PDA Depth Control of a FPSO Swimming Robot

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Abstract: **This paper introduces a Proportional, Derivative and Adaptive (PDA) depth control method for a swimming and walking robot designed for Floating Production Storage and Offloading vessel (FPSO) inspections. The depth of the robot is controlled by adjusting the mass of the buoyancy tank on the top of the robot while keeping the overall robot volume constant, so that the robot weight is adjusted around its neutral buoyancy point. The robot can swim to a given depth in short time without too much overshoot, and maintain that depth even with the disturbance from the thrusters that drive the robot moving horizontally. The control algorithm is adaptive to varying depth to let the robot have similar dynamic performance in any depth in the tank.**

Keywords: Swimming Robot, PID control, PDA control

I. INTRODUCTION

Floating Production Storage and Offloading (FPSO) and Floating Storage and Offloading (FSO) vessels are increasingly being used for production and storage of oil from offshore fields. A typical FPSO contains 15 km of internal safety critical welds that require detailed offshore inspection on a 5 year cycle. These welds are prone to fatigue cracking due to the drastic increase in loading as the majority of FPSOs in the world are converted ocean going vessels, which are now carrying heavy oil that exceeds their original design loads.

Current methods of inspection of these welds have major drawbacks as they require the FPSOs to be dry docked, emptied and cleaned with consequent disruption to production. This means that 90% of the costs of inspection are associated with the disruption of production and emptying and cleaning the FPSOs. The inspections are also mainly visual and manual and therefore subjective with no hardcopy results. Operators and surveyors are exposed to hazardous conditions e.g. toxic gases, working through abseiling, on ropes and via scaffolding.

The objective of the FPSO project is to develop Non-Intrusive In-Service Inspection Robotic System for Condition Monitoring of Welds inside FPSOs [1,2]. The robot, carrying a scanning arm and Non-Destructive Testing (NDT) sensors, will be able to swim in oil to a test site (though at this stage it has been tested in water). Then actuated wheels move the robot more accurately for the scanning arm to deploy NDT inspections. The design of the robot, reported more fully in [3] is shown in Figure 1.

All the electrical components and electronics controllers for controlling the robot are placed in a sealed and pressurized box which is the central part of the robot. The central box is pressurized by inert gas for the intrinsic safety requirement of working in oil.

The buoyancy tank to swim the robot vertically is mounted on the top of the robot. The robot depth is controlled by changing the buoyancy around its neutral point. There are two approaches to do so. One is to change the mass of the robot while keeping its volume constant. The other one is to change the volume of the robot while keeping its mass constant. A prototype of a robot with a constant volume buoyancy tank has been developed and tested in water.

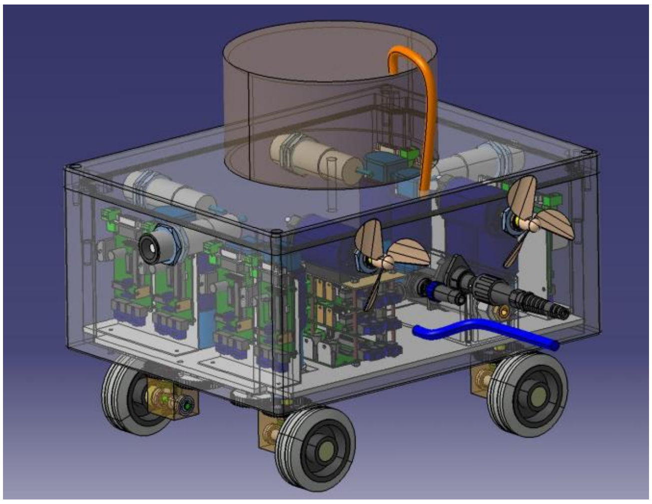


Fig. 1. Overview of the robot

The horizontal swimming motion of the robot is driven by two thrusters on the side of the robot. By controlling the two thrusters, the robot can be pushed to swim forward or be pulled to swim backward, the robot can be turned while the two thrusters run in opposite directions.

The robot is also a wheeled robot that can move on the floor guided by ultrasonic sensors. The wheels underneath of the robot can be turned to any angle so that the robot can be driven to move in any direction and rotate around its centre point when the wheels are placed to form a circle. The ultrasonic sensors mounted on the front, back and side of the robot can measure the distance from the stiffeners and the wall, locate the robot parallel to the weld that is going to be inspected, find the corner to start the inspection, then the scanning arm takes over to perform the inspections.

The robot control is composed of a host computer and some on-board PIC control modules, including DC servo modules and I/O modules. Each servo module drives one DC motor and all the I/O signals go through the I/O modules. The communication between the host PC and the control modules is through RS485 communication. Any number of the module combination can be used as long as not exceeding the maximum allowance, 32 modules. This makes the system easily be expanded and the umbilical of the robot is just one thin cable. The modules are compact and light that is suitable for carrying on board. The control diagram is shown in Figure 2.

