Design and Prototype of a Magnetic Adhesion Tracked-Wheel Robotic Platform for Mooring Chain Inspection

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Abstract

The development of climbing robots for mooring chain applications are still in its infancy due to the operational complexity and the geometrical features of the chain. Mooring chains are subjected to high tidal waves, harsh environmental conditions and storms in daily basis. Therefore, the integrity assessment of chain links is vital and regular inspection is mandatory for offshore structures. The Magnetic adhesion tracked-wheel crawler robot technique presented in this study is suitable for mooring chain climbing both in air and underwater (in-situ conditions). The robotic platform which is presented in this paper can climb mooring chains at a maximum speed of 42 cm/minute with an external load of 50 N. A numerical study was conducted to investigate the adhesion module and structural design related analysis. Numerical results are validated using a prototyped robot in laboratory conditions. The proposed robot can be used as a platform to convey equipment *i.e.* tools for non-destructive testing applications.

Key Words

Mooring chain; Chain climbing robot; Crawler Robot; Magnetic adhesion robot; Tracked-wheel crawler; Inspection platform; Numerical modelling; Robot Design.

1. Introduction

An exponential increase of floating oil and gas productions systems has recorded around the world due to the high demand of modern world's energy consumption. 277 floating production units (FPU) were recorded by the November 2013 and 62% of that were categorized as Floating Production Storage and Offloading (FPSO) [1]. The history of the mooring chain began in 1808 with advancements of the shipping industry. Maintaining a floating structure within a given (pre-specified) tolerance can be introduced as the primary purpose of a mooring system. Necessity of integrity ensuring arises with the in-situ conditions that mooring chains are subjected in regular basis, such as high tidal waves, storms, hurricanes, effect of salt water and harsh environmental conditions. Chain Overload, out-of-plane bending, wear effect between chain links, corrosion and manufacturing defects can be introduced as the main contributors to mooring breaking which then can leads to significant damages such as vessel drift, riser rupture, production shutdown and Hydrocarbon release, etc, As an example, "Gryphon Alpha" had to spend

$1.8 billion to resume after it's mooring failure [2]. In the period of 2001-2011, there were 21 accidents recorded with a 8 high casualty for human life [3]. Most modern systems are designed to handle a single breaking but multiple breaking can easily lead to a catastrophic incident. According to the reported data from the North Sea (1980-2001), every 4.7 year a floating production unit /system has experienced a mooring failure [4] . Approximately £2M-10.5M can cost due to a single mooring failure [5]. After analysing the potential damages to the humans as well as environment, a periodic inspection became mandatory for mooring systems [4]. Mooring chains are not designed to indicate integrity measurements therefore mooring integrity management of FPSO (floating production storage and offloading) needs to be addressed with a capability of handling in-situ conditions, because most of the offshore oil production systems are not able to move for inspection or repair. Most common inspection method is to use Non-destructive testing (NDT) trained divers but due to the health and safety concerns, divers are not allowed to inspect splash zone area [4]. Replacing mooring chains for inspection are a costly and not reliable method due to the operational conditions. There are significant amount of research have been conducted and industrial integrity management tools are presented but it is important to establish a platform that has the capability of convey NDT tools along the chain lines. It is necessary to access the chain physically for most of the reliable integrity management methods such as, ultrasound/sonic testing [6] , guided wave inspection [7], mechanical measurements, etc. To conduct an extensive non-destructive investigation in a mooring chain, working environment, combination of an autonomous/semi-autonomous robot mechanism with a NDT tool is needed.

The aim of this paper to propose a lightweight, permeant magnetic adhesion, wheeled robot which can be used as a platform to convey NDT equipment. The technique that is presented in this paper can be used for in air and adaptable to use in underwater. The presented robot consists of four tracked-wheel modules. Modules are placed orthogonal to each other in order to support the movement along the chain links. The paper presents the structural design, structure displacement analysis, motor selection, adhesion force requirements, prototyping of the concept, and experimental testing of the prototype. A magnetic flux concentration module is designed and presented in this paper to handle the given payload.

2.Related work

Due to the complexity of the climbing, only a few attempts have been made to establish a robotic / automated system which can operate both in air and water. Most of them are research based and unable to extend beyond the initial laboratory experimental stage. Moreover, when considering the climbing and crawling robots, chain climbing can be introduced as an area which needs to be exploited. The Inchworm influenced amphibious robot that has two gripper arms to climb is presented in 2013 [8] [9] and it weighted 450kg in air. Total weight of the robot was approximately 750 Kg. Anchor chain inspection and cleaning robot is presented in 2004 [10] as a human-like climbing mechanism. A mooring chain inspection robot is presented in [11] can be used in the chain manufacturing stage. This system inspects welding joints on chain links during the manufacturing stage. Gravity assisted cable mechanism is presented in 2008 [12] but allocated gravity assisted crawler–

cable mechanism was unable to perform as expected [13]. The Welaptega subsea mooring inspection system is powered with a remotely operated vehicle (ROV) and automated mooring chain measuring devices (visual and NDT measurements) [14]. When considering the offshore environments and mooring chain's catenary curvature, heavy and longer robots are not easily deployable [4]. Above mentioned robots are deployed by mechanical means by using divers. Due to operational conditions, it is practically not possible to handle a large weight in a cost-effective manner. Therefore, an additional deployment tools and supports are needed. The ROVs are unable to access the chain in air, therefore these systems can only be used in under water. Moreover, accessing the splash zone may not possible with a ROV due to the limitation of underwater ROV manipulation. Visually aided ROV inspection is common in industry but according to the history of mooring chain accidents and breakings, conventional ROV inspection cannot be considered as a reliable method [3] [4]. The above mentioned state of the art automated approaches are not able to provide a practical solution which can cover the entire chain in in-situ conditions. Therefore, it is essential to create a light weight, fast and automated system which can climb/walk/crawl in both air and under water in operational conditions.

3. Design process of the climbing platform

3.1 Design requirements

Physical nature of the mooring chains and the in-situ environmental conditions create a significant requirement for an automated robotic system that has high tolerance. Mooring chains are often subjected to high environmental changes such as tidal waves, wind, storms, etc., Chain link which is shown in Figure 1 demonstrate rusted and uneven surfaces. Therefore, robustness of the robot needs to be accounted. Robot deployment ability is identified as one of the main design requirement, due to the harsh offshore condition that robot has to operate. As an example, the deployment of a heavy robot is much harder in offshore environment. Moreover, a robot with an enclosed structure (around the chain) is harder to put on / put off. Ability to change between orthogonal chain link is considered as the second s requirement because mooring chains are made with 2 sets of enclosed links and they are kept orthogonal to each other. There is a discontinuity from one parallel chain link to the next consecutive parallel link. So the robot crawling / climbing needs to account that. Amphibious adhesion module and suitable locomotion are also identified as the main areas that needs to be addressed during the design. Adhesion module needs to be selected according to the mooring chain's physical nature. Such as, curved, rusted , ferromagnetic , amphibious and un even. Also the selected locomotion mechanism needs to handle the physical nature of mooring chains such as, robust, rough , curved, un even and discontinuous surfaces. 35Kg of a target maximum net weight is considered during the design stage in order to ease the deployment with 2 operators. Mooring chain size can be varied according to the place, application, load capacity etc. The mooring chain which is in figure2 is used in this study.

