Ferromagnetic Climbing Robot for Industrial Flaw Detection: An Implementation of Computer Vision

Peter Oyekola
Department of Mechanical Engineering,
Tennessee Technological University
petertosin@gmail.com

Abstract

In order to maintain a safe working environment, there is a constant need for the inspection of structures for failure. One common problem faced during inspection is restricted access to the inspection site. Furthermore, inspectors use sensors like cameras and non-destructive testing kits to detect structural failures such as cracks and corrosion. Still, due to the size and complex geometry of most structures, inspection is expensive, time-consuming and potentially unsafe.
This paper, therefore, describes the design of a robot that can be used for non-destructive Inspections of various range of structures to improve and automate structural inspections. In order to achieve this aim, different existing robotic designs have been reviewed, with focus on wall-climbing robots in similar environments. The final design combines a set of actuator motors, magnetic tracked wheels to aid vertical movement on magnetic structures, as well as a wireless camera for visual inspection and manoeuvring the robot system for the identification of surface cracks and corrosion using YOLOv4 machine learning algorithm. The structure of the tracks allows the robot to climb over uneven surfaces like bulwark, obstacles etc. which allows inspections in unfriendly and inaccessible environments therefore reducing costs and inspection time considerably.

Keywords
Computer Vision, Ferromagnet, Inspection, Robot,

1. Introduction

Structural failures are a significant cause of loss of life and the second principal cause of asset failures in industries, (Speight, 2014) (Ratnayake, 2012) and the study of this failures are a necessary step in mitigating incidence and possibility of future failures. This process requires acquiring knowledge on the failure mechanisms of structures and their breakdown. As seen in L. Yunovich et al. research (Yunovich, M., Thompson, N. G., Balvanyos, T., Lave, 2001) on the direct costs implications of corrosion in the industry, it becomes clear that although corrosion cannot be avoided entirely, we can, however, reduce the impact of structural failures by being proactive in industrial maintenance culture.

Studies also show that the primary reasons why this failure occur are due to inadequate awareness or attention to the causative factors of corrosion, inadequate risk analysis at the design stage or before any component change, lack of information etc. (Elsevier's R&D Solutions for Oil and Gas, 2018). This industrial failure could be identified through routine inspections which include the measurements of wall thickness, corrosion rate, defects and cracks. Furthermore, this becomes straightforward when applied in an industrial environment where the primary materials used are made of Carbon steel or other ferromagnetic materials which are highly susceptible to corrosion; hence these facilities requires effective corrosion management (H. Koch et al., 2001) to reduce the rate of failure occurrence.

The vulnerability of material to corrosion is determined partially by forecasts based on water chemistry, temperature environment of operation this makes marine structure highly vulnerable to failure as they are continually being exposed to fluid all through their life span. An obvious solution to reduce the effect of structural failures requires the development of a dexterous inspection system which will introduce a level of automation as well as ease amount of effort expelled during the inspection of industrial structures. Although research in machine learning techniques is relatively young and developing, its applications in engineering solutions are worth an intensive study.

Since the adaptation of industrial robots into the manufacturing lines, traditional methodologies have been severely disrupted being that they primarily thrive on repetitive tasks, usually in organised assembly lines. These repetitive instances have pushed adaptation of robotics by the design and development of a new breed of robots that can also function optimally in unstructured environments which are usually subject to a high level of uncertainty. These service robots incorporate a greater level of mobility, autonomy, environmental and situational awareness. Of this class of robots, the climbing robot can be found. They are specially designed to transverse three-dimensional structures using adhesive technologies that are concurrently developing as technology age deepens. These robots are specifically designed to allow free movement out of well-defined operational scope.

This research proposes to develop a track driven robotic inspection solution which shows future potential in its adaptation for industrial use. The current design aims to leverage the use of an automated inspection technique whose algorithm has seen recent development and adaptation in self-driving cars, obstacle avoidance, automation logic etc. in the identification of surface cracks, corrosion as well as other pretrained defect generally found in practical applications.

The Computer-Aided Design model (CAD) employed in this paper was designed using SolidWorks 2018, which was subsequently modified for design optimisation and static and dynamic analysis of the adhesion system. Additionally, the robot hardware components and control module were all based on the Raspberry Pi 4B configuration computer board, which allowed for Bluetooth and wireless computer communication through a Secure Shell (SSH) module.