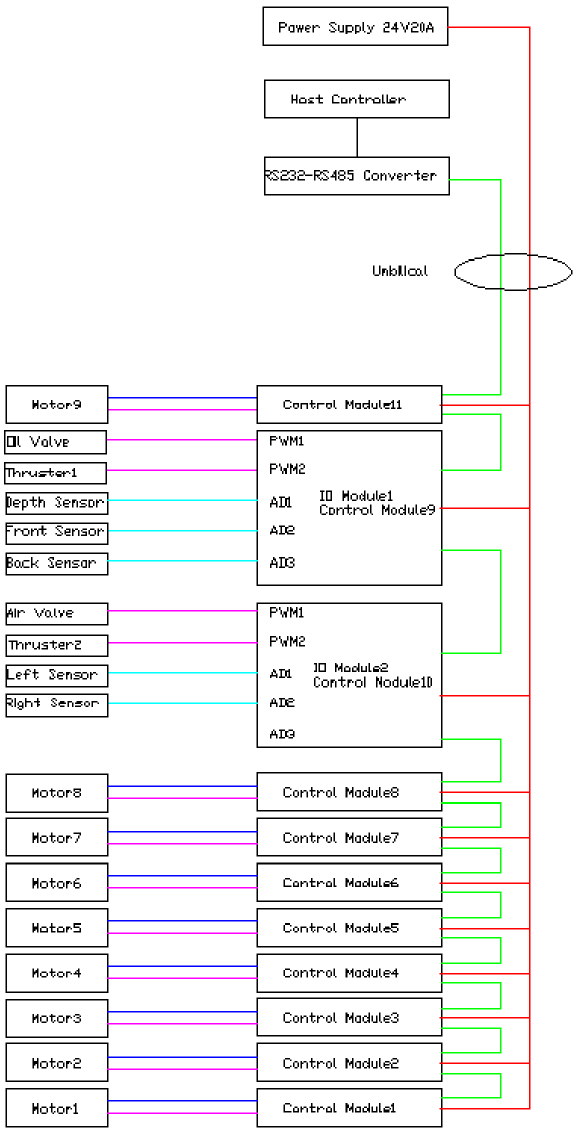


Fig. 2. Robot control diagram

II. Depth Control of the Robot

A. *Depth Control approach*

Due to the highly under-damped dynamics in oil, one of the difficulties of controlling the robot is to drive the robot to a desired depth quickly and then to maintain this depth while swimming, despite disturbances from the action of the thrusters. This is realized by changing the buoyancy around its neutral buoyancy point. The variable buoyancy tank diagram is shown in Figure 3. It essentially consists of a sealed tank, with three valve controlled openings.

This design uses simple on-off valves to control the entry of oil and air in and out of the buoyancy tank so that the overall mass of the robot is changed. Both the valves are direct coil action valves because the operating pressure starts from 0 Bar. When the oil valve is opened, by letting compressed air into the tank, the oil in the tank is pushed out, so that the overall weight of the tank is reduced; on the contrary, by releasing the compressed air to the atmosphere, oil will be pushed into the tank by its own pressure, so that the overall weight of the buoyancy tank is increased.

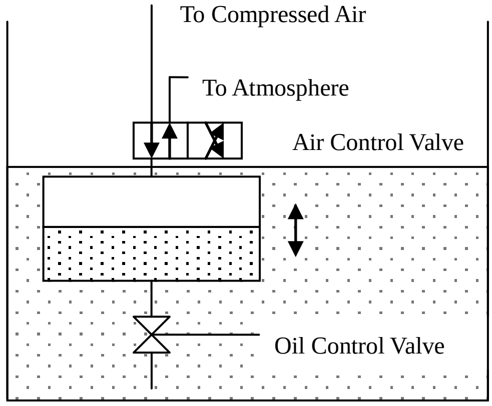


Fig.3. Diagram of buoyancy control tank

The depth of the robot is sensed by a pressure transducer. The output of the pressure transducer is sent to the controller via an A/D converter. As defined in the specifications of this project, the depth of the oil is up to 10m, the crude oil is from 20 to 40 degrees API, corresponding to density from 0.934 to 0.825 g/ml. The maximum pressure at 10m depth in the oil is 0.934bar (assume the atmosphere pressure is at sea level), less than the pressure at the same depth in water. Therefore, the measuring range of the pressure sensor is chosen to be 0 to 1bar gauge pressure.