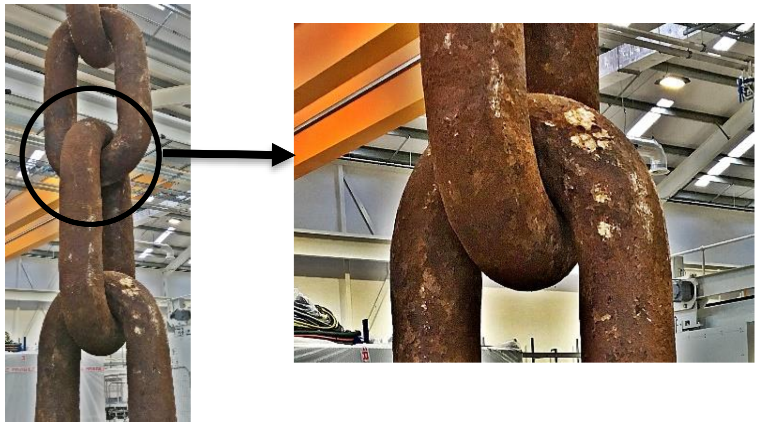


Figure 1: Mooring chain’s uneven, rusted surface (sample image)

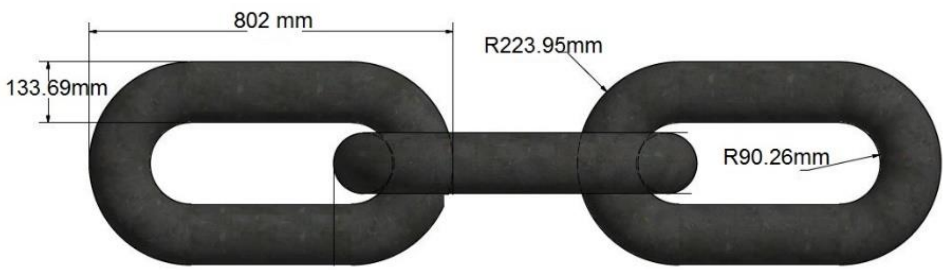


Figure 2: Schematic of the mooring chain used in this investigation

3.2 Concept of the climbing robot

Mooring chain links are orthogonal to each other, so the idea of the robot is to use two sets of tracked-wheel units that are kept in orthogonal position to represent orthogonal links One tracked-wheel unit moves on one chain link whilst other moves on an adjacent orthogonal chain links (refer Figure 3). Therefore, each orthogonal set of tracked-wheel units enable the robot to move along the chain. Unit A and B (refer Figure 4a) represent parallel links in one side, where unit C and D represent orthogonal side’s parallel links. During the climbing, A- B &C-D tracked-wheel units engage with the relevant chain surfaces to support the motion as illustrates in the figure 4b. Permeant magnets are considered due to the amphibious nature of mooring chains and zero energy consumption. Uncertainty of the adhesion module is minimised due to the passive adhesion quality of the permanent magnets.

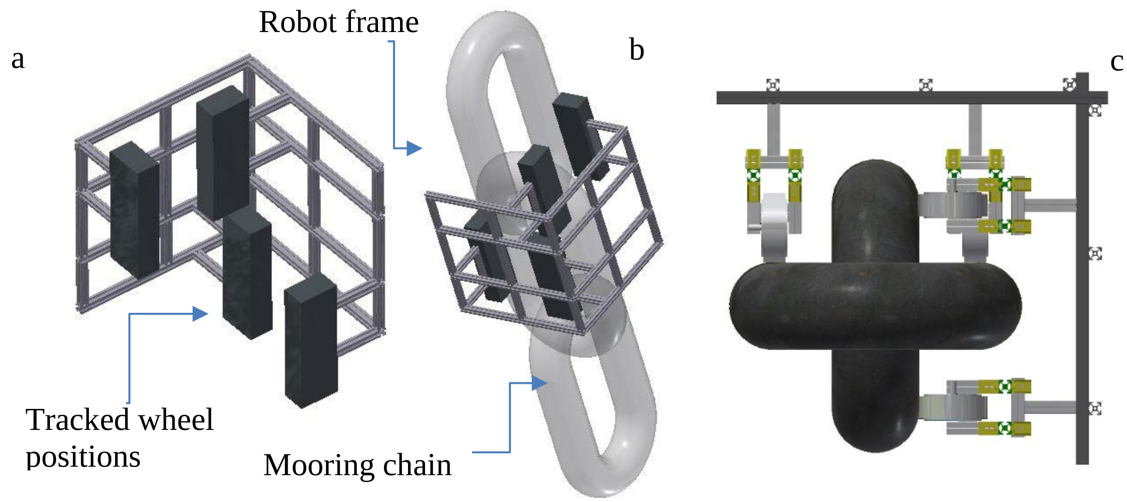


Figure 3: Conceptual design of the platform. a,b – conceptual design of the robot. C- orthogonal tracked-wheel placement (cross section view)

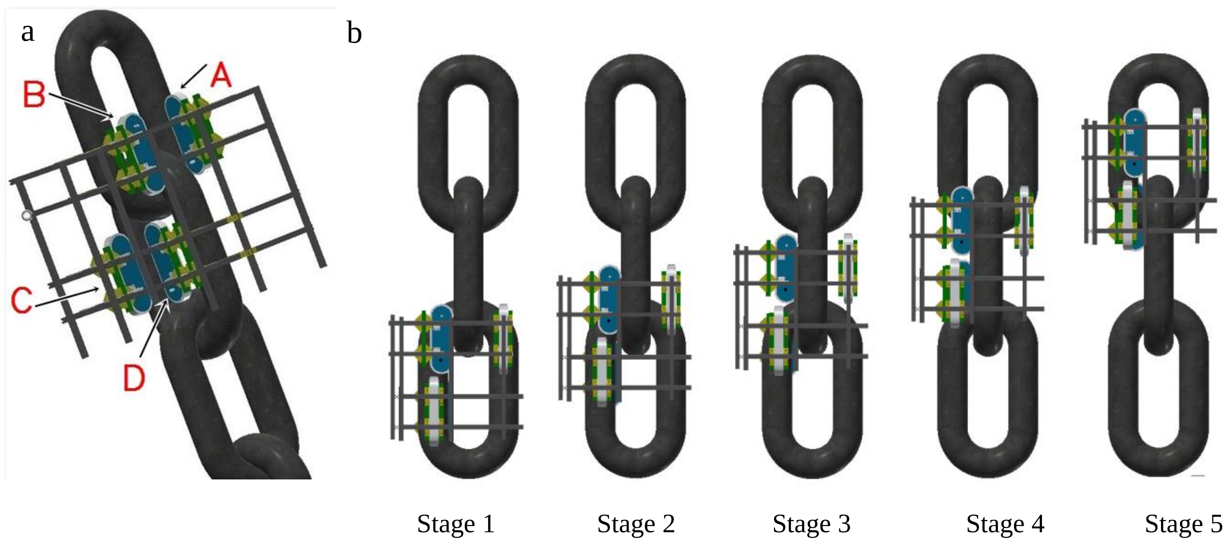


Figure 4: Conceptual design explanation. a- Tracked-wheel unit placement. b- Robot climbing sequence

3.3 Design of the robot frame

Easy deployment ability and retrieve ability is considered is during the robot physical frame design. A structure/ frame that needs to put around a chain link is not practical due to the in-situ mooring chain conditions. Therefore, a light weight "L" shaped frame which can be put on to the chain link is designed and analysed. CAD design presented in Figure 3(a) is designed to hold orthogonal crawlers that fit on to a specified chain links (Figure 3c). Un-enclosed characteristic of the "L" shaped design allows robot operators to deploy/retrieve the robot on to the chain easily. According to the concept of climbing, at a given point 2 tracked-wheel units are attached to the chain whilst the other 2 suspended in air. It was necessary to understand the displacement behaviour of un attached tracked-wheel units in

3D space. If the displacement of the un attached units are significant, vertical climbing can be disturbed because they need to be placed on the chain surface. Therefore, a numerical modelling study was carried out to understand the displacement behaviour of un attached tracked wheel units.