1.1. Research rational and motivation

The structural integrity of key equipment and facilities is an important aspect of business continuity and maintaining a sound infrastructure like tunnels, pipelines, storage tanks, beams, columns etc. require routine inspection and maintenance. Though, most structures are designed for stability for a given period, prolonged exposure to harsh environments, use of equipment for what it was not designed for and loads distribution significantly increases the unreliability of these structures amongst many others.

The limitations of advanced inspection systems are the need for expensive equipment, analysis and interpretation of data which requires highly skilled operator. Although with advanced in technology, these devices are now portable and compact, it is still fairly bulky and frequently requires setup time.

the critical area of research that needs to be addressed as relating to robotic inspection is the manipulation of the robots for multi service inspection.

Recent advances in robotic technology have seen increase in the use of service robot for inspection which have imposed several requirements on the robotic system relating to locomotion abilities, localization, and transfer of data however, we see that these robots are designed for specific use in a predetermined environment which makes them less effective for use in other areas of application

Though inspection of structure can be challenging due to the diversity of inspection requirement for different structure. And all this uncertainty must be considered in the design of robots capable of meeting minimum requirements for the necessary inspection.

1.2. Problem statement

Metallic structures constitute a large part of industrial materials due to its huge range of applications. Most metals used in industrial applications corrode, though the rate of corrosion vary based on type and quantity of constituent alloying element making up the material (TERENCE BELL, 2019). Failure is mostly cause by aging, corrosion, and cracks

Although most company's policy on safety is 'Zero Accidents or Incidents', it is relatively easy to ignore the consequence of failure due to crack and corrosion as it is sometimes not obvious by visual inspection until its too late especially for subsurface type corrosion such as crevice corrosion (Kennell et al., 2008). According to (Yunovich, M., Thompson, N. G., Balvanyos, T., Lave, 2001) in his work on the direct costs related with metallic corrosion in the US industry. the annual direct cost of corrosion in the was $276 billion (3.2% of the country's GDP at the time). He claimed that the major industries where this issue was predominant were infrastructure (economic loss of $22.6 billion), production and manufacturing ($17.6 billion), transportation ($29.7 billion) government($20.1 billion) and utilities ($47.9 billion) (Cor-Pro Systems, 2013).

The consequence of this failures can sometimes be catastrophic and often leads to loss of man hours, stoppage of production and even death for severe cases.

human limitation like stress, work rate, accessibility issues, hazardous environment can severely affect quality inspection of critical equipment and some proper pipe inspection cannot be done. This therefore necessitates the need for a mobile advanced system that can be easily deployed for use in a more efficient and accurate inspection of failures in structural members.

1.3. Research aims and objectives

The objective of this study is to design a robot that can

- transmit visual feedback over a given distance range
- vertically inspect magnetic structures using magnetic crawlers
- automatically identify defects through image processing

1.4. Classification of failure

The basic forms of structural failure are

- Failure due to extremely high loading or low structural strength of material e.g. (Excessive wind, beam strength etc.)
- Failure due to overloading (design error, construction error) is caused by unpredictable factors such as foundation movements, creep, shrinkage etc.
- Failure due to naturally occurring hazards such as quakes, flood, impact etc.
- failures caused by deteriorating climate
- failures due to misuse of a structure or not realizing the critical nature of certain factors during the use of a structure

in James Chang (Chang & Lin, 2006) review of 242 storage tanks incidents, 74% of these incidents occurred in the petroleum industry out of which the main causes of this failures were fire and explosion, lightening and equipment failures such as sabotage, crack and rupture etc.

1.5. Thesis outline

The introductory chapter gives an overview of inspection and the rational motivation for the contributions presented in this thesis. First inspection technologies and applications were reviewed, and this background forms the foundation for the development work presented in this thesis.

Chapter 2 contains a review of previous work relating to inspection robotics, existing technologies used in detecting flaws in different areas of structural application, physical modelling techniques and control methodologies.

Subsequently, an overview of the design process and requirements for the developed conceptual model are contained in the third chapter. This includes the mechanism design, moto-gearhead selection, material selection and specification, joints, drivetrain design and control system will also be discussed as well as the methodology of implementing computer vision.

Chapter 6 evaluates the overall performance of the platform by conducting and analysing a series of experiments.

Chapter 7 concludes this thesis with a summary of performance and recommendations for future work from the results presented in this thesis.

2. Literature Review

Inspection robots have been studied in the past by lots of researchers as a solution to the issue of structural inspection.

