

# Tracked-Wheel Crawler Robot for Vertically Aligned Mooring Chain Climbing

Design, simulation and validation of a climbing robot for mooring chains

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**Abstract**— Only a few attempts have been made to investigate the possibilities of developing chain climbing robot due to the complexity of the structure and physical nature of chain links. Mooring chains are subjected to large tidal waves, harsh environmental conditions and storms on a daily basis. Therefore, periodic inspection of the integrity of chain links is important. Work reported in this paper investigates the possibilities of mooring chain climbing by using tracked wheel locomotion. The permanent magnet adhesion, tracked wheel crawler robot developed for this purpose can climb on mooring chains both in air and underwater with a variable speed according to the inspection requirements (maximum speed of 42cm/minute). It is able to handle an external downward force of 50N during the climbing motion. Numerical modelling based analysis of a magnet adhesion module and the strength of the robot structure is validated with prototyping and testing of the concept.

**Keywords**—Mooring chain inspection; Chain Climbing Robot; Crawler Robot; Magnetic adhesion crawler.

## I. INTRODUCTION

Mooring chains were first introduced in 1808 to improve the securing of larger ships. Maintaining a floating structure within a given (pre-specified) positioning tolerance is the primary purpose of a mooring system. The amount of floating oil and gas production systems has significantly increased due to the world's high energy demand. Ensuring the integrity of mooring systems for FPSO (floating production storage and offloading) needs to be addressed with a capability of handling in-situ conditions, because most of the off-shore floating oil production systems are not able to move for inspection or repair. The necessity of ensuring their integrity arises because mooring chains are subjected on a regular basis to high tidal waves, storms and harsh environmental conditions. Single line mooring failure can cost approximately £2M-10.5M [1]. There were 21 accidents due to mooring failures between 2001-2011 and there were 8 multiple mooring chain breaking incidents [2]. Due to the breaking of a mooring system (chain), vessel drift, riser rupture, production shutdown and hydrocarbon release can occur with high cost of the outage. For example, the Gryphon Alpha field had to spend \$1.8 billion to resume after it's mooring failure [3]. Therefore, integrity of mooring chains is an important factor when considering the industrial and environmental safety of FPSOs. Using Non-Destructive Testing (NDT) methods with divers (NDT operators) is the most common method of mooring

chain inspection. Due to health and safety concerns, using divers is not practical, especially in the splash zone area. Due to the high maintenance cost and high probability of damage, lifting mooring chains out of the water for inspection is not reliable. It is necessary to access the chain in-situ for most of the reliable inspection methods such as, ultrasound, guided wave NDT inspection [4], mechanical measurements, etc.,. A combination of an autonomous/ semi-autonomous robot mechanism with a NDT tool is needed to conduct an extensive non-destructive investigation in the mooring chain working environment. The aim of this research project was to develop a lightweight, tracked wheel, permanent magnet adhesion robot that can be easily placed on a chain and retrieved quickly. It should be able to access mooring chains both in air and underwater to perform NDT to investigate possible defects such as cracks and corrosions.

The presented robotic system consists of four tracked crawler modules for locomotion. Only two crawler modules are attached to the body of the mooring chain at a given time using magnetic adhesion while the other two are suspended in air. This is due to 90 degrees orientation difference between two adjacent mooring links. A magnetic flux concentration technique is adopted to optimize the dimension and weight of the adhesion module. This prototype system can successfully travel along vertically aligned mooring chain links. The paper presents the structural design, FEA analysis, motor selection, adhesion force requirements, prototyping of the concept, and experimental testing of the prototype.