FEA study 01- Static structural module in Ansys workbench was used in this study with a mesh of 262884 element. Frame material properties were obtained from table 1. The layout presented in the Figure 5(a) was used in the study under gravity. Tracked-wheel unit displacement in 3D space are presented in figure 5(b,c,d). According to the study, maximum displacement was occurred along the x axis (refer Figure 5c) which is 0.394mm. 0.394mm is relatively low when compared to the width if the chain link (133mm approximately).

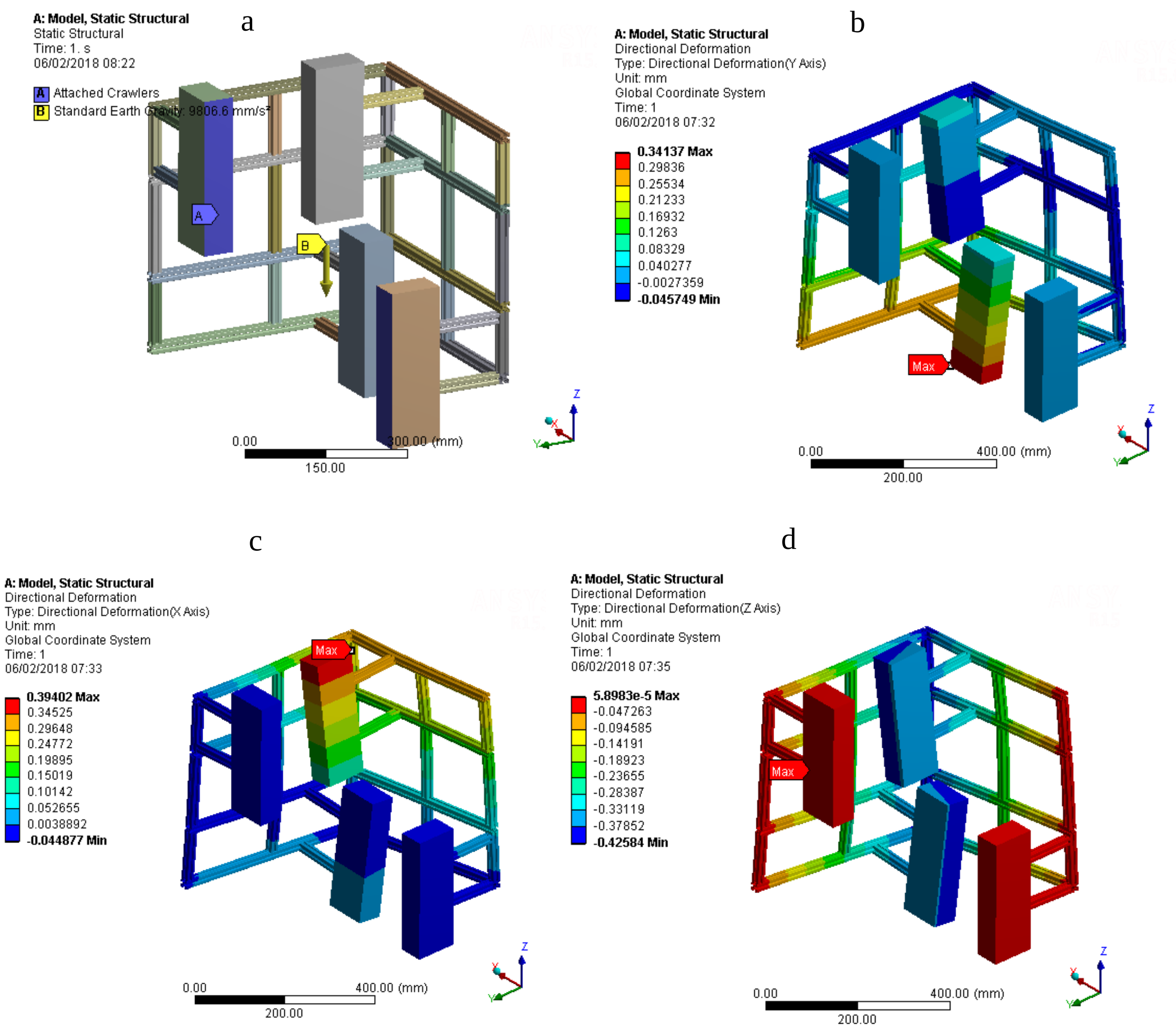


Figure 5: Structural defamation analysis: No payload. a- model lay out, b-x axis deformation, c- x axis deformation, d- z axis deformation

FEA study 02- Static structural module in Ansys workbench was used in this study with a mesh of 262884 element. Frame material properties were obtained from table 1. The layout presented in the Figure 6(a) was used in the study. Tracked-wheel unit displacements in 3D space are presented in figure 6(b,c,d). According to the study, maximum displacement was occurred along the x axis (refer Figure 6 c) which is 0.814mm. 0.814mm is still relatively low when compared to the width if the chain link (133mm approximately). Therefore, it is possible to conclude the proposed “L” shaped frame/ tracked wheel unit’s displacements are significantly low and the impact of tracked-wheel orientation due to the structural displacement is negligible.

