NON-DESTRUCTIVE TESTING ROBOTS (NDTBOTS) FOR IN-SERVICE STORAGE TANK INSPECTION

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Abstract—Petrochemical storage tanks are inspected mostly with outages to assess the extent of underside corrosion on the tank floor. Emptying, cleaning and opening a tank for inspection takes many months and is very expensive. Inspection costs can be reduced significantly by inserting robots through manholes on the tank roof and perform non-destructive testing. The challenge is to develop robots that can operate safely in explosive and hazardous environments and measure the thickness of floor plates using ultrasound sensors. This paper reports on the development of a small and inexpensive prototype robot (NDTBOT) which is easy to make intrinsically safe for zone zero operation. It hops around a floor to make measurements without using external moving parts. The paper describes the design, experimental testing of the NDTBOT and results of steel plate thickness measurement while operating in water.

Keywords: Storage tank inspection, NDTBOT, In-service inspection

1. INTRODUCTION

Storage tanks constructed of carbon steel are likely to degrade due to the storage materials, such as crude oil, oil products, petroleum chemical and petrochemical raw materials. Most tanks are constructed of steel plates that are welded together to form the structure. Corrosion, and in some circumstances, cracks can form over time leading to leakage of the contents, resulting in severe economic losses and environmental pollution (Chang and Lin, 2006). To avoid any damage to the environment, inspection, evaluation, and repair activities are performed periodically according to safety regulations API 653 (American Petroleum Institute, 2014), EEMUA Publication 159 (Engineering Equipment and Materials Users Association, 2014). Most of the tank welds and surfaces that are subjected to these elements are reachable from the outside, such as the walls and the dome. Current manual inspection method requires the tank to be out of service for some weeks depending on the size of the tank. The inspection operation requires transportation of the product to other tanks or location and cleaning the tanks before a human inspector can gain access into the tank and perform Non-Destructive Testing (NDT) inspection. These factors pose several disadvantages such as the cost implication, period to get an inspection done and ultimately loss of revenue due to downtime. Also, high-risk exposure of workers to chemicals during the cleaning operation and inspection task is another limitation to using a human to carry out these tasks. However, only external corrosion and weld can be inspected from outside Kalra et al. (2006), while internal corrosion on tank floors can only be inspected from the inside.

Several in-service storage tank floor inspection robots have been proposed e.g. Sattar et al. (2007), Maverick (1998). These are large machines that are difficult to deploy from the roof and difficult to certify as safe for zone zero operation because of moving components such as motors and large power requirements. Managing their long umbilical (>100 m) is also a major headache.

The aim of our work is to develop small low power robots that are easy to deploy, do not require power cables or wheels, use few actuators, and use very low power electronics that are permitted in zone zero. Robot cost should be low so that swarms of NDTBOTS can be used to perform the inspection and safely abandoned where robot recovery is difficult or even impossible. Section 2 describes the NDTBOT design and prototype, section 3 describes control motion testing, and section 4 presents results of in-service steel plate thickness measurement.

2. INITIAL NDTBOT DESIGN AND PROTOTYPE

The first prototype of the NDTBOT has been developed to test its motion and NDT capability in a water tank. It comprises of two sealed boxes, a buoyancy tank (B.T.) mounted on top of a box housing the electronics. The NDTBOT is made negatively buoyant by pumping in surrounding liquid and positively buoyant by pumping it out. The latter mode lifts the robot off the floor while at the same time providing a thrust force to displace it sideways. In this way, the robot is made to hop around the tank floor. A zero degree ultrasound probe mounted on the bottom box makes measurement of floor plate thickness. This box houses a submersible and reversible electric pump and a microcontroller. The first experimental prototype supplies DC power to the electronics box via a cable and retrieves NDT data with a serial communications cable for processing with a commercial flaw detector placed outside the tank. To meet the objectives stated in section 1, a future prototype will carry a power pack and the flaw detector inside the electronics box and send NDT data to the outside using wireless communications (not developed at present). The design aims to obtain the smallest robot dimensions to present a small footprint on the floor and allow entry into the manhole of a petrochemical storage tank with minimum size of 300mm diameter.

For the robot to perform an inspection in oil in an explosive and flammable environment, the robot operation must avoid any spark which can create an explosion in the tank due to heat and the presence of vapour mixture. The buoyancy tank (B.T.) will contain only flammable liquid and vapour but no heat sources and hence needs no protection. The bottom box housing all the electronics (battery, micro-pump, microcontroller, flaw detector and ultrasound probe) will be encapsulated in a flameproof epoxy to exclude all air. The micro-pump is made of flame-proof material and will not get hot as it will be operated for short periods to move the robot around. Cable glands used on the first prototype are designed for underwater IP68. Therefore, with no moving parts, a sealed water tight box, and all electronics epoxy potted, the overall robot is likely to obtain ATEX approval for operation in flammable and explosive environments and be used in a storage tank for in-service inspection.

The final robot will be designed to meet the standards EN 60079-11, EN 60079-26 and EN 60079-18 intrinsically safe to operate in zone 0, in which ignitable concentration of flammable gases or vapours is present continuously.