## II. STATE OF THE ART

According to the literature, only a few attempts have been made to develop a robotic / automated system to climb on mooring chains due to the complexity of chain orientations and difficult physical conditions of chain links. Moreover, those researches were unable to extend beyond the initial laboratory experimental stage. The "MoorInspect" was a robotic-inchworm influenced climbing robot with two paws [5], weighed 450 kg in air and carried NDT equipment to give a total weight of 750 kg. The "ICARE" anchor chain inspection and cleaning robot [6] is another climbing robot which uses a human-like climbing method. When considering the offshore environment and a mooring chain's catenary curvature, heavy and large length robots are not easily deployable. The above-

mentioned robots are deployed manually by using divers and boats. It is not practically possible to handle a large weight in a small boat with divers (without lifting equipment). Therefore, additional deployment tools and supports are needed. A novel automated ultrasonic inspection system to inspect welding joints on chain links during the manufacturing process is presented in [7]. The project “Chain Test” was carried out to develop a robotic system that can be operated without lifting a chain out of the water and bringing it on-board a platform [8]. According to internal project reports, a gravity assisted crawler–cable mechanism was unable to perform as expected. The “Welaptega subsea mooring inspection system” is powered with a remotely operated vehicle (ROV) and mooring chain measuring devices (visual and NDT measurements) [9]. ROVs are unable to access the chain in air, therefore these systems can only be used under water. Moreover, accessing a chain in the splash zone may not be possible with a ROV due to the limitation of underwater ROV manipulation. Visual aided ROV inspection is common in industry but according to the history of mooring chain accidents and breakings, conventional ROV inspection is not a reliable method [2]. When considering the above attempts, human influenced climbing method, cable assisted climbing method and ROV assisted methods are not able to provide a practical approach which can cover the entire chain in working conditions. Therefore, it is necessary to create a light weight, fast and automated system which can climb/walk/crawl in both air and under water in actual working environments.

### III. DESIGN REQUIREMENTS

It is required to design a robotic system for automated NDT that has a tolerance to industrial offshore mooring chain working conditions, because mooring chains are often subjected to environmental conditions such as tidal waves, winds, storms, rough-uneven surfaces, etc. As an example, the mooring chain in figure 1 shows mostly corroded and uneven surfaces. Therefore, it is necessary to establish a system to handle the physical nature of a mooring chain. A stud-less mooring chain shown in figure 1 was used for this research. Therefore, deployment ability is the main focus of our robot design. The robot should be able to be deployed and retrieved with minimum effort. So, it is important to make the system lightweight (expected maximum structural weight 30Kg without NDT). The selected adhesion mechanism should be capable of keeping the robot attached to the chain during the entire motion.

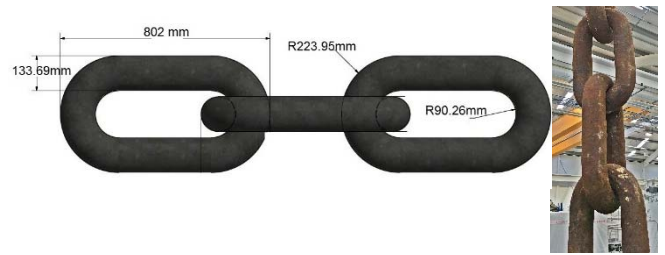


Fig. 1. Mooring chain dimensions /chain used in this research

## IV. DESIGN

### A. Concept of the mooring chain climbing robot

The robot consists of two main sets of tracked crawler units. One set of the crawler unit moves on one set of chain links whilst the other set moves on the adjacent orthogonal chain links. Due to the amphibious nature of the climbing robot, introducing an adhesion mechanism that uses permanent magnets with zero energy requirements is an advantage. The design concept uses 4 crawler modules that are activated during to the entire climbing motion to create a “slide off” effect which helps the crawlers to leave the surface at the end of a chain link. At any given location, at least 2 crawlers are in contact with the chain link which forces the structure to crawl in a linear trajectory.