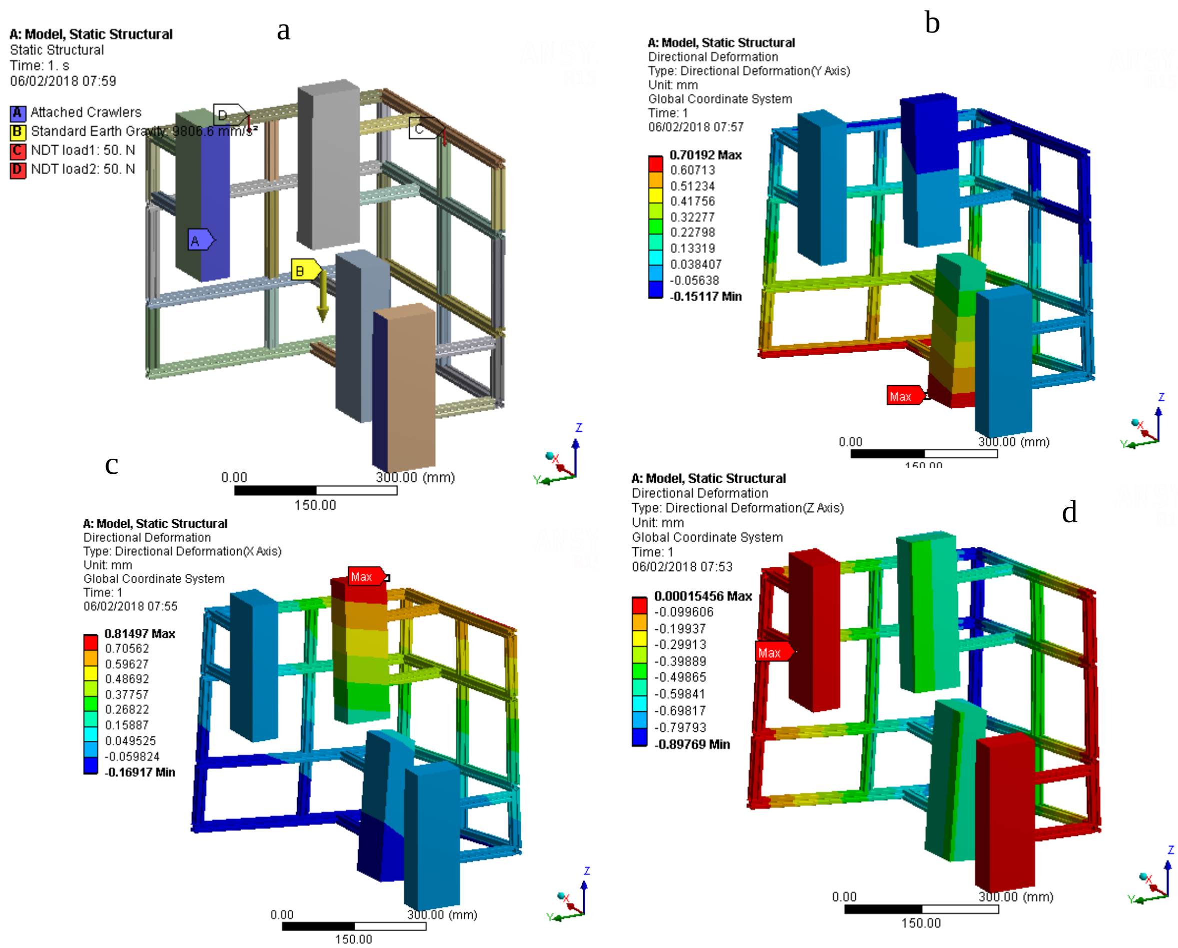


Figure 6: Structural defamation analysis: 100N payload. a- model lay out, b-x axis deformation, c- x axis deformation, d- z axis deformation

Table 1: Frame design / modelling parameters

Parameter	Parameter value
Material	EN AC-51400 Cast Aluminium
Density	2.7g/cm^3
Young's Modules	70 GPa
Tensile Strength: Ultimate	200MPa
Tensile Strength: Yield	120Mpa
Poisson's Ratio	0.33

3.4 Design of the motor payload requirements

Due to the orthogonal placement of crawler units (tracked wheel), each of them is powered with an external motor and a gearbox. The required torque calculation [Tmot] to drive the robot structure up along the chain link against the resultant structural downwards forces and magnet adhesion forces is previously studied in in the literature [15] (refer Eq.01)

$$T_{mot} \geq \left[\text{Resultant Weight} \times \text{Distance to the surface} \right] + \left[\text{Magnet force} \times \text{Effective radius} \right] \quad \text{Eq.01}$$

Eq.01 is adopted for Figure 7 as follows;

$$T_{mot} \geq W \times \{(r_1+r_2) \times [(W-Wc)/W] + r_2 \} + (\mu F_m \times R) \quad \text{Eq.02}$$

Required speed of the robotic platform is calculated by using Eq.03

$$S_r = RPM_{g+m} \times [2\pi \times R] \quad \text{Eq.03}$$

where, Output RPM of the gearbox + motor combination-[RPM_{g+m}], effective radius of the track-wheel – [R] , Net speed of the robot [S_r].

According to the orthogonal tracked-wheel concept of climbing, at least two set of tracked-wheel units contribute to the motion at a given point. Therefore, each crawler should be capable of delivering half of the torque which is calculated in equation 2 (approximately 16 Nm). Speed of the robot is calculated as 42 cm/min. Inspection methods are not presented at this stage of the research but the speed of the robot needs to be allocated according to NDT inspection requirements.

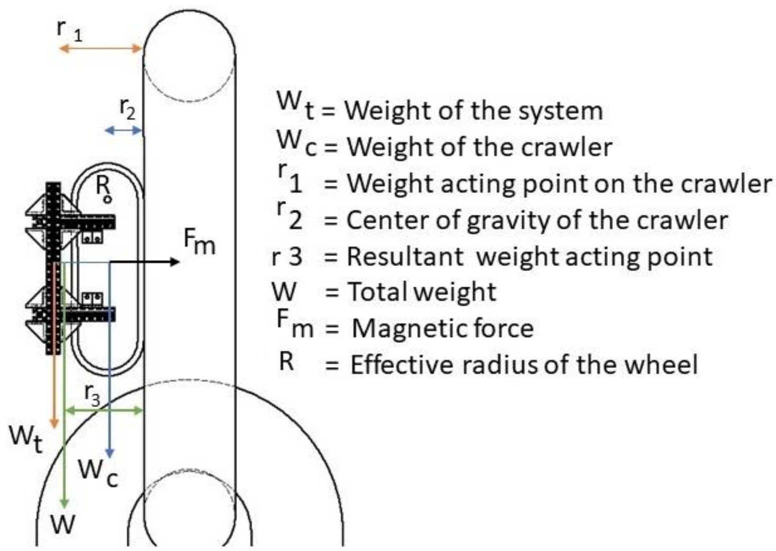


Figure 7: Tracked-wheel force diagram

3.5 Design of the tracked wheel unit

Selection of locomotion is carried out with the information provided in the previous research[15]. Due to harsh operational conditions (*i.e.* rough, robust, curved, uneven, amphibious nature) of the mooring chain surfaces, it is convenient to use track wheeled locomotion mechanism. Tracked wheel model was selected because passive track adaptation according to the uneven surfaces gives an additional traction advantage, payload capacity is reasonably high and control complexity is comparatively less. CAD models which are presented in Figure 8 are designed with the realistic sizes and parts. In order to avoid the effect of parallel misalignments of the chain links (slight differences in angles related to parallel links), it is necessary to keep the total length of the crawler track less than the gap between two parallel links. Therefore, the total length of a crawler has kept less than the gap (< 355 mm).

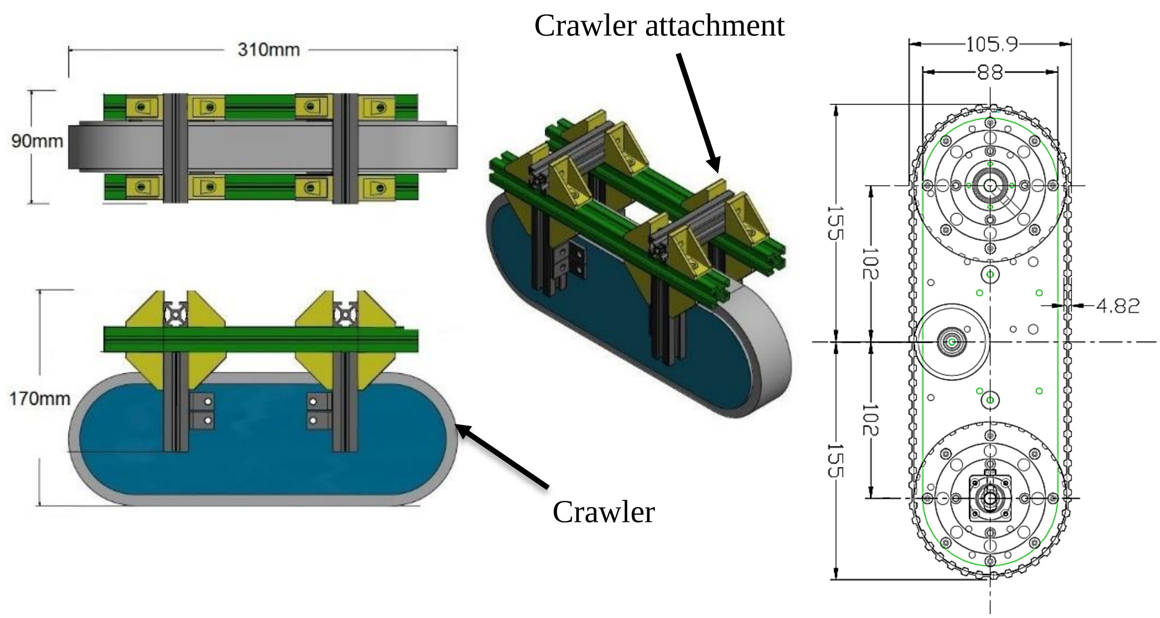


Figure 8: Tracked-wheel design and internal dimensions inside the tracked-wheel unit