2.1. Flaw detection mechanism

Inspection personnel are trained to recognize specific signs of decline with potential of leading to structural failure. Defects signifies a loss of structural integrity, sometimes may be visually obvious like corrosion or crack along the exterior of structures (surface cracks). Other times, defect can only be detected using specialised equipment such as internal cracks, deck delamination etc.

2.1.1. Ultrasonic inspection

This method of inspection is a widely used form of non-destructive testing Ultrasonic Inspection where beams of high frequency acoustic wave are introduced into a specimen to detect surface and subsurface discontinuities, measurement of material thickness and distance to a flaw. An ultrasonic beam travels in a medium until it reaches an interface or discontinuity.

Interfaces and internal discontinuities interrupt the wave flow and therefore reflect a part of the incident wave. This reflected signal depends on the nature and orientation of the interface or flaw and acoustic impedance of the reflector. two types of ultrasonic inspection are shown below.

2.1.2. Ground Penetrating Radar (GPR)

This technique is often used for bridge decks. high frequency electromagnetic pulses are transmitted from a radar antenna onto the deck. reflected pulse is used to estimate medium change. Hence this makes it applicable in thickness measurement, detecting internal flaws etc.

2.1.3. Visual inspection

This is the most basic non-destructive testing method. Owing to the high cost of advanced inspection techniques, it is sometimes preferred to use the cheaper options like visual inspection which requires minimal use of instruments or equipment, and no need for secondary processing (FHWA, 2001). As mentioned previously, visual inspection can only detect surface defects. However, the downsides of this method are

- It is dependent on the training of the inspector, visual perception, and state-of-mind.
- It is dependent on external factors for instance intensity of light, complexity of structure, and accessibility

Results from visual inspections has a wide range of variability (FHWA, 2001) as they are entirely dependent on the person conducting the survey.

These then question the reliability of visual inspection procedures as it remains subjective and dependent upon external factors.

2.2. Adhesion mechanism

The mechanism used in climbing structures are basically vacuum adhesion (negative pressure) dry adhesion and electrostatic adhesion. In recent time, the magnetic adhesion principle has been proposed and implemented practically. In principle, it implies the use of heavy actuators and can only be used vertically on ferromagnetic structures like storage tanks, container, vessel hulls etc.

In the past years, several applications of robot include technical inspection, maintenance, failure or breakdown diagnosis in unsafe and inaccessible environment (Balaguer et al., 2005). And the task involves a huge variety in structures such as pipeline inspection, wind turbine (Sattar et al., 2009), surface flaw detection of tanks and offshore platforms (Saiigdeok Park et al., 2004), power plants (AZAIZ, 2010), Non-destructive testing (Hongjun et al., 2005) and in the aviation industry for inspection (Perelli et al., 2013). Furthermore, robots have also been applied in inspection of civil structures (Miller, 2004), military operations and cleaning operations (Elkmann et al., 2002). This then forces the design of adaptable adhesive mechanism for application in diverse environments.

2.2.1. Suction

This is a frequent approach used in climbing robots as the vacuum offers ease of control and ability of traversing over several structural surfaces of different material. This method offers a simple structure with good adaptability to different structures (including non-ferromagnetic surface). Vacuum can be generated using suction engine (Schmidt et al., 2011), (M. Wang et al., 2013)vacuum generator with connecting lines (Z. H. Wang et al., 2009), external hydraulic (Albitar et al., 2013), motor driven plunger pump (Guo et al., 2008), centrifugal impeller (Zhao et al., 2004), (Wu et al., 2011) and passive suction cups (Yoshida & Ma, 2011) which creates the negative pressure in the suction cup or chamber for wall-climbing in practical applications. Its main drawback however is the amount of vacuum required to achieve the desired adhesive force. The delay in achieving this pressure adversely affect the speed of operation of the robots with this mechanism. Also, if there happen to be a gap in seal maybe as a result of surface irregularity, there is the tendency of loss of grip. This then makes this principle practically fit for smoot surface, non-porous applications.

2.2.2. Magnetic adhesion

This method of adhesive mechanism is highly preferred due to its reliability, energy efficiency, adhesive force and speed of operation although it requires the use of heavy actuators. Magnetic adhesion can however be used on ferromagnetic structures which makes its unsuitable for use in most civil structural applications like concrete or glass structures.