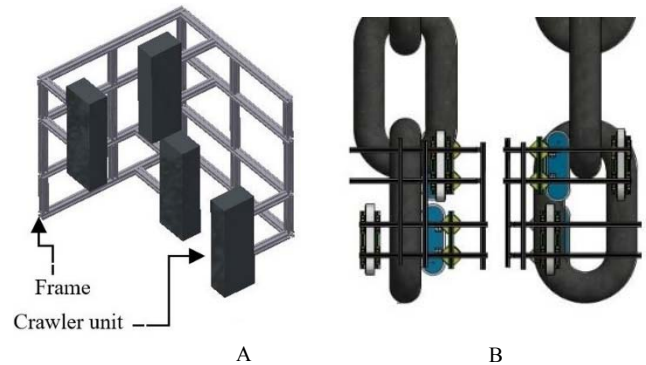


Fig. 2. (A) Concept of the design. (B) placement on mooring chain

### B. Frame design

Deployment and retrieval of the robot is required to be conducted with minimum effort. Therefore, minimizing the weight of the robot (less than 30 kg) and deployment ability were considered during the design of the main structure. An “L” shaped structure was designed by using Autodesk Inventor CAD software (figure 3). An “L” shape design allows operators to deploy/retrieve the robot on to the chain easily. It was necessary to check the integrity of the structure because it has to hold a given payload and weight of the crawler units. A study was carried out to identify the stress and frame deformations by using ‘COMSOL Multiphysics’ and ‘Inventor Stress Analysing’. At a given position, the structure is attached to the chain surface by two track-wheel units. Therefore, structural

deformation was studied by considering 2 crawler units suspended in air whilst the other two were rigidly attached to a chain link. Maximum frame deformation of an unsupported crawler without a payload is 0.2411mm and maximum stress is 15.04MPa. It is necessary to consider the payload capacity during the frame design stage. Therefore, simulation was carried out with a payload of up to 20kg (196.13 N). Due to the symmetry of the frame, pay load was equally distributed and added to the both sides of the frame. Payload stress and deformations were recorded as in figure 4.

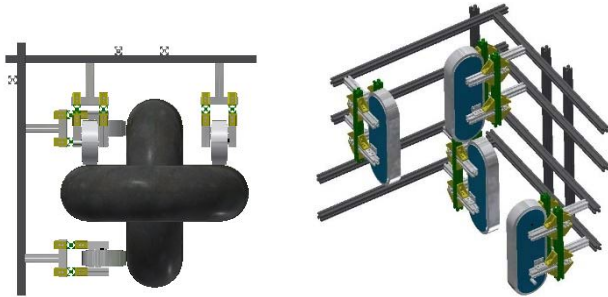


Fig. 3. "L" shaped frame design with crawler unit placements

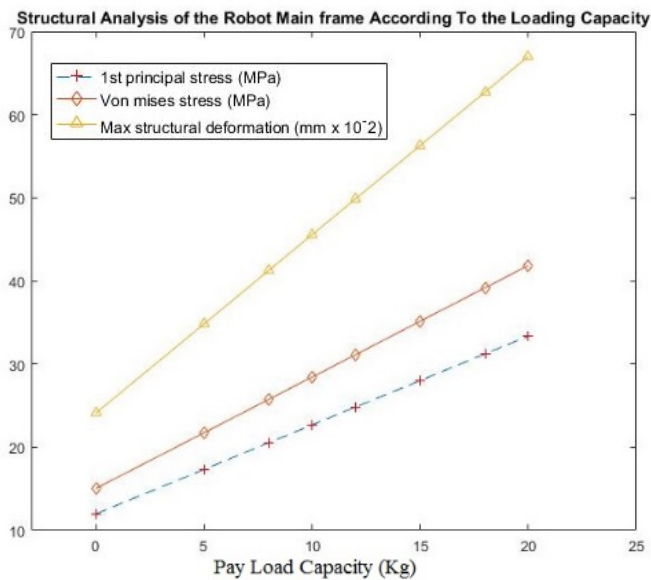


Fig. 4. Frame deformation and stress

C. Crawler unit design

A tracked wheel is the most suitable and reliable motion mechanism to use because link surfaces are rough and slippery. Surface of the mooring chain is rough and uneven due to corrosion, tracked wheel crawlers were selected because passive track adaptation to uneven surfaces gives an additional traction advantage. CAD model of the crawlers and attachments are shown in figure 5. During the crawler design, it was necessary to consider the following aspects: size, length,

attachment possibilities of magnets and motors, etc. To avoid the effect of parallel misalignments of the chain links (slight differences of angles relative to a parallel link to another), it is necessary to keep the total length of the crawler wheel track less than the gap between two parallel links. Therefore, the total length of the crawler has been designed to be less than the gap.