3.6 Optimisation of the adhesion module

Mooring chains are made with thick iron rods which is ideal to employ a permanent magnetic adhesion system. Magnetic adhesion is the most suitable adhesion mechanism when the surface is uneven, curved and ferromagnetic, because of its non-contact and passive adhesion qualities. Required adhesion force (Fa) can be calculated by using equation presented in [16] (refer Eq.04)

$$Fa \geq \frac{W \times \sin(\alpha)}{\mu} - w \times \cos(\alpha) \qquad \text{Eq.04}$$

where, the robot's parameters are weight - (W), coefficient of friction - (μ) and vertical plane's inclination - (α). Net weight of robot is 191.23N (approximately).
According to the Eq.04 required minimum total adhesion force is calculated as 382.46N
2 track-wheel units are support the movement; therefore, each tracked wheel unit should be able to provide a minimum adhesion force of 191. 23N.Using a back plate to minimize the magnetic flux leakage which leads to focus more magnetic flux towards the required area is studied in the literature [17] [16]. Same technique is adopted in this research to calculate a sufficient adhesion force. It is required to keep magnets tangent and perpendicular to the chain surface to get an optimum adhesion force. Therefore, magnets are inserted in the crawler as illustrated in Figure 12. In the present study, magnets to chain surface air gap is 9 mm due to the mechanical clearances of the tracked-wheel unit.

FEA study: Stationary simulation was conducted in COMSOL Multiphysics with use of "Magnet field, no current(MFNC) module. Free tetrahedral mesh was created with maximum element size of10mm and min element size 0.1mm. Data presented in the table 2 is used in the numerical modelling. Figure 9(d) CAD model was designed according to the schematic presented in figure 9(a,b,c). A 201.58 N force was produced by the experimental magnet (N52, neodymium) arrangement. Figure 10, illustrates simulation results of focused magnet flux lines when the back plate is present and un focused flux lines when back plate is not in use. 30%(approximately) increase of adhesion force was obtain by introducing the back plate.

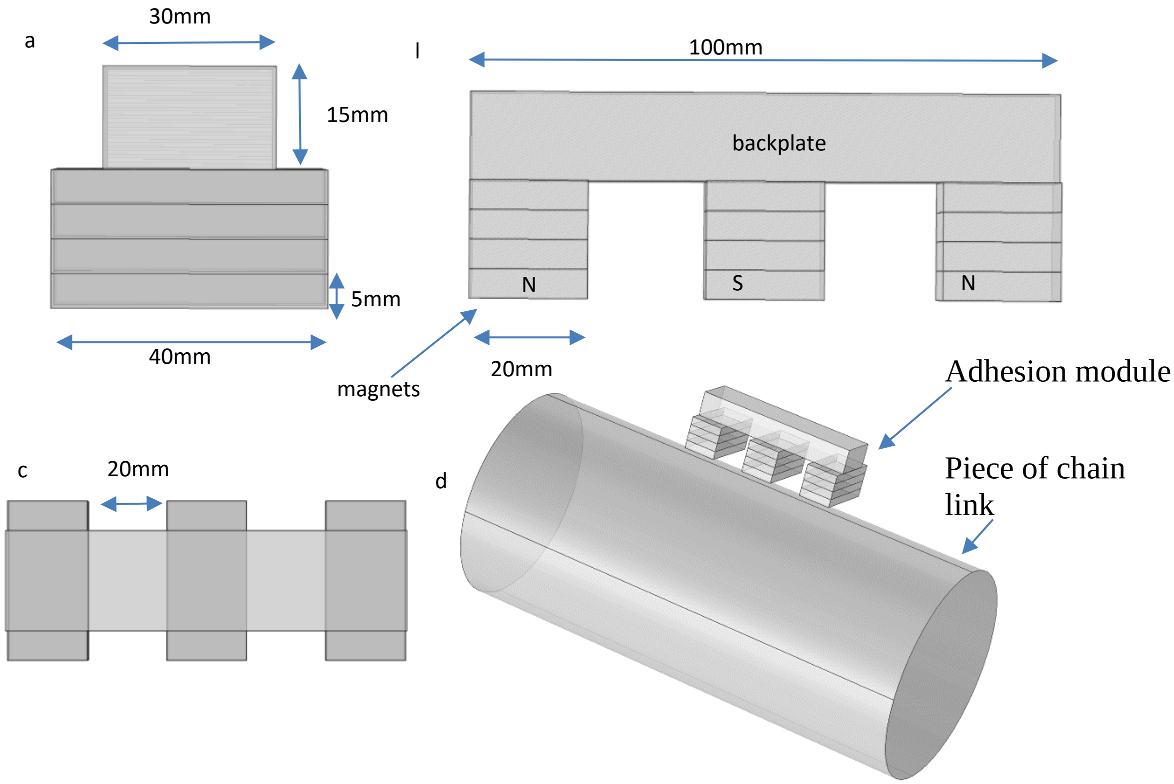


Figure 9: Design of the magnetic adhesion module. a,b,c-schematic of the magnet backplate design. d- Numerical modelling layout (COMSOL)

Table 2: Modelling 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 (used during the required force calculation)