Figure 1, shows the first prototype of the NDTBOT ready for testing in a laboratory water tank. Dimensions of the rectangular box shaped B.T. are 114x89x56 mm while the box housing the electronics is 140x102x77 mm. The mass of the whole system in air is 1.67kg.

2.1. Buoyancy control system

For underwater vehicle motion, thrusters are usually used. However, there are two disadvantages of this method: high energy consumption and prohibited use of thrusters in a flammable and explosive environment. Also, energy storage is limited for submersible vehicles. Robots on data gathering missions where they sit on the bottom and gather acoustic, video and chemical data over extended periods of time need to conserve or harvest energy.

Our NDTBOT uses a controllable buoyancy system to obtain motion with a single reversible micro-pump. It has the advantages of low cost, low energy consumption, simple operation, does not provoke perturbations in the environment of inspection and does not need to carry a heavy power cable.

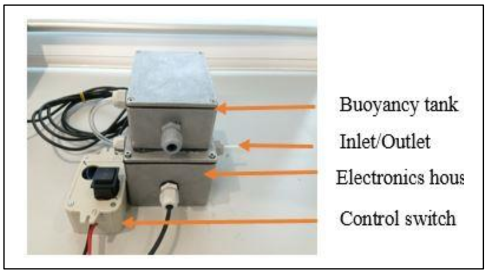

Figure 1: The NDTBOT

2.2. NDTBOT buoyancy tank and electronic house

The robot’s variable B.T. and electronic house are rectangular aluminium boxes, with IP rating suitable for marine and industrial environments with operating temperature of -20°C to 280°C. The buoyancy system starts on the surface of an oil tank at a positive buoyancy value close to the neutrally buoyant point. The tank will have both liquid and air trapped in the B.T. Adding more liquid to the B.T. will compress the air and increase its pressure. The pump therefore has to be capable of working against this pressure both when injecting liquid into the tank and also when ejecting it against external pressure at different depths. Maximum expected height of a petrochemical tank is around 10m. The liquid pressure at a depth of 10m will be 2 bar. Figure 1 indicates that operating the pump at 6V (to use minimum power) will be sufficient to work against internal and external pressures of 2 bar with a flow rate of 200ml/min. If required, at 12 V the pump can work at pressure of 6 bar with a flow rat of 500ml/min. The volume of fluid that flows into or out of the NDTBOT B.T. to make it descend/ascend in the inspection tank determines the forces available for motion and can be calculated using equation (1).

$$V_d(t) = \dot{V} \times t \qquad (1)$$

Where $V_d(t)$ is the volume of liquid added to the B.T., t is the time taken to add the liquid and $\dot{V}$ is volume flow rate. The amount of fluid $V_d(t)$ added in a given time t depends on the pump input voltage (flow rate). Table 1, shows data with different voltages applied to the pump and the weight of liquid (water in this case) that is added in this time.

Table 1: Added weight of water starting at neutral buoyancy

Input voltage(V)	Volume added (ml)	Liquid weight (g)
6.0	7.5× t	7.5× t
8.0	10× t	10× t
10.0	12.7 × t	12.7 × t
12.0	15 × t	15 × t

Using Boyle's law that describes how the pressure of gas tends to increase the volume of gas decreases, equation (2).

$$P_1 V_1 = P_2 V_2(t) \text{ and } P_2 = \frac{V_1}{V_1 + V_d(t)} \times P_1 \qquad (2)$$

P_1 and V_1 represent the original pressure and volume of liquid in the B.T. at neutral buoyancy and P_2 represents pressure at a new volume V2. $V_d(t)$ is the volume of liquid being added to the B.T.

At time (t = 0s) the pump is off, the NDTBOT is at the surface and pressure inside the B.T. is atmospheric pressure i.e. P_1 = 1 bar. Table 2 shows the corresponding increase in internal pressure when fluid is injected into the B.T. With an applied voltage of 6V, the pressure reaches approximately 1.9 bar in 35 seconds with an added liquid volume of 263 ml.

Table 2: NDTBOT tank characteristics

Time (s)		0	5	10	15	20	25	30	35
6 Volts	Pressure (Bar)	1	1.07	1.15	1.25	1.36	1.49	1.66	1.86
	Volume $V_d(t)$ ml	0	37.5	75	112.5	150	187.5	225	262.5
8 Volts	Pressure (Bar)	1	1.1	1.21	1.36	1.54	1.79	2.12	2.60
	Volume $V_d(t)$ ml	0	50	100	150	200	250	300	350
10 Volts	Pressure (Bar)	1	1.13	1.29	1.15	1.81	2.27	3.04	4.59
	Volume $V_d(t)$ ml	0	63.5	127	190.5	254	317.5	381	444.5
12 Volts	Pressure (Bar)	1	1.15	1.36	1.66	2.12	2.94	4.81	13.16
	Volume $V_d(t)$ ml	0	75	150	225	300	375	450	525