More frequently, electromagnets are used to generate the magnetic force as seen in (Shores & Minor, 2005), (M. Armada et al., 2005). Permanent magnets have also been employed in combination with wheels or tracks (Sánchez et al., 2006). This has a huge advantage as the adhesive force do not require any form of power requirement as opposed to the electromagnetic method (M. A. Armada et al., 2005). Another method of applying the magnetic adhesion mechanism is the use of magnetic wheels directly to generate the adhesion (Saiigdeok Park et al., 2004). The adhesion force is determined by the magnetic properties of the type of magnets used, characteristics of the structure and distance between the surface and the suction mechanism.

2.2.3. Dry adhesion

This is also known as Van Der Waals force and it inspired by the way wall geckos adhere to surfaces without slipping or falling (Asbeck et al., 2009) (Carlo & Metin, 2006). This method has been practically applied in climbing robots which makes use of the dry adhesion mechanism which generates Van Der Waals forces between the surface and the micro-fibril tape attached to the robot.

Wall geckos stick to surfaces using their feet, they have fine hairs of roughly 5 microns in diameter on their toes which sits hundreds of nanofibers (spatulae) 200 nanometres in diameter (Unver et al., 2006). The physical properties of the hairs let them bend and adapt to a variety of surface roughness.

For movement to occur, three operations are carried out; first, the robot attaches to the surface, the gradual loading to increase the adhesion force, finally the removal of adhesion to surface by peeling to move towards another point. Examples of application of this method are seen in a crawler mechanism robot which use flat sticky polymer on belts (Seo & Sitti, 2011), leg-wheeled robot of four legs and an incorporated passive wheel (Liu et al., 2013), spoked wheeled-leg robot with adhesive fibres on all spokes (Daltorio et al., 2009) and a six-legged robot with Polydimethylsiloxane attached on feet climbs structure using dry adhesion mechanism (Boscariol et al., 2013).

2.2.4. Electrostatic adhesion

This method is based on the principle that when an adhesive material/ pad placed near a wall, the electrostatic adhesion voltage results in electrostatic charge on the pad and an opposite charge in induced on the structure (Koh et al., 2011). This mechanism can be applied in wood, glass, construction material etc. Its main advantage is its low power requirement, simplicity, noise, ability to work on dusty and wet surface etc. it is however inferior when adhering to wet concrete (Koh et al., 2011) and it is best suited for short distance application due to the possibility of getting clogged. Applications of this mechanism is seen in (Chen et al., 2013) whose battery powers the electrostatic adhesion force on the electrode panel

2.3. Locomotive mechanism

Generally utilised locomotive systems are the tracked system, legged, wheeled and sliding system and each offers its advantages and disadvantages for a variety of operational scenarios (Guo et al., 2008) (Liu et al., 2013).

The legged system has been severally implemented with a number of joints and can be used for several task not limited to environmental exploration, disaster management, surveillance etc. Also, some robotic system utilises the four or six-legged arrangement with increase in the degree of freedom account for better mobility especially on uneven and rough surfaces. For situations where terrains are uneven and rough, the wheel and tracked system might not be the best selection and h due to this terrain adaptability, legged robot are considered more suitable for this application. Legged robots use discreet points on the terrain rather than other methods which requires a large area of contact for movement. Also, there is more flexibility and mobility in terms of degrees of freedom of the legged joints as its legs can be extended while maintaining body position at a constant body level thereby controlling the robots centre of gravity which makes the robot less likely to tip over or fall (Daltorio et al., 2009) (Boscariol et al., 2013).

2.4. Climbing inspection robotics in practical application

Having established that most industrial machines and equipment are made of ferrous materials, the presence of iron in structures therefore increase the possibility of rust formation due to interaction with the surrounding humidity and pollution. This eventually leads to corrosion of structures. Upon occurrence of corrosion, the structure undergo fatigue which adversely affects the structural integrity (Papavinasam, 2013).

Practical application of inspection robots is usually in tight spaces, tall structures as well as hazardous environments. In the industry most especially manufacturing plants, some critical points might not be easily assessed by humans, hence equipment like remote cameras, endoscopes and thermal imaging camera are usually deployed is such scenario. Sometimes, inspections of this nature often involve a stop work order for damage assessment. Additionally, tall structures such as petrochemical storage tanks, cranes and wind turbine do not accommodate the conventional failure inspection techniques because of the labour-intensive effort required. Sometimes scaffolds, ladders and climbing gears are required together with handling of complex and expensive equipment. This requires the use of personnel's the are limited by physical and mental strain.