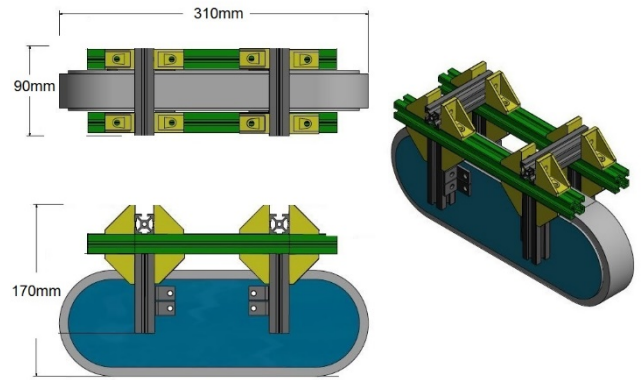


Fig. 5. Crawler unit (tracked crawler) design CAD model

D. Optimization of the magnet module

When the robot's parameters are weight (W), coefficient of friction (μ), vertical plane's inclination (α), required adhesion force (Fa) can be calculated by using equation (3) [10].

$$F_a \geq \frac{W \times \sin(\alpha)}{\mu} - w \times \cos(\alpha) \tag{3}$$

According to the equation (3) required magnet force was calculated as 191.23N. Previous research done in [12], [11] was used to enhance the magnetic adhesion forces by introducing a back plate (high permeability yolk). Magnets were kept at 9mm distance from the link surface due the mechanical clearances of the track-wheel unit. Table 1 data and figure 6 model of magnet, back plate and chain link was used during the stationary simulation in COMSOL Multiphysics. A 219.16 N force was produced by the experimental magnet (N52, neodymium) arrangement. Figure 7, illustrates simulation results of focused magnet flux lines and magnetic flux density.

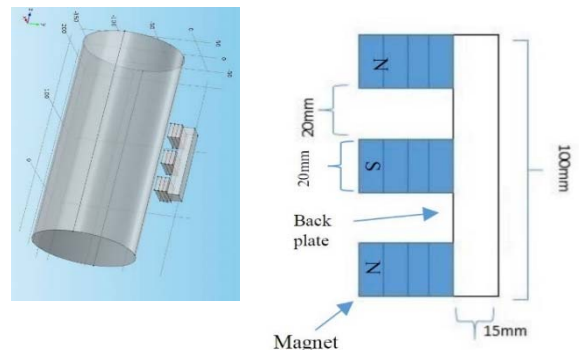


Fig. 6. CAD model and dimensions used for simulation

TABLE I. SIMULATION PARAMETERS

Parameter	Parameter value
Magnet Relative permeability	1.05
Residual Flux Density (Br)	1.45T
Magnet size /back plate size	L 40mm,W 20mm , H 5mm / L 100mm , H 15mm , W 40mm
Iron relative permeability	4000
Coefficient of friction	0.5
Weight of the robot	19.5 Kg