An 8 bit A/D converter is used for the depth signal acquisition. The depth is calculated as

$$Depth = Reading*10m/2^8/Liquid\ Density \qquad (1)$$

Where *Reading* is converted pressure sensor feedback which is from 0 to 255.

The depth resolution is

$$R = 10m / 2^8 / LiquidDensity$$

In the case of measuring depth in lighter crude oil, the resolution of the depth is

$$R = 10m / 2^8 / 0.825 = 47mm,$$

which is acceptable for the application.

If higher resolution is required, higher bit A/D converter can be used. For example, the resolution of a 12 bit A/D converter for the depth measurement in the lighter oil is

$$R = 10m / 2^{12} / 0.825 = 2.96mm$$

B. *PDA Control Algorithm*

This Proportional, Derivative and Adaptive (PDA) control algorithm for regulating the depth, is derived from a normal PID control algorithm. PID control is widely used in many control applications, such as motion control, temperature control, flow control and so on [4]. It helps us to get the output to where we expect in short time, with little overshoot and minimal error. To this is added an adaptive control that depends on the depth. The control loop is shown in Figure 4.

In this control algorithm, the *SetDepth* is the depth that the robot is expected to go; the *RealDepth* is the depth information acquired from the depth sensor; the *Er (Error)* is the difference between the *RealDepth* and the *SetDepth.*

$$Er = Real\ Depth - Set\ Depth.$$

The output of the algorithm is the opening time of the oil valve to let oil in and out of the tank.

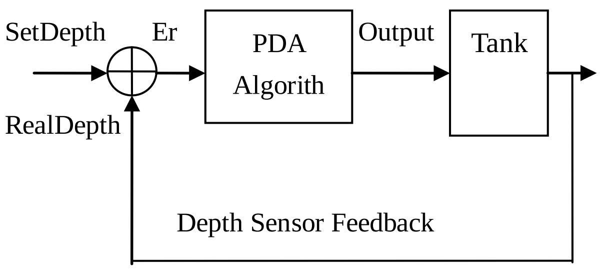


Fig. 4. Control loop

- Proportional control

In a proportional control algorithm, the output is proportional to the input error, as in equation 2,

$$Output = Kp * Er \qquad (2)$$

Note that the *Output* is directly related to opening time of the simple ON-OFF valves. With the proportional control, the further the real depth away from the set depth, the longer the oil valve opening time, so that more oil is let in or out of the tank. Bigger *Kp* results in quicker robot action.

If only the proportional control is applied, there is unavoidable overshooting and oscillation around the set depth. Especially in liquid, the robot cannot settle down in a short time.

- Derivative control

By adding derivative control to the algorithm, as in equation 3

$$Output = Kp * Er + Kd * Sp \qquad (3)$$

where *Sp* is the speed of the robots depth motion, which is

$$Sp = Current\ Depth - Previous\ Depth$$

The derivative control is like adding a brake to the robot. When the speed is high, corresponding to bigger difference between two depth samples, the output is brought down. By tuning the derivative coefficient *Kd*, the overshooting can be prevented effectively.

- Adaptive control

The depth factor must be concerned in order to let the robot have the same dynamic performance at different depths. There are two ways to do this. One is to regulate the pressure of the compressed air supply according to the depth, so that the pressure difference between the inside and outside of the oil valve always remains the same. In this case, the output is not related to the depth, but extra hardware is needed for pressure control. Another way, which is used here, is to keep a constant compressed air supply pressure, and control the opening time of the oil valve according to the depth. In this case, the deeper the robot is situated, the shorter the time to let the same volume of oil into the buoyancy tank because the outside oil pressure increases. The output is calculated as

$$Output=(Kp*Er + Kd*Sp)* (1-Ka*RealDepth/MaxDepth) \qquad (4)$$

On the other hand, the deeper the robot is, the longer is the time required to push the same volume of oil out of the buoyancy tank, because the pressure difference between inside and outside of the tank decreases. The output is calculated as

$$Output = (Kp*Er + Kd*Sp)*Ka* RealDepth/MaxDepth \qquad (5)$$

Where *Ka* is the adaptive coefficient.

The PDA coefficients *Kp, Kd* and *Ka* are tuned by the user. In different environments and with different payload, the coefficients that give the best robot performance are different. In general, increasing the gain *Kp* will let the robot go to the set depth more quickly, but causes more overshoot and oscillation. Increasing the gain *Kd* will deliver sharper braking to prevent the overshoot, but will slow down the robot action. The adaptive coefficient *Ka* tunes the robot performance in different depth. The value of *Ka* is $0<Ka<=1$.

The robot performance can be optimized by tuning the coefficients. However, some other factors that affect the robot performance must be addressed.