Several robots have been developed for inspection in recent years and they all have a wide range of industrial application such as offshore platforms, shipyards, petrochemical and general storage tanks, bridges, buildings, power plants etc.

Inspection robot used in detection of defects for different types of structure was designed by Kalra et al (Kalra et al., 2006). the robot was fully autonomous and had wall climbing ability with ultrasonic module used in flaw detection. Also, inspection robots have been applied in conical and spheroidal towers and tanks as seen by Shao (Unver et al., 2006).

Diverse designs adapted to suit specific structural purpose includes insects inspires wall climbing robot (Padrón et al., 2002) used in bridges, gecko like robot, etc. Dedicated sensors mounted on the robot chassis could be used in the detection of defects such as pinholes, cracks, corrosion (Saiigdeok Park et al., 2004).

Robots have also been applied in inspection of welds as seen in luk et al (Luk et al., 2001) where the robot was developed to inspect welds in the main reactor cooling gas duct in a nuclear power station and have also been deployed in the inspection wind turbine blades using ring configuration (Lee et al., 2016) and to detect porosity and cracks in hulls of marine equipment such as ship hulls (Mondal et al., 2002), inspection of container (Shen et al., 2015), aircraft structural inspection such as RobAir which was developed for inspection of fuselage and wings (Hongjun et al., 2005) (Perelli et al., 2013) and as well as for structural inspections using wall climbing technology to inspect narrow space and complex pipes environment (Tâche et al., 2009).

Several robots have also been developed to assist in cleaning of structural elements like ship's hull, roofs of structures, etc. underwater cleaning robot designed with flexible crawling mechanism is presented in (Albitar et al., 2013) also, specialised robots have been applied in cleaning of glass structures in high rise buildings as seen in (W. Wang et al., 2007). For cleaning robots employed in ship hull cleaning, it employs the use of high-pressure spray on the surface of the hulls as an effective means of particle removal (YI, 2010).

Additionally, robots used in sandblasting and painting adopt magnetic crawler to enable vertical movement across metallic structures (Faíña et al., 2009) (C. S. Wang et al., 2010).

Application of robotics in security, surveillance, disaster management and even military applications cannot be overemphasised as we now rely on this technology and it significantly lower fatality rate and have proved very efficient in practical experiments and real-life scenario. City-Climber robot (Xiao & Sadegh, 2012) for instance was designed for disaster control, weapon delivery, surveillance and reconnaissance purposes. also, (Bahr et al., 1996) developed a security wall-climbing robot with six legs suction mechanism.

This study aims at developing a climbing robot for industrial application in failure detection. This can be applied universally at its design is not limited to a unilateral area of application. The adhesive mechanism selected was the magnetic crawler system due to its high traction, speed and obstacle manoeuvrability such as the design used in ship's hull inspection in H. Haocai research (Huang et al., 2017) where the robot was designed for automatic ship's hull inspection using ultrasonic probes.

3. Summary of Methodology

3.1. Basic Requirement

3.1.1. Locomotion

With the requirement of generic surface mobility, selection of climbing mechanism is required. More importantly is the ability to traverse or transition between planes as well as stability in discontinuous surfaces. Changing from planes is a very challenging task in climbing robots and if not properly investigated, instability could lead to weak adhesion forces which could result in detachment of the robot from the surface. If this occurs while inspection is ongoing on structures high above ground level, this could potentially result in damage to the system (Faíña et al., 2009), (Francke, 2012). Due to this requirement, the track/caterpillar system is adopted. This provided high traction and ease of implementation.

3.1.2. Adhesion requirement

The preferred adhesion mechanism must conform to industrial materials currently used. Most industrial structures as ferromagnetic in nature while most surfaces are generally uneven, rough, rusted or fluid stained and some might be corroded to varying degree. Hence the preferred solution adopted is the magnetic adhesion system using rare earth neodymium magnets.