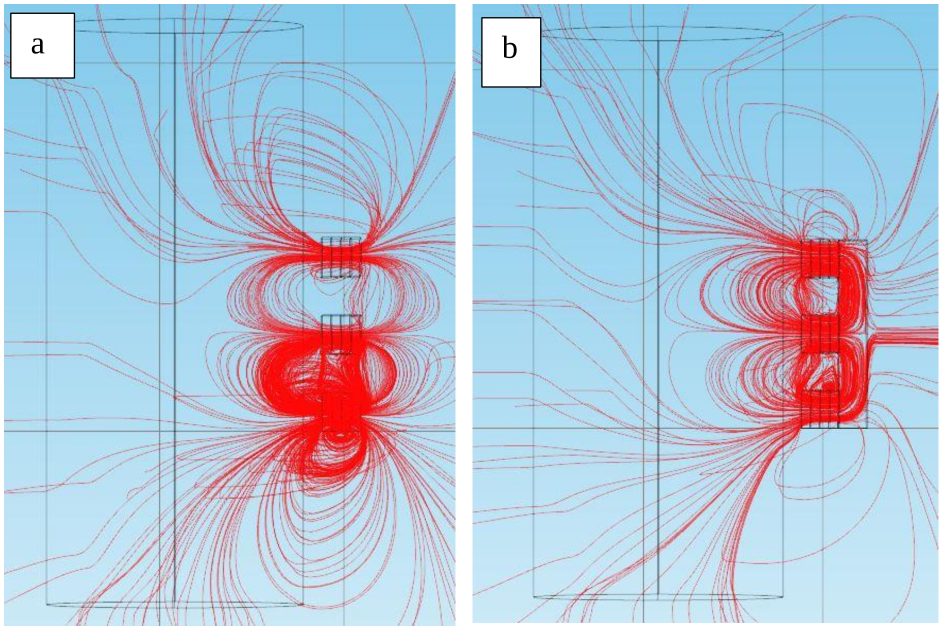
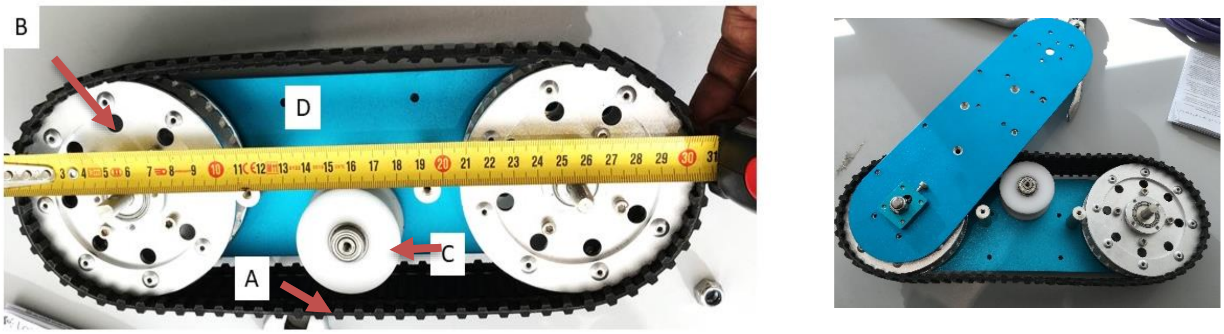


Figure 10: Numerical results of the magnetic flux distribution. a –un focused magnetic flux lines when there is no back plate. b– flux line concentration towards chain surface when the back plate is introduced

5. Prototype

4.1 Prototype and assembly of crawler unit, adhesion module and "L" frame

As it has explained in the previous section, prototype of the proposed "L" frame is constructed (refer Figure 13). Figure 11 illustrates the mechanical components of the prototyped tracked-wheel unit. Then adhesion module is inserted (refer figure 12 a). Small changes in the air gap between magnet – chain surface (due to the un even surface of mooring chains) leads to a sudden increase/decrease of adhesion force. Therefore, a small, support wheels are introduced in between magnets to remain the air gap steady during the entire motion (refer 12 b). The support wheel and crawler is made out of aluminium to avoid any interference with magnets. Small cuts are introduced to the crawler to keep the magnets in place as illustrates in Figure 12(b) (it is important to keep a constant air gap between two magnets). The "L" shaped main frame was prototyped and the four tracked-wheel units are attached to the frame (refer Figure 15). Additional 10 cm of aluminium extrusions are used during the prototyping for mechanical and practical advantages (*i.e.* handle the robot during the experiment, lift the main frame above the ground level, etc.,).



A – Rubber track, B – Aluminum wheel, C – Tension wheel, D – Aluminum cover

Figure 11: Mechanical parts of the prototyped tracked-wheel module / inside view

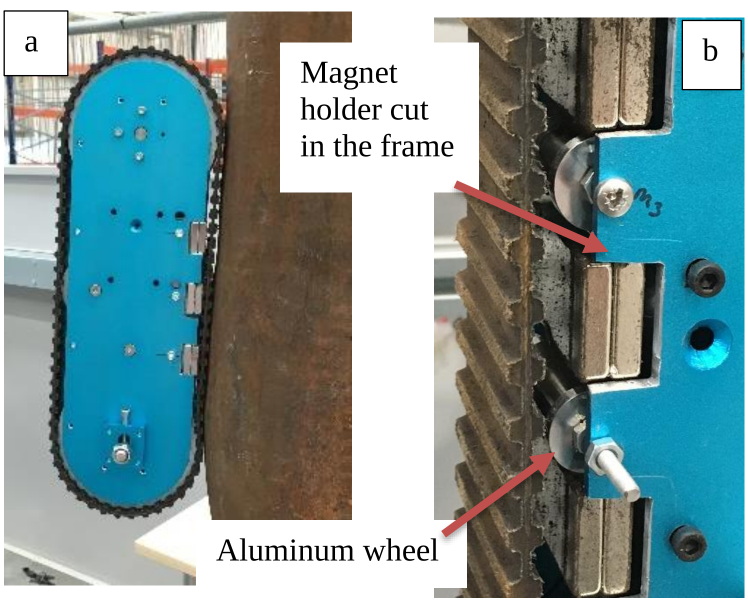


Figure 12: Prototyped tracked-wheel unit. a- magnet inserted tracked wheel unit =. b – small cuts in the frame and aluminum support wheels.

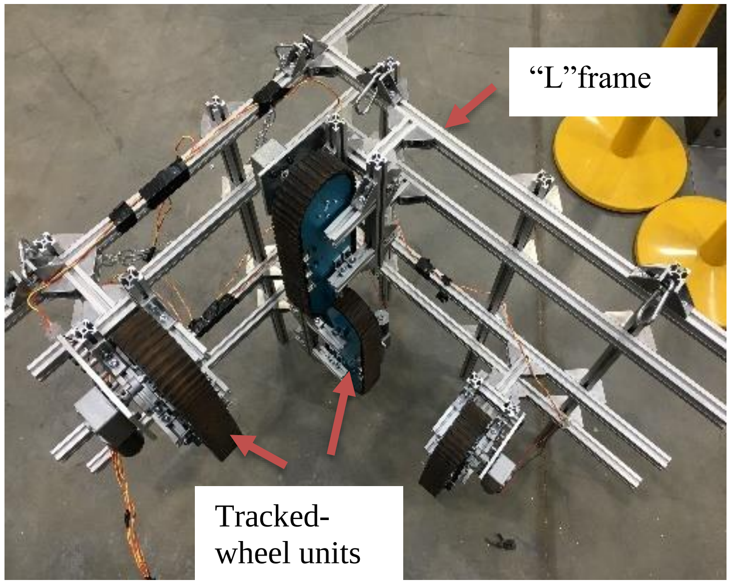


Figure 13: Prototyped L shape frame with crawlers

4.3 Motor attachment and control unit

Each crawler unit is equipped with a brushless DC motor and a suitable worm gearbox to supply the calculated/ required torque. To save the space between orthogonal chain links and crawlers, motor is attached to the crawler with a 90˚ attachment (refer Figure 14) The aim of the present study is to establish the basic principle of lightweight and fast crawler based robot solution. Therefore, the flow chart operation described in the Figure 15 is used to drive the robot platform along the mooring chain.

