MOORING CHAIN CLIMBING ROBOT FOR NDT INSPECTION APPLICATIONS

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Inspection of mooring chains is a dangerous and costly procedure covering inspection above and below the waterline. The paper presents initial results from the RIMCAW project which was aimed at designing and building an inspection robot able to climb mooring chains and deploy NDT technologies for scanning individual links thereby to detecting critical defects. The paper focuses on the design and realisation of the inch worm type novel crawler developed and tested in the TWI Middlesbrough water tank.

1. Introduction

1.1. *Background*

With increasing global energy demand, the number of floating oil and gas production systems have increased dramatically since the 1990s. It is not possible to move most floating oil production systems for inspection or repair. Moreover, mooring systems which are used to attach the floating platforms to the seabed often experience high tidal waves, storms and other harsh environmental conditions. Therefore, ensuring integrity of mooring chains is crucial, because single mooring line failure can cost approximately £2-10.5M [1]. There were 21 accidents due to mooring failures between 2001 and 2011 including 8 multiple mooring chain breaking incidents [2]. Mooring chain breakage can cause vessel drift, riser rupture, production shutdown and hydrocarbon release. For example, “Gryphon Alpha” had to spend $1.8 billion to resume operations after its mooring failure [3]. Replacing mooring chains to inspect the original is expensive and there is a high probability of causing damage. In view of these issues, the RIMCAW project was formulated to develop a mobile crawler robot able to climb on mooring chains while in service and be able to perform in-situ inspection in both air and water.

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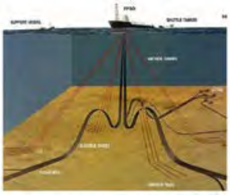
1.2. *Review of mooring chain inspection systems*

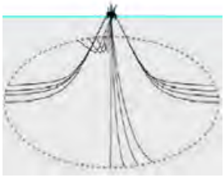
Attempts to establish effective climbing robot mechanisms have been made but due to the mechanical complexity mooring chains as climbing structures, research has not progressed beyond initial experimental stages. The “MoorInspect” inchworm climbing robot [4] was huge and weighed 450 kg in air and carried NDT equipment to give a total weight of 750 kg. The ICARE platform is another heavy climbing robot for subsea cleaning and inspection of anchor lines [5] which uses a human-like climbing method with two paws. Such heavy robots are not easily deployable in offshore environments, nor do they have sufficient manoeuvrable capabilities to climb over the chain links in realistic scenarios when there is chain link mis-alignment and catenary curves in the chain structures. These robots are deployed manually by using divers and boats. Therefore, it is not practically possible to handle heavy large platforms in small boats with divers without major lifting equipment.

A novel automated ultrasonic inspection system to inspect mooring chains during the manufacturing process [6] where the welded joints on chain links are inspected during manufacture. The main aim of the project “ChainTest” was to develop a system which can be operated without bringing the chain on board [7]. A mechanism was developed but during final tests, the robot was unable to perform the inspected as designed.

1.3. *Design requirements*

Mooring chains are often subjected to high environmental changes due to tidal waves, wind, etc. Therefore, it is required to design an automated/robotic system that can tolerate real-world in situ conditions. The mooring chain link structures are curved and mostly rusted with uneven surfaces, so the inspection system should be able to handle the physical nature of mooring chains. Following detailed analysis, it was concluded that a compact climbing robot able to work in subsea environments needed to be developed for the solution to have any commercial viability. Furthermore, it was clear that the robot must be able to handle climbing on a range of chain scenarios and sizes as shown in Figure 1.





a. Taut-leg scenario in deep water b. Catenary chains in shallow water c. Mooring chains range

Figure 1 - Mooring chain scenarios and range of sizes

The robot should be easily deployed and retrieved. Therefore, it is necessary to make the system lightweight while still able to carry a payload of ≈12kg. The adhesion mechanism for vertical climbing should be sufficient to keep the robot attached to the chain during motion. Moreover, due to the amphibious nature of mooring chains, the developed robot must be marinized to operate in real-world normal and abnormal conditions.

2. Design methodology

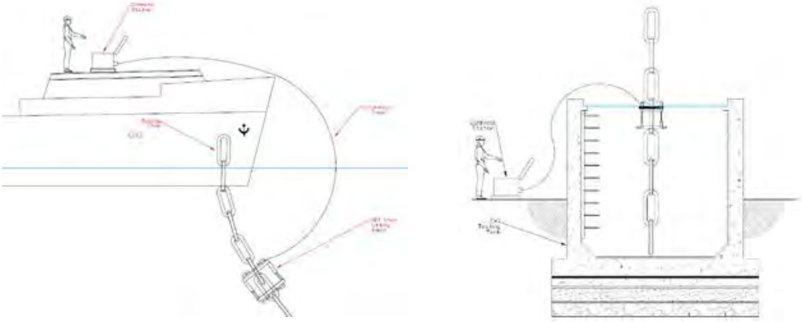
2.1. *Deployment plan*

Methods to deploy the robot were studied in detail to identify all procedural requirements as testing of the developed platform was planned to take place in a 7m deep test tank at TWI Middlesbrough with a 10-link chain suspended from an overhead gantry system into the water. The dimensions of the chain are outlined in the Figure 2.

