes

Pipe length is an important design consideration. A complete in-line inspection of a very long continuous pipe section may take a considerable time and require more resource provisions than shorter inspections. In the case of a tethered inspection, there are virtually no limitations of any resource that can be provided via a tether. However, the length of the tether itself is the critical limitation, preventing access to remote sections of very long pipe. In the case of tether free operation, the robot has to depend totally on on-board resources, the depletion of which is clearly a function of the duration of the inspection and ultimately a function of the pipe length.

Small Inside Diameter

Small inside diameters translate to severe physical space limitations for the design and packaging of the various components of the robot. A train like design with carts connected by articulated joins is inevitable. The space limitations impose constraints on the shape and dimensions of the mechanical parts as well as on the packaging of the electronics (configuration and dimensions of the Print Circuit Boards) and on the wiring of the robot. Many parts and components must be miniaturized to simply fit, which is at times a major challenge.

Sharp Angles

Sharp angles along a very long, small inside diameter pipe cause intense friction on the tether of a tethered in-line crawler. This friction invalidates any tethered solution since it violates the above-mentioned first requirement of the in-line inspection device (i.e., the ability to traverse the entire pipe in a reasonable time, without getting stuck). As a result such a device must be tether-free, cutting it from the outside world during operation.

Sharp angles have additional design implications pertaining to the shape and dimensions of the carts, joins, locomotion mechanism (wheels, skids, etc.) and wiring of the robot. For instance, Figure 1 shows the relationship between the maximum outer diameter and the maximum length of a cylindrical cart capable of traversing a 1-D U-shaped section of a 6 inch inside diameter pipe.

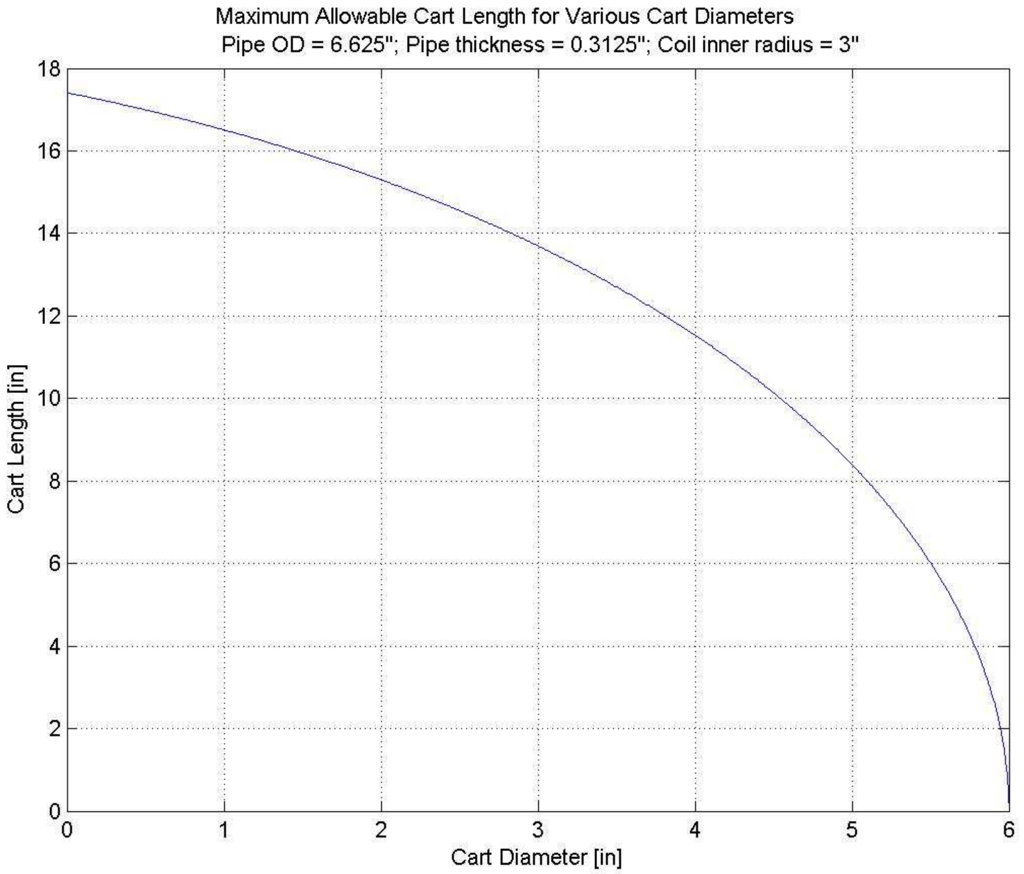

Figure 1 - Maximum Size of a Cylindrical Cart Able to Traverse a 1-D 180° Section of a 6” ID Pipe