C. Other factors that affect the robot performance

- The sample frequency

While regulating the depth, the sample frequency is expected to be as high as possible to get quick action. However, in practice it is matched to the slow dynamics of the robot so that only changes in depth are captured. On the other hand, if the sampling frequency is too low, the robot is not regulated before it goes too far from the set point, this could cause instability of the robot.

- Disturbance from the thrusters

Two thrusters are used to drive the horizontal robot motion.. However, the thruster forces can drive the robot up and down due to mechanical error or disturbance dynamics. To prevent too much disturbance from the thrusters, the robot is designed to be weight balanced. In other words, the gravity centre and the buoyancy centre are in a line vertically, so that the robot does not tilt while swimming.

- Disturbance from the umbilical

The buoyancy is controlled by changing its buoyancy around its neutral buoyancy point. Therefore, any extra force from the robt's umbilical could move the robot. Although the weight of the umbilical is light, the disturbance cannot be ignored. Some floats are tied on the umbilical to balance the weight, so that the umbilical weight disturbance is minimized.

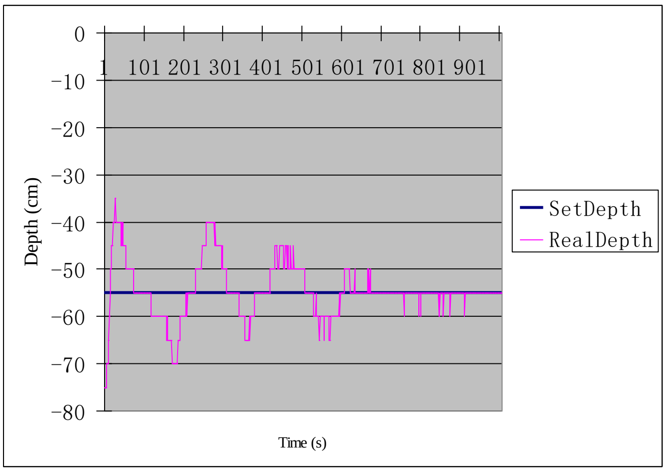
III. Experiment Results

Despite all the factors that affect the robot's performance, it has still proved possible to regulate the robot depth. The main coefficients that affect the robot swimming performance are the PDA coefficients.

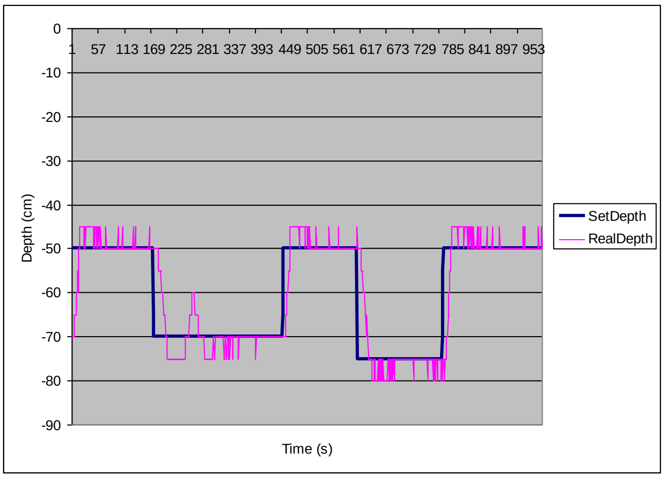
As in all PID control algorithms, the values of *Kp, Kd* and *Ka* need to be tuned to improve the robot performance in various conditions. The *Output* of the algorithm is the opening time of the oil valve, which should be less than the sample period, 500ms in this system.

The robot has been tested in our lab in a water tank. The robot depth is regulated around a depth of 55 cm. Figure 5 (a) shows the robot performance with a big proportional coefficient (Kp = 100) and small derivative coefficient (Kd = 20) which causes the overshooting and oscillation. The robot settling time to within measurement error of 5 cm is about 600 seconds

A properly tuned PDA depth control is shown in Figure 5 (b). Step changes in the setpoint are obtained quickly with the robot settling down to the required depth within the measurement error of 5 cm in about 20 seconds.



(a) Kp = 100, Kd = 20, Ka = 1



(b) Kp = 60, Kd = 30, Ka = 1

Fig. 5. Depth control experiments

IV. Conclusion

This paper presents a very simple depth control of a swimming robot. The control hardware is low cost but is able to control the robot's depth by applying a PDA algorithm. The main problem of this non-model based controller is the requirement to tune the PDA parameters manually for different operating conditions. The control method has been tested in a 1.5 m deep water tank in our laboratory. With properly tuned coefficients, the robot can move to the set depth point quickly without too much overshoot and maintain that depth precisely. However, it remains to test the algorithm in deeper tanks and in oil.

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