3. NON-DESTRUCTIVE TESTING EXPERIMENTS

The ultrasonic testing (UT) methods used in the experiment are the pulse-echo technique: contact NDT and non-contact NDT with immersion probes. In the former case the probe contacts the surface via an ultrasound couplant (water in this case). In the latter case, the ultrasound probe is kept at a constant stand-off distance from the surface with sound transmission through the liquid. A single transducer which acts as a transmitter, as well as the receiver, was used to measure the thickness of six different steel plates. The goal of this experiment was to measure the thickness of different steel plates using the NDTBOT submerged in a water tank and compare these measurements with prior measurements of real thickness with a Vernier caliper and results obtained with contact UT. The experiment was conducted in three steps. First, the plate thickness of different metal plates was measured using a Vernier caliper at different places and averaged to give a single thickness. Then, a conventional immersion ultrasound transducer (UT) was used to determine the thickness with manual scanning (contact NDT). Finally, the UT probe was integrated with the NDTBOT with the probe at a constant stand-off distance from the plate surface (non-contact NDT) to ascertain the thickness of the same steel plates.

Figure 2 shows an experiment with three submerged steel plates. An Omniscan flaw detector, power supply and control pendant were placed outside the tank and connected to the NDTBOT ultrasound probe and pump electronics.

The probe used in the experiment was a conventional UT, single element, diameter 12.75 mm, with frequency of 2.25MHz.

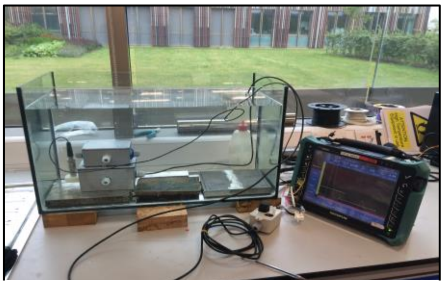

Figure 2: NDTBOT thickness measurement of submerged steel plates

Table 3 shows the results. The margin of error as a percentage was calculated with equation (3):

$$\%\text{Margin error} = \frac{\text{Thickness measured} - \text{Real thickness}}{\text{Real thickness}} \times 100 \qquad (3)$$

Table 3: Initial, measured thickness and %margin error

Plate number	Real thickness (mm)	UT Contact thickness (mm)	UT NDTBot thickness (mm)	UT Contact % margin error	NDTBot % margin error
1	21.45	21.90	21.31	+2.10%	-0.65%
2	19.80	20.75	19.48	+4.80%	-1.61%
3	21.82	21.64	20.72	-0.82%	+5.04%
4	21.41	21.90	21.31	+2.29%	-0.47%
5	13	14.38	12.94	+10.62	-0.46%
6	14	14.68	13.76	+4.85%	-1.71%

The UT contact margin of error is higher than the NDTBOT margin error when compared to the real material thickness. This is due to greater variation of pressure applied to the hand-held ultrasonic transducer during UT contact scanning. Therefore, NDTBOT measurement of plate thickness with non-contact NDT could give more accurate results than an operator performing the measurements with contact NDT in an opened and vented tank.

4. CONCLUSION AND FURTHER WORK

A first prototype of the NDTBOT was developed to test its motion capability with a simple active buoyancy control method and to determine the quality of plate thickness measurements with non-contact ultrasound NDT. The NDTBOT thickness measurements with an immersion ultrasound probe obtain more accurate results than manual contact NDT. Therefore, the results give confidence that sending in NDTBOTS to look for corrosion thinning on the floors of storage tank can give equivalent or better results than manual NDT performed by a human operator.

Future work will attempt to miniaturize the NDTBOT for low cost production, with on-board power, flaw detection, NDT data retrieval, communication, localization and control capability for prolonged and autonomous inspection. The design will be engineered with selection of suitable components, materials and procedures for safe operation in zone zero environments. It will be tested in petroleum product such as diesel or kerosene and oil sludge to analyse the capability of NDTBOT in real world storage tank inspection.

REFERENCES

1. American Petroleum Institute. *API Standard 653: Welded Steel Tanks for Oil Storage*. Washington: American Petroleum Institute, (2014).

2. J. Chang and C Lin. (2006). *A study of storage tank accidents*. Journal of Loss Prevention in the Process Industries, 19(1), pp.51-59.

3. Engineering Equipment and Materials Users Association. EEMUA Publication 159: *Above ground flat bottom storage tanks: A guide to inspection, maintenance and repair*. London: Engineering Equipment and Materials Users Association, (2014).

4. P. Kalra S. Weimin, and G. Jason, *A Wall Climbing Robotic System for Non-Destructive Inspection of Above Ground Tank,* IEEE CCECE/CCGEL, Ottawa, (May 2006).

5. Maverick Demonstration “Submarine that goes in Gasoline”, Solex Robotics, http://www.solexrobotics.com/Solex6.html.

6. T. P. Sattar, E. H. Leon-Rodriguez and J. Shang (2007). *Amphibious NDT Robots, Climbing, and Walking Robots: Towards New Applications*, Houxiang Zhang (Ed.), ISBN: 978-3-902613-16-5, pp 128-136 (InTech, DOI: 10.5772/5078.