Inside Diameter Variations

Inside diameter variations also have important implications on the mechanical design of the robot and its locomotion:

- The cross section of the mechanical parts (e.g., outer diameter of carts and joins) must be small enough to handle each narrowing of the pipe, as well as the effect of any sharp angles as illustrated in the previous Section.
- The guiding mechanism of the robot against the inner wall of the pipe (i.e., wheels or skids) has to be flexible enough to handle the variations of the inner diameter and still maintain its guiding functionality throughout the length of the robot.

Being Cut-off from the Outside World

We already established that pipe geometry and physical space constraints imposed a tether-free operation of an in-line pipe inspection robot. With its umbilical cord cut, the robot must rely on its on-board resources to complete the inspection journey effectively.

Autonomy

With no link to the outside world, the robot must be autonomous. That is, it must be programmed to handle all situations that may arise during its traversal of the pipe. This "intelligence" is a direct function of the depth of analysis of the operational environment that the robot might encounter during its traversal of the pipe. One traditional question that always comes up in discussions of autonomous robots is: "What happens if it gets stuck inside the pipe?" This question must be addressed no matter how improbable the actual event of the robot getting stuck might be. The challenge of autonomy is to think about and design to the normal (highly probable) situations as well as the abnormal (improbable) ones.

In addition to a thorough control algorithm that takes into consideration the various modes of operation and all of the situations that might arise during an in-line inspection, it is important to give the robot certain mechanical and navigational capabilities that are required during emergencies. These capabilities allow it to recover from bad situations, sometimes at the expense of interrupting the inspection. For instance, the robot's ability to reverse direction and back off is important in case an unforeseen obstacle prevents it from continuing its forward motion.

Total Dependence on On-Board Resources

In addition to the "intelligence" in its control algorithm, the robot must have enough of the required resources to complete the inspection. This includes the mission-critical energy source that feeds all electrical and electromechanical components of the robot (i.e., electronic circuits, motors, etc.). Without energy all robot functions come to a complete halt. Therefore, on-board energy consumption must be monitored to ensure the completion of the inspection. Having no access to an outside energy source and given the limited capacity and relatively short charge cycle of batteries, the challenge is in the sustainability of the energy source.

Other critical on-board resources pertain to the processing and storage of the raw inspection data. The reliability of the hardware and software of the on-board computer is crucial. The robot must also have large enough on-board data storage capacity to save the data stream generated during the entire inspection in case it cannot transmit the data wirelessly to an outside computer during the inspection. Indeed, wireless data transmission is physically impossible during the in-yard inspection of a coiled tubing string (while still coiled on the reel) due to the many layers of steel tubes separating the robot from the outside world.

Provisions to deal with on-board energy and electronic failures should be considered. This may involve a "brute force" mechanism to eject the robot from the pipe.

Implications on Sensor Design

A key module of the in-line inspection device is one or more NDE sensor carts. The selection of the sensor technology utilized in the device is a major design decision. The pipe material is a determinant factor in making such a decision. The NDE designer typically selects one of the sensor technologies known for their NDE effectiveness for the target pipe material. For instance, Magnetic Flux Leakage (MFL) and Ultrasound (UT) are two popular sensor technologies for Ferromagnetic pipes. However Eddy Current and Remote Field Eddy Current are utilized for non-Ferromagnetic metallic pipes.

Energy Constraints

Given the limited nature of the on-board energy source, the energy consumption requirements of the NDE sensor become critical criteria in the selection of the sensor technology. The goal now is to maximize the effectiveness of the NDE sensor while minimizing its required energy consumption. These design criteria make MFL sensors, which can be built with permanent magnets, preferable to UT sensors for Ferro-magnetic pipes.