a. CAD model of test mooring chain with dimensions b. Picture of the testing chain

Figure 2 – Details of test sample mooring chain

It was important that the prototype RIMCAW system realised was able to satisfy all the testing requirements planned and of a real deployment scenario as presented in Figure 3.



a. Real-world subsea RIMCAW scenario b. Tank facility testing scenario at TWI

Figure 3 - Deployment RIMCAW scenarios

2.2. *Concept design and analysis*

Five different design concepts were developed, as presented in 4 with different locomotion and adhesion/gripping mechanism configurations being explored from which different crawler ideas emerged. Each design was analysed and investigated with respect to the outlined crawler criteria and the associated engineering challenges. The final design, Figure 5e, concept was selected after a detailed Delphi study involving the full technical team revealing that it was best suited to meet all the technical, fiscal and time requirements.

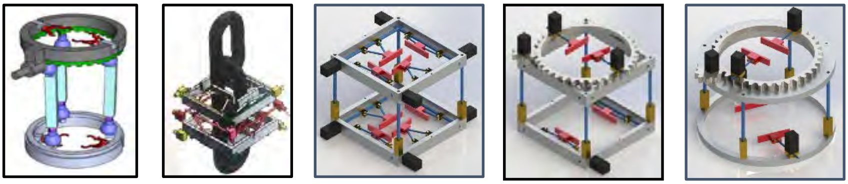

a) Concept 1 b) Concept 2 c) Concept 3 d) Concept 4 e) Concept 5

Figure 4 – RIMCAW concept designs developed and investigated

3. RIMCAW robotic platform

3.1. *Mechanical design*

The final RIMCAW robot design and actual robot is shown in Figure 5; this was based on a standard Stewart platform, comprising six prismatic actuators attached in pairs to three positions on the platform’s baseplate, crossing over to three mounting points on the top plate. This design allows the robot to control the pitch, roll and yaw of the top and bottom baseplates. This controllability of the platform’s crawling orientation is crucial as it needs the robot to traverse the various catenary curves of mooring chains likely to be found in real scenarios. In addition, this configuration allows the robot to contract and expand allowing it to crawl by inch worming along the chain links. The method of positioning and securing the robot onto the mooring chain structure had been extensively studied and a latch/ hinge system was incorporated into the design to allow simple opening of the simplify the deployment process for end user.


a) Final detailed CAD model b) Actual RIMCAW robot c) Command station and umbilical

Figure 5 - Detailed Mechanical Design

3.2. *Electrical design*

For testing and trials, a custom designed command and control box was required to supply power to the RIMCAW robot as shown in Figure 6. After researching British Standards for safe operating electrical power supplies in a submerged water environment, it was found that the 30V DC was the permissible SELV (Safety Extra Low Voltage) for 'Swimming Pools and Basins' outlined in BS EN 7671:2008, Regulation 702.410.3.4.1. Four IP68 enclosures with dimensions 260x160x120 mm were used to house all electronics. To minimise cables and entries, the electronics were divided into sub-sections of the electrical system. Box 1 housed the electronics required for the Stewart platform, Box 2 housed the electronics required for the gripping function, Box 3 housed the power electronics, and Box 4 housed the communications systems.

3.3. *Software design*

The control of the low-level systems (actuators and sensors) was accomplished via local specialised controllers. The mid-level systems (Raspberry Pi and Arduinos) were used to coordinate the control functions specified by the top-level interface. The top-level system (GUI) provides operators with a simple means of controlling the chain crawling functionality using visual feedback from the onboard cameras.

As development progressed, the software architecture evolved, and the messaging protocol and variable details were finalised. The robot's roll, pitch, yaw, crawling motion, upper and lower grippers and gripper rotation could all be controlled via one message sent from either the keyboard, joystick or GUI interfacing devices. A ROS switch node was developed to provide an easy means of switching between the different forms of top level control.

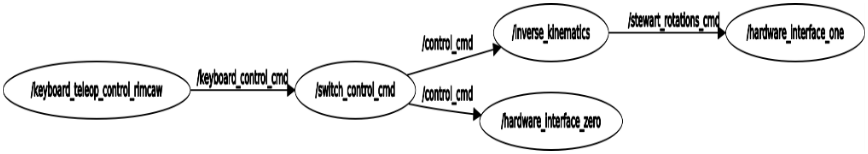


Figure 6 - ROS node/ topic network

Figure 6 shows the ROS node and topic communication structure with keyboard control outlined. The kinematics of the Stewart platform is a well-documented problem and used to control the 6 actuators as required. In robotics, singularities can pose serious problems to the overall operation and hence proximity to such singularity points needs to be monitored and avoided. To mitigate this issue, precautions had to be built into the control system where the inverse kinematics node, motions and orientations were restricted. The desired roll, pitch and yaw angles were limited to ±10° range and the x, y positions were locked to zero, allowing only movement in the z axis for performing the climbing function. For the chain climbing function, movement outside this constraint is not felt to be necessary at the initial stages. If the inverse kinematic solver derived any extension outside of its defined boundaries, the move request would be ignored, and the previous orientation would not change.