3.1.3. Load requirement

In the investigation of structural health conditions, appropriate sensors and actuators are required to be mounted on the robot platform which are the main equipment form which relevant data can be obtained. The robot must therefore be capable of supporting a reasonable weight of inspection payload capacity and instruments such as camera, ultrasonic probes and environmental sensing probes

3.1.4. Performance requirement

- The robot should be light weight and mobile for easy transportation and setup.
- Robot should be able to move at constant speed with multi directional motion ability to change direction at any point.
- Integrate inspection sensors which can support water and dust ingress without compromising data,
- Maintain inspection alignment
- Robot must have enough traction to function on wet surfaces irrespective of positional orientation
- Robot should also be able to navigate generally occurring obstacles such as joints, weld points etc. up to a height of 20 mm without loss of adhesion.

3.2. Mechanical development concept

In designing the locomotion mechanism of this project, major consideration was given to climbing mechanism which could best be employed in the navigation of ferromagnetic structures usually found in most industrial setup. Attachment to structures will determine the robots' scope of inspection which counts towards performance of the system as well as current requirement expected of inspection systems.

Magnetic adhesive systems tend to have greater adhesive force for every unit area in contact with the structure. This force is ten times greater on ferromagnetic structures. To this effect, a compact system is required as the addition of magnets in this thesis will be on predesigned tracks.

The mechanical design of this project is divided into four basic phases

- Robot arm design
- camera mount design
- Chassis design
- Magnetic adhesion design

3.3. Automated visual inspection

This section focuses on the Automated Visual Inspection (AVI) of defects using machine learning and computer vision equipped on the robot. This form of inspection can be used in assessing surfaces which will be difficult to assess by human operators such as high pressure or radiation environments and other areas where a direct unobstructed view of the inspection plane cannot be obtained without the use of optical instruments or device such as microscopes, telescope and the more use of digital cameras more recently. The robot which holds a mounted camera to provide real time analysis of sections to be inspected. The image feedback is then analysed to build up an automated defect classification system based on extracted features of the surface captured, training image set as well as the application of statistical inference algorithms.

3.3.1. Inspection methodology

In the inspection of structures, there is a similar configuration across all setup which involves the illumination of the target through either natural lights or other means, this illuminate's scene is then captured by the camera to generate a digital image governed by the incorporated camera lens which introduces a field of view of the areas to capture this digital image is then sent for processing to generate a final description of the inspected surface.

It can therefore be seen that the AVI systems are usually made of two major which are the real time capturing and the processing subsystems. The former is majorly hardware based and consist of the digital camera, source of illumination etc. while the latter is majorly software based to analyse and gives an indication of surface conditions.

4. Results & discussion

In order to have a better understanding of the various forms of motion and translational displacement, the robot arm was analysed using MATLAB Sim-mechanics to determine its performance which forms the basis for understanding the arm kinematics of the system for future autonomous operation. Furthermore, the results of the robot's performance and vision application are briefly summarised

4.1. Robot arm analysis

The kinematic analysis and arm simulations were done using MATLAB peter Corke's Robotic toolbox, which simplifies the required task of analysing the arm kinematics. The arm kinematics and dynamic were based on the general Denavit-Hartenberg (DH) notation.

The DH parameters as described explicitly by the structure of the implemented robot arm used to create a vector of link object is seen in the table 1 below

Table 1. link parameters for the robot arm

Joint (i)	Joint Angle (θ_i)	Distance (d_i mm)	Length ($\alpha_i\ mm$)	Twist Angle ($\alpha_i\ deg$)
1	θ_1	70	0	90
2	θ_2	0	105	0
3	θ_3	0	128	0
4	θ_4	0	70	0
5	θ_5	0	0	-90
6	θ_6	10	0	0

Where the angle of the joints is all variables given the revolute joints in the system, the value of zero in the table are only placeholders for the joint variables.

The forward and inverse kinematics of the arm has been successfully implemented on the robot using Peter Corke's MATLAB robotic toolbox as earlier presented. This provides a reliable and accurate method to ensure smooth and continuous operation of the arm. The joints position for the inverse kinematics was done in such a way as to avoid unnecessary redundancies which are usually exploited when the arm reaches its limits.

In controlling the arm, the modes of control adopted is the wireless computer control where the operator can determine the robot position by manually setting the angles of the end effector through a slider widget on the remote computer which involved the forward kinematics without the need for further angular estimation. This gives the operator a higher degree of robot control as necessitated by the uncertainty of its final application.

4.2. Robot performance

The final robot model (figure 1) had a total dimension of 320 mm X 250 mm X 160 mm excluding the mounted robot arm for the first model, while the second robot was 300 mm X 180 mm X 100 mm. This falls within the range of existing inspection robots which are commercially available. Additionally, the total weight of the full assembly was 6.2 Kg and 2.2 kg, respectively. This values of size to weight factors, therefore offers for the application of the designed model where requirements for autonomous control as well as installation of additional payloads for inspections and testing are needed.