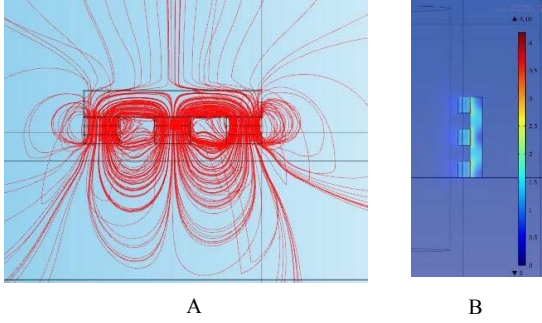


Fig. 7. (A) Flux lines , (B) Magnetic flux density

## V. PROTOTYPING AND VALIDATION

## A. Prototype and assembly of crawler unit, adhesion module and “L” frame

Using the previously discussed simulations and CAD designs, a prototype of the crawler unit and the “L” frame was built. Simulation studies suggested that the magnet module should be placed at the centre of a crawler unit. Therefore, the adhesion module was inserted inside the tracked-wheel unit (figure 8(A)). Aluminium extrusions were used to prototype the “L” shaped main frame and the four crawler units were attached to the frame (figure 8(B)). Additional 10cm lengths of aluminium extrusions were used during the prototyping for future mechanical changes

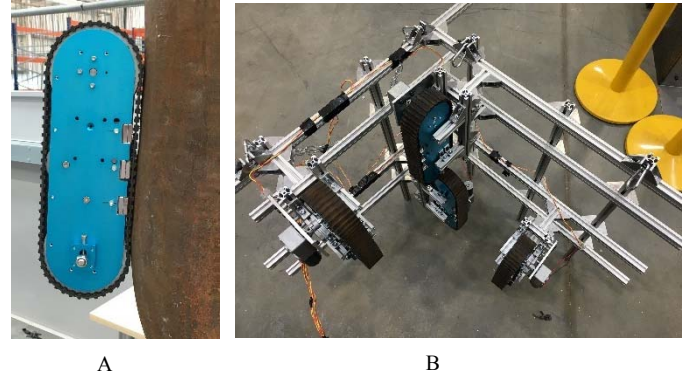


Fig. 8. (A) Magnet inserted crawler unit, (B) “L” frame

## E. Selection of motors

Each crawler unit is powered with an external motor and a gear box which generates enough torque  $[T_{mot}]$  to drive the robot structure up along the chain link against the structural downwards forces and magnet adhesion forces. Torque calculation in Eq.1 is previously studied in [10] Output RPM of the gearbox + motor combination- $[RPM_{g+m}]$  and effective radius –  $[rc]$  of the track-wheel determine the net speed of the robot  $[S_r]$  (refer Eq.2)

$$T_{mot} \geq \left[ \begin{array}{l} \text{Resultant} \\ \text{Weight} \times \end{array} \begin{array}{l} \text{Distance to} \\ \text{the surface} \end{array} \right] + \left[ \begin{array}{l} \text{Force} \\ \text{from} \times \\ \text{adhesion} \end{array} \begin{array}{l} \text{Effective} \\ \text{radius} \end{array} \right] \quad (1)$$

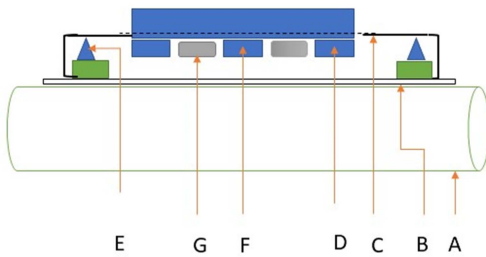
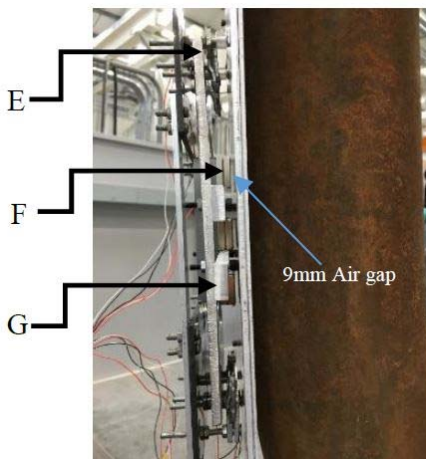
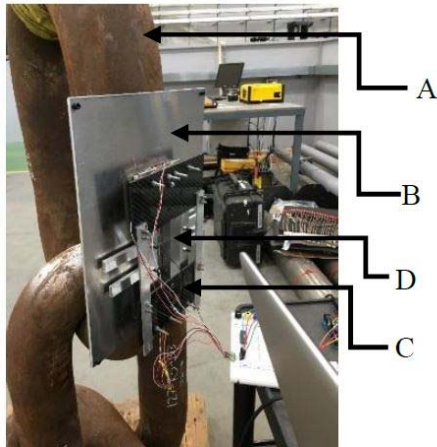
$$S_r = RPM_{g+m} \times [2\pi \times rc] \quad (2)$$