Physical Space Constraints

NDE sensors have their own spatial requirements in order to function properly and effectively. For instance, MFL sensors require local magnetization of the pipe section being inspected, which in turn requires the placement of the magnetizing components of the MFL sensor as close to the inner pipe wall as possible. The distance between the inner pipe wall and the detectors of the MFL sensor (i.e., the liftoff) must also be minimized in order to increase the sensitivity and accuracy of the sensor. As another example of spatial sensor requirements, UT sensors work

properly only in the presence of a bonding medium that bonds the detector elements of the sensor to the pipe surface (i.e., reflector).
The challenge arises from the conflict between the spatial requirements of the NDE sensors and the physical space constraints inside the pipe. The following mechanical obstacles that are typically found on the surface of the inside pipe wall are a few examples of such constraints:

- Scale— found in used tubular plant equipment such as furnaces and boilers
- Flash line inside coiled tubing— a major speed bump along the entire length of a coiled tubing string
- Butt welds— due to excess weld material left on the inside surface of a weld area

These mechanical obstacles are certainly capable of disturbing the bond between the detector and reflector of a UT sensor, which negatively impacts the reliability and accuracy of the sensor. They would also damage the MFL sensor components that must operate very closely to the pipe wall, rendering the minimization of the MFL sensor liftoff and the magnetization of the pipe wall much more challenging.

Sharp Angles represent another major physical space constraint to NDE sensors that must operate near the inside wall surface of the pipe (e.g., MFL) or be continuously bound via a medium to the wall surface (e.g., UT). According to Figure 1, in order for the NDE sensor cart to remain close to the wall surface (i.e., a sensor cart with a large outer diameter) and traverse a pipe section featuring a sharp angle, the sensor cart must be very short. The need for a more reasonable sensor cart length that allows for the packaging of the necessary sensor components introduces the idea of collapsible and expandable sensor carts. The cart collapses into a smaller profile just in time to go through a sharp angle and expands immediately thereafter to resume its normal mode of operation required for a reliable inspection. However, the mechanical design of a collapsible NDE sensor that maintains its effectiveness in its expanded operational state is not trivial.

The Presence of a Medium Inside the Pipe

The presence of a gas or liquid medium during the inspection has its own implications on the design of the robot. Usually the presence of a medium inside the pipe implies that the pipe is pressurized, which is the case of transmission, gathering and distribution oil and gas pipelines. However, sometimes the presence of some medium inside supposedly empty pipes is found because of the environmental conditions around the pipe. For instance, it is very likely to find sea water inside coiled tubing strings being inspected in an off-shore location.

The mere presence of water or any liquid imposes the requirement to properly seal all electronics and the wiring conduits across the mechanical parts of the robot. In case of a pressurized medium, the seals as well as the mechanical parts must be designed to withstand the pressure level inside the pipe.

Finally, any corrosive properties of the medium itself must be taken into consideration. All parts and components of the robot that are exposed to the medium inside the pipe must be either made of or shielded with appropriate materials that better resist the corrosive effects of the medium.

*it*Robotics' Solution for In-Line Inspection

In this section, we describe a robotic NDE solution for in-line pipe inspection. This solution is developed by *it*Robotics, a Houston, Texas based company. *it*Robotics' product is called the Small Pipe Inspector (SPI). It was initially designed for the in-yard testing of oilfield coiled tubing (CT). During an in-line inspection session, the SPI crawls through an entire CT string ranging from 10,000 to 30,000 feet in length while still coiled on its reel. This mode of inspection avoids the need to uncoil the CT string for inspection, saving a fatigue cycle of the string. CT strings feature the challenge of inside wall mechanical obstacles. Specifically, almost all CT strings feature a flash line that runs along the entire length of the tube with a height of up to .09 inch and a width of up to .08 inch. Relative to an inside diameter of 2.5 inch or less and a wall thickness of 3/8 inch or less, the flash line represents a major "speed bump" for any crawler inside the pipe.

Figure 2 -- The Small Pipe Inspector (SPI)

In addition, it is not uncommon to encounter butt welds in CT strings. These welds, especially the ones carried out in the field, may feature bleeding or excess of weld material inside the wall, causing a major obstacle to a pipe crawler.

The SPI is currently being customized for the in-line inspection of tubular plant equipment such as furnaces and boilers. Such piping systems feature the challenges of sharp angles (down to 1-D 90% elbows and 1-D 180% U shaped pipe sections), as well as inside diameter variations.

Locomotion

The design of the SPI locomotion takes into consideration the length, geometry and physical space limitations of CT in a coiled state on a reel.

Tether Free Operation

Being tether free, the SPI is capable of traversing hundreds of CT string loops around the reel freely. The inside diameter of the smallest CT reel is 5 feet. The SPI version being customized for tubular plant equipment is also tether free, allowing it to go through pipe sections with sharp angles.