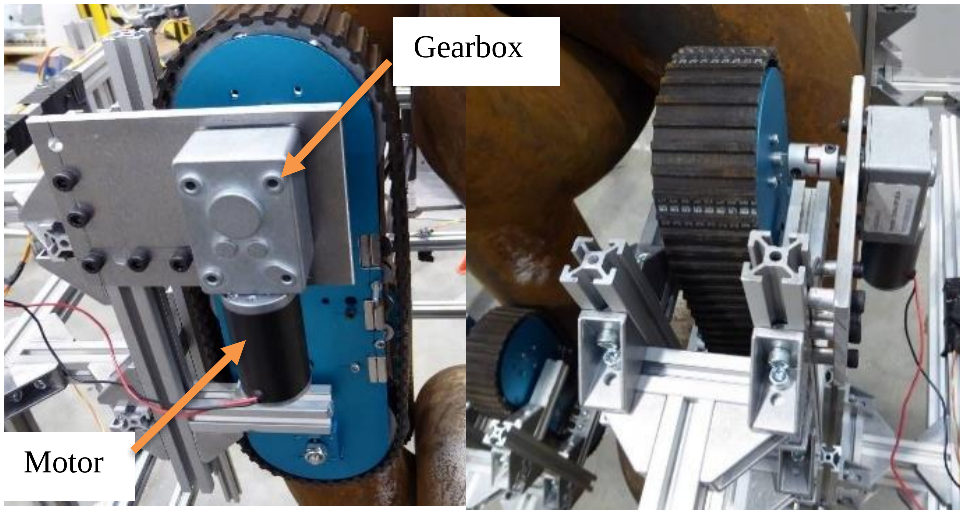


Figure 14: Motor and Gearbox attachment

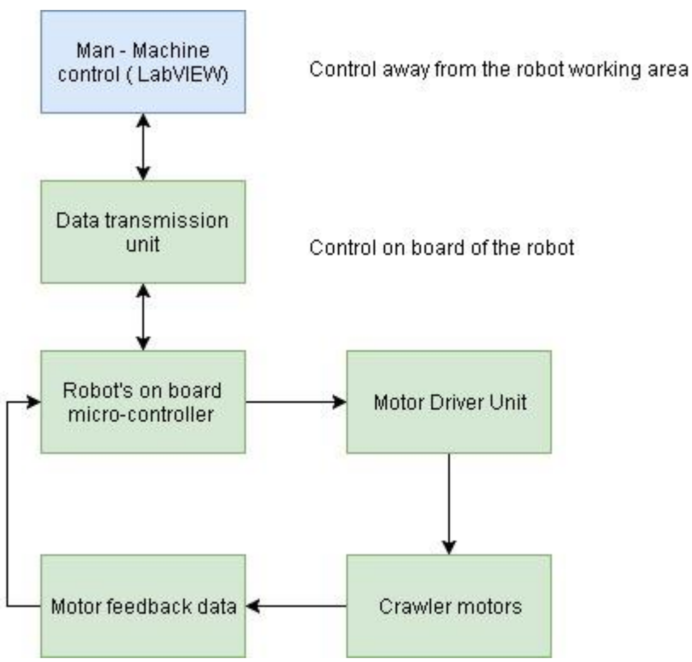


Figure 15: Control diagram of the robot

5. Testing and Validation

5.1 Adhesion forces validation test rig

During the design and numerical modelling of the adhesion modules, a magnet setup was proposed. The test rig in Figure 17 was used to validate the magnetic adhesion results which are simulated in the FEA study. The frame and magnet holding plates were made with (3-5 mm) carbon fibre and aluminium plates. Magnets were attached to an aluminium plate that with a free moment towards the direction of magnetic forces and the plate is kept on four set of load cells. To enhance the accuracy in reading, load cells were configured as a Winston-bridge. The amplified signal of the load cell was connected to a microcontroller to get readings. Aluminium spacers are introduced to maintain the same air gap as it is in the FEA simulation. During the preparation of the test rig, known weights form 1 N – 70 N are used to calibrate the reading scale. Experimental magnet sets in Figure 16 are tested in the test rig and forces are recorded in table 3. Recorded experimental adhesion results and FEA results has a good agreement and the maximum variation is 6.07 N. Change of air gap distances (±0.5mm) while setting up the test rig and sensitivity of the loadcells (0.2% manufacturing error in the sensor) can be introduced as possible factors for the error between FEA and experimental. According to the results, it is possible to conclude the validity of FEA study and force calculations.

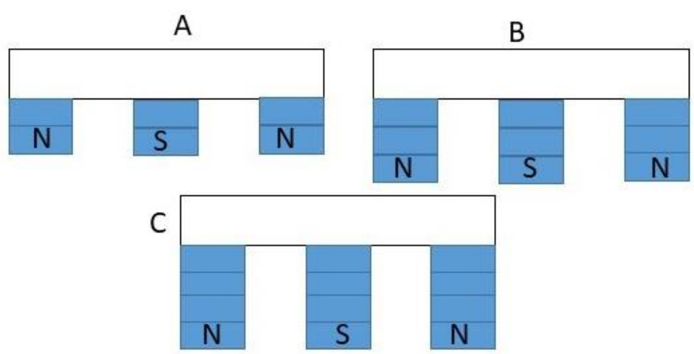
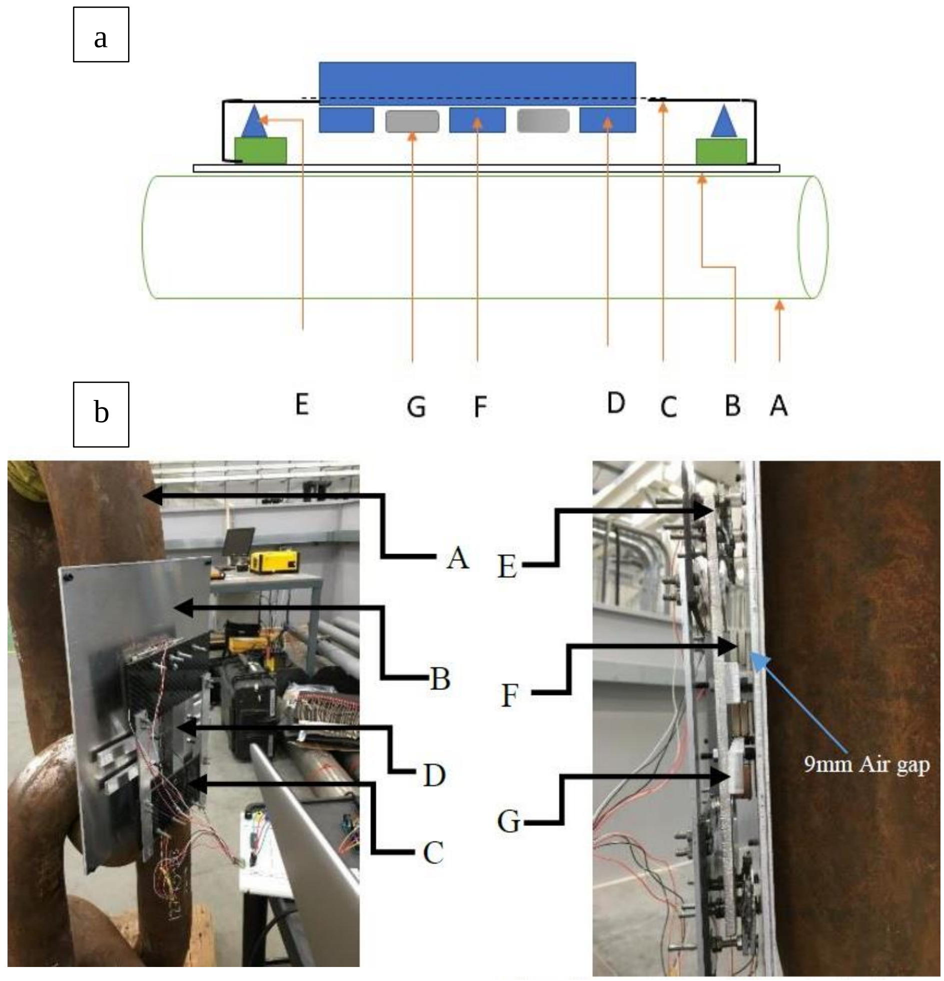