According to the equation (1) required net torque  $\geq 30.00\text{Nm}$  (approximately). As the design arrangement, at least two crawler tracks are in contact with the chain surface at a given point. Therefore, each crawler should at least contribute with  $15.00\text{Nm}$  torque (approximately) to the system. According to the calculations, speed of the robot should be  $42 \text{ cm/min}$ .

## B. Magnetic forces validation test rig

The test rig in figure 9 was used to experimentally validate magnetic adhesion results which were simulated in FEA studies. It comprises of a frame and magnet holding plate constructed with (3-5mm) carbon fibre and aluminium plates. Magnets were attached to the aluminium plate which was free to move in the direction of the magnet forces. The plate was kept on a set of four load cells. To enhance the accuracy of the force measurement rig, load cells were configured as a Winston-bridge. Amplified signals of the load cells were connected to a microcontroller. Aluminium spacers were employed to maintain the same air gap as used in the numerical modelling. Experimental results of adhesion forces generated were very close to the simulation results though higher than the simulations. Maximum difference between results was  $13.44 \text{ N}$ , (FEA- $219.16\text{N}$  , Experimental- $232.60\text{N}$ )





A-Mooring chain, B- Base plate, C-Carbon fiber test rig, D-Iron Back plate and magnets, E-Load cells, F-Magnets, G-Spacers

Fig. 9. Magnetic adhesion rest rig

### C. Motor attachment and control unit

Brushed- DC motors were added to the robot crawler system (figure 10). To ensure sufficient space between orthogonal chain links and crawlers, the motors were attached to the crawler with a 90 degree worm gear box. The flow chart operation described in figure 11 was used to drive the crawlers up/down along the mooring chain.



Fig. 10. Motor and gearbox attachment

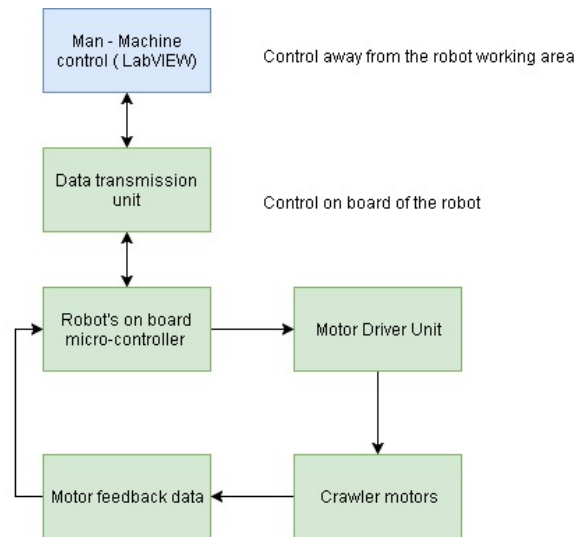


Fig. 11. Robot operation control diagram

### D. External load test

A stability check was performed with external applied forces (external weights). According to experimental results, the robot remained attached to the chain link surface with up to 50N of external force.