Autonomy

The SPI is autonomous. It is able to operate inside pipes with or without the presence of a pipe medium or differential pressure. It can be programmed to reduce speed, stop, and reverse direction to more thoroughly inspect pipe sections with suspected damage. Autonomy is also leveraged in emergency situations, allowing the robot to reverse direction and exit the pipe.

Diameter Variations and Mechanical Obstacles

With the built-in flexibility of its mechanical parts that are responsible for locomotion (e.g., wheels), the SPI is able to accommodate inside diameter variations of up to 25%. This feature also allows the SPI to protect itself from being damaged by any mechanical obstacles along the inner wall of the pipe. Indeed, the SPI can crawl safely through CT strings with flash lines and butt weld obstacles.

NDE Sensors

The SPI is designed to accommodate several NDE sensors. It currently features an MFL sensor consisting of up to ten sensor elements. Each sensor element captures the three components of the magnetic field (i.e., axial, radial and tangential) as illustrated in Figure 3 below.

On-Board Resources

The SPI includes the necessary on-board resources for autonomous, tether free inspection of up to 30,000 feet of coiled tubing. This includes

- a sustainable energy source, including a bank of batteries,
- a multi-processor on-board computer with powerful data acquisition and data processing abilities, and
- large storage capacity, sufficient to save the raw data generated during the entire inspection.

Data Interpretation and Reporting

After completing the inspection, the data is downloaded from the SPI through a USB port into a computer file for analysis and reporting. The software displays graphs and charts interpreting the inspection session and identifying defects and pipe features. Changes in wall thickness, pits, and butt welds are easily detected and reported to the user.

A pipe range can be specified with zooming capabilities or the user can automatically position the display to the next defect. Navigating from defect to defect is effortless. Comprehensive reports can be generated summarizing all defect data captured during the inspection. Figure 3 offers a snapshot of the reporting tool.

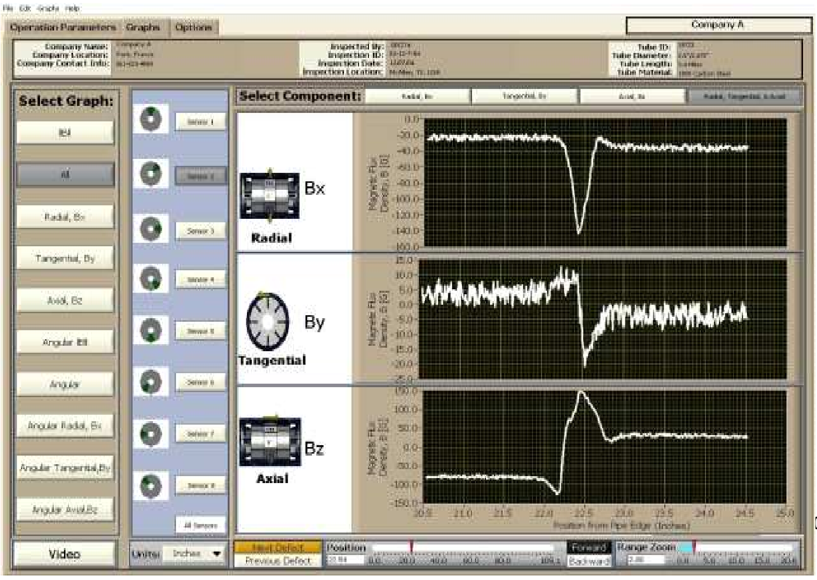

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Figure 3 – Software Report Display

Conclusion

The geometry and mechanical features of most piping systems in the Energy industry and other industries represent severe spatial constraints that render the design of robotic in-line pipe inspection systems very challenging. Almost all areas of the design and all subsystems of the robot are impacted directly or indirectly by these constraints.

A number of challenges facing robotic NDE for in-line inspection were discussed in this paper. An in-line inspection solution that addresses these challenges was also presented. More robotic NDE development work is required to satisfy the established need of the industry for robotic in-line NDE.

About the Author

Anouar Jamoussi is the President and CEO of itRobotics, a Houston based company focusing on the development of robotic in-line inspection systems for very long small-diameter piping systems. He has a strong background in computer software engineering with over 17 years of experience in the software and robotic industries. He holds a Ph.D. in Computer Science from the University of Houston and a M.S. degree in engineering from L'Ecole Centrale de Paris, France.