Figure 16: experimental magnet adhesion modules



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

Figure 17: Magnetic adhesion validation test rig. a -schematics of the test rig, b- test rig

Table 3: Simulation vs experimental results (magnet set -refer Fig 18)

Studied Magnet set	Numerical Modelling Results	Experimental Results	*Error %
A	164.95	155.504	-6.07%
B	182.17	185.35	1.72%
C	201.58	205.714	2.01%

*Error calculation = [(Experimental -Numerical)/ Experimental] ×100

5.2 Laboratory climbing sequence test

The climbing sequence illustrated in Figure 18 is recorded from the laboratory experiment trial. The crawler robot is placed on the mooring chain and up/down movement is inspected. The experimental trial was conducted in an industrial environment. Therefore, additional safety cable was used to enhance the safety (internal laboratory safety regulation). Robot was able to attach to the chain and climb between chain clinks.

In the present stage of the research, mooring chain inspection mechanism is not concerned, therefore the above climbing is tested with robots own weight. A stability check is performed with external applied forces (external payload) (Figure 19). According to the experimental results, robot stayed attached to the chain link surface up to 50 N of external forces (all the safety cables were released during in the stability test experiment)

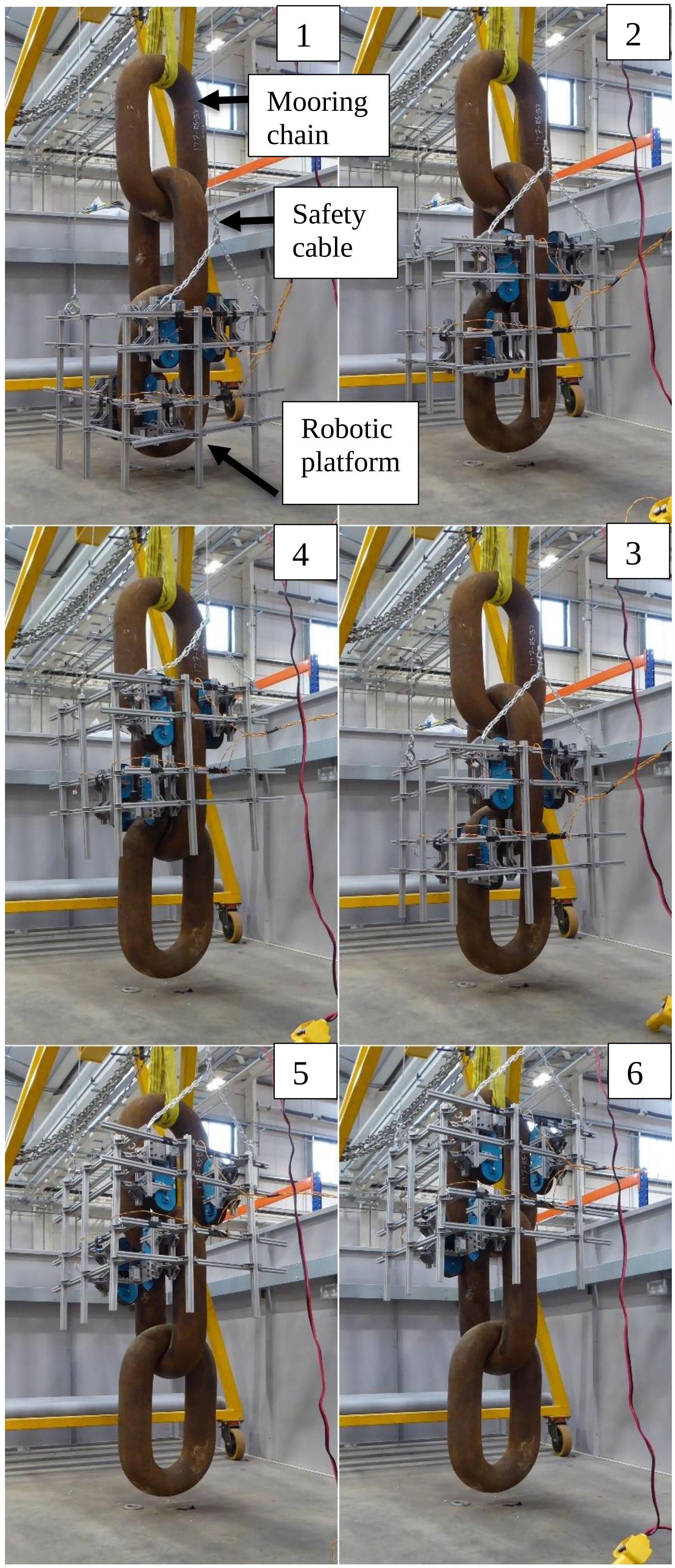
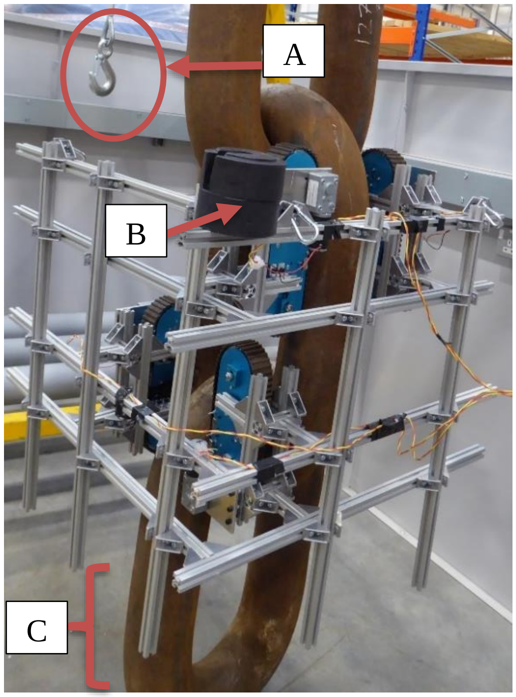


Figure 18: Robot platform climbing experiment



A- Un mounted safety cables, B- External weights (10N -50N),
C – Robot not resting on the ground

Figure 19: Stability test against external loads

6. Conclusions and Further work

Tracked-wheel magnetic adhesion robot was presented as a platform for mooring chain applications. Optimization of a neodymium permanent magnet adhesion module to obtain a required adhesion force was carried out by using FEA software package COMSOL Multiphysics and the simulated results were validated against the experimental results. Complete robot system was tested on a three-link mooring chain segment to study climbing capability and stability against external forces. During this study, a light weight, magnetic adhesion robot with orthogonal crawler units (tracked crawler) has been prototyped and tested.

As the future improvements of the research it is necessary to introduce an active control mechanism that can correct the robot when it starts slipping or slightly changing its path due to an external forces or mooring chain surface conditions. Mooring chains are amphibious structures and the robot structure should be able to travel underwater. Therefore, it is necessary to marinise motors and controllers to setup an underwater laboratory trial. A straight mooring (consecutive links are orthogonal to each other) chain is used in the present study, the robot will be upgraded to overcome misalignments of chain links (misalignment 5-20 degrees). Moreover, required degree of freedom will be introduced to the crawler units as a further improvement of this work.

7.Acknowledgement

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