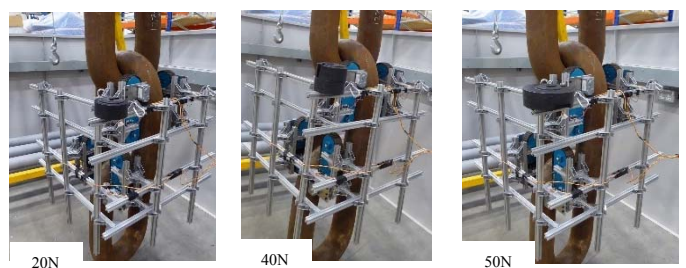


Fig. 12. Stability test with external loads

### E. Testing of the mooring chain climbing robot

The crawler robot was placed on a mooring chain segment comprising of three links and its up/down movement was tested (figure 13). The experimental trial was conducted in an

industrial environment. Therefore, additional safety cables were used to enhance the safety factor.

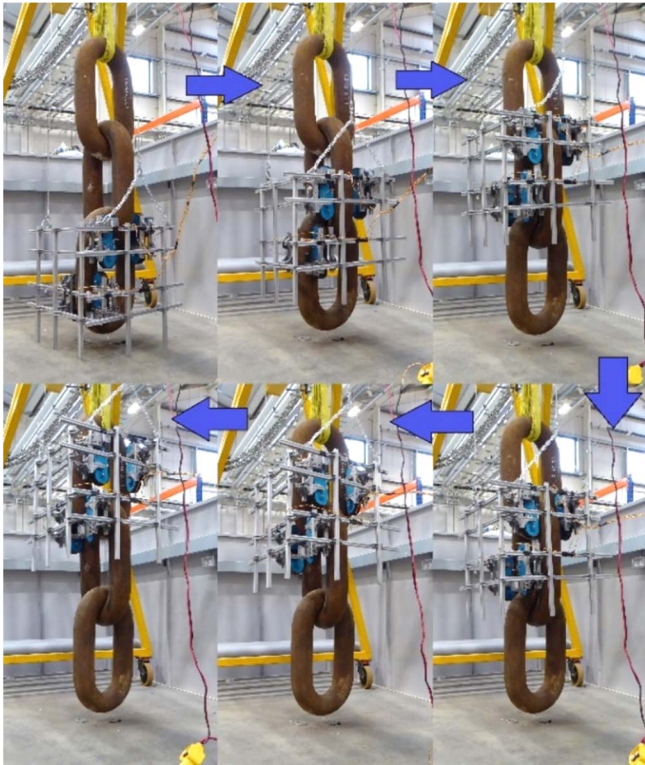


Fig. 13. Mooring chain climbing sequence

## VI. CONCLUSIONS

A lightweight, prototype L-shaped tracked-wheel robot was designed and built that could be placed easily around a mooring chain. The robot adheres to a chain using a permanent magnet system. The neodymium permanent magnet adhesion module was optimised using finite element analysis (FEA) software COMSOL Multiphysics to obtain the required adhesion force. Simulation results were checked against experimental results. Structural analysis and validation experiments were carried out by using CAD design software (Autodesk Inventor) and FEA software (COMSOL) to develop a robust structure. The complete robot prototype system was tested on a three-link mooring chain segment to study climbing capability and stability against external forces. The feasibility of using orthogonally placed, magnetic adhesion, tracked crawler units to climb on mooring chains has been established.

## VII. FURTHER IMPROVEMENTS

A straight mooring chain (consecutive links are orthogonal to each other) has been used in this part of the research. In practice, chains may have a catenary curve, have links that are at a twist angle relative to each other (link misalignments). The current robot design will be modified to overcome misalignments of

chain links. Future work will research designs to introduce an active control mechanism that can correct the robot when it starts to slip due to mooring chain surface issues, changes its path due to external forces or has to climb on links that are twisted relative to each other. Both the in-air and underwater sections of a mooring chain are required to be inspected. Therefore, the robot should be able to travel underwater. It will be necessary to marinize the motors and controllers and setup underwater laboratory trials.

## ACKNOWLEDGMENT

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