4. Experimental testing

4.1. *Procedure*

A structured approach was formulated to perform testing and demonstration of the realised RIMCAW climbing robot. Three tests were planned to verify the integrity of key aspects of the design; if there was failure of one, the remaining tests could not proceed. These tests are as follows:

- Test 1 to assess the neutral buoyancy. This was performed by slowly winching the robot into the tank and verifying that the weight of the platform was cancelled out in water via the attached floatation foam
- Test 2 was to assess the water ingress integrity of the robot; after complete submersion of the platform, all the electronic components and devices had to be confirmed to be fully functioning, and
- Test 3 was to assess the functionality of the mobile robot, verifying the crawler’s ability to climb the test chain.

The command station was set up next to the test tank at TWI Middlesbrough and a split screen display was set up to view the video from Figure 7. Compressed air was connected to the enclosures via a regulator, set to 0.3 Bar. Using winch straps connected to the eyebolts of the platform, the TWI staff picked up and slowly lowered the platform into the tank.

a. Command station b. Testing and preparation area

Figure 7 - Testing area and command station deployed at TWI Middlesbrough

4.2. *Test 1 – Neutral buoyancy*

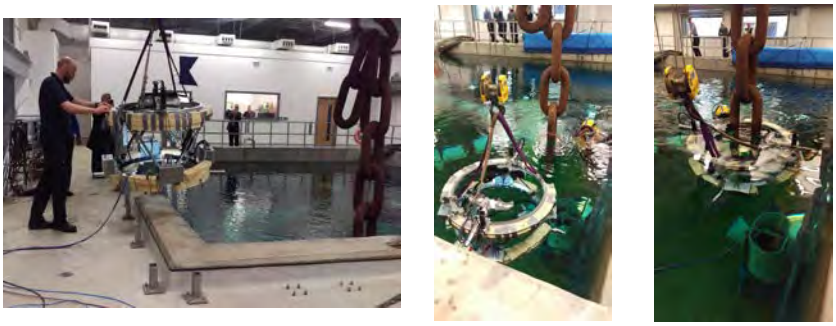
For this test the robot was slowly submerged using a gantry system over the tank. The operators of the gantry were instructed not to provide too much slack or move the robot too quickly. At a certain point during the lowering process, the winch straps became slack as the buoyancy was confirmed. The buoyancy was able to counteract the weight of the robot. However, it was noted that part of the platform remained slightly above the water line, indicating that the robot had positive buoyancy. This was deemed to be acceptable as the buoyancy could be adjusted during the testing process if it was found to affect the climbing functionality.

4.3. *Test 2 – Water ingress integrity*

The robot was submerged for ≈15 minutes, to allow for all trapped air bubbles to escape. Air leaks are indicated by a visible streams of air bubbles, which were then searched for. The seals on all the enclosure lids were found to be satisfactory. Minor leaks were found to be coming from the cable glands on the gripper control box indicating it was not tightened properly. Proceeding with Test 2 was deemed to be satisfactory provided that compressed air was connected to maintain the positive pressure in the enclosures for maintaining water ingress integrity. While still in the water, the functionality of sensors and actuators was checked. The Stewart platform and manipulators were moved and were verified to be functioning correctly.

4.4. *Test 3 – Chain climbing functionality*

The mooring chain was introduced into the tank before the robot was lowered next to it. Two overhead gantry systems could not bring their end effectors together, requiring the platform to be lowered into the tank, with sufficient slack on the winch to allow the diver to move the robot onto the mooring the chain, Figure 8.



Step 1: Robot raised off ground for moving to water tank
Step 2: Robot lowered into water tank
Step 3: Robot moved onto chain by diver

Figure 8 - Deployment of RIMCAW robot prototype platform

This was executed without any problems, the one diver was able to successfully manoeuvre the robot around the chain, close it and lock the latches, Figure 9. However, when it came to grasping the mooring chain, the grippers could not reach the chain. This was found to be an electrical limitation preventing the actuators from achieving full extension.

a) Submerged robot
b) Diver opening latch
c) Robot placed onto chain

Figure 9 - On-board camera view of the attachment to the mooring chain

5. Conclusions

There were several technical challenges and problems that were experienced during the design and testing phases. Minor software and electronic problems, prevented completion of the final functionality tests. Although NDT inspection testing of mooring chains was not completed, the developed RIMCAW robot met the initial design specifications for mobility and is able to operate underwater on mooring chains as required. The robot is being considered for further improvement to meet different underwater inspections applications. The aim is to make improvements to facilitate developments and testing so that commercially viable means of inspecting underwater assets is possible.

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