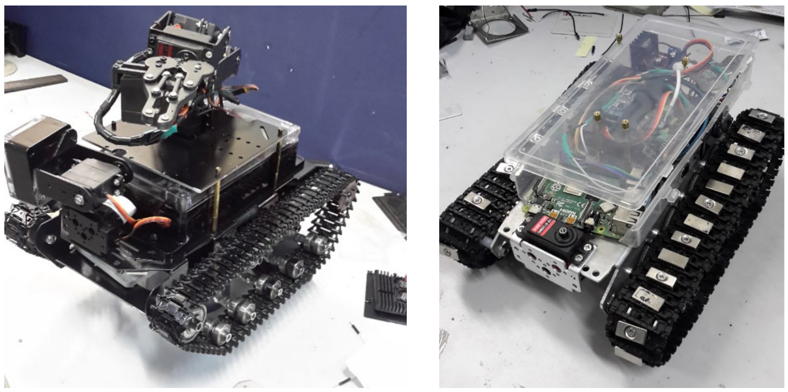

Figure 1. Robots 1 and 2 model

Given that the robot was designed to fulfil a variety of task, a generic design was selected as equipped with both computational capabilities as well as communication and long-range control with the requirement of a minimum level of control. All parts and equipment were therefore based on the commercially available items which makes them easily replaceable as well as upgradable as deemed fit by the end-users.

The track locomotion system provides sufficient ground contact area which increases frictional force. This allows it to navigate most terrain that could be encountered in the industry although only limited by the speed of operation. Locomotion was tested on a variety of environment ranging from smooth ground to unstructured and grassy terrain with successful outcomes howbeit a slight variation in operational speed which is shown in table 2. The first robot had a slower speed across horizontal surfaces with its top speed given as 0.88km/h on smooth cemented and asphalt surfaces. This top speed reduced to 0.8km/h for a grassy terrain and the variation between the time values derived from the experiments was due to the uneven nature of the testing environment causing the robot to slightly deviate from a straight-line path. It was also was successfully able to navigate incline planes of up to 35 degrees. The second robot, on the other hand, had far better speed on a horizontal and inclined plane with maximum top speed of 2.97 Km/h and vertical inclined navigation up to 150 degrees as shown in table 3. Finally, the robots were able to navigate obstacles up to 60mm and 10 mm respectively without loss of adhesion.

Table 2. Average time for 4m top speed experiment

S/N	Robot 1 Ave. Time (s)			Robot 2 Ave. Time (s)		
	cement	Asphalt	Dry grass	cement	Asphalt	Dry grass
1	16.39	15.58	17.67	5.96	4.60	6.82
2	15.96	17.24	17.99	6.04	5.20	6.98
3	16.85	16.45	18.01	5.90	4.84	6.50
4	16.30	15.25	17.62	6.09	4.93	7.01
5	16.64	17.01	18.34	6.03	4.68	6.94
AVE	**16.43**	**16.31**	**17.93**	**6.00**	**4.85**	**6.85**
Speed (m/s)	**0.24**	**0.25**	**0.22**	**0.67**	**0.82**	**0.58**
Speed (Km/h)	**0.88**	**0.88**	**0.80**	**2.40**	**2.97**	**2.10**

Table 3. Inclined speed test for robots (1m)

S/N	Robot 1 inclined Test on Wood			Robot 2 inclined Test on Steel				
	10^0	**20^0**	**30^0**	**30^0**	**60^0**	**90^0**	**120^0**	**150^0**
1	6.25	7.53	10.23	2.98	3.57	5.02	6.30	8.00
2	6.53	7.40	10.79	3.20	3.85	5.07	6.18	7.75
3	6.47	7.51	10.78	2.80	3.56	4.54	5.99	8.07
4	6.39	7.67	10.20	2.92	3.24	5.30	6.50	7.93
5	6.46	7.66	10.26	3.21	3.80	5.33	6.40	7.99
AVE	**6.42**	**7.55**	**10.45**	**3.02**	**3.60**	**5.05**	**6.27**	**7.95**
Speed (m/s)	**0.16**	**0.13**	**00.10**	**0.33**	**0.28**	**0.20**	**0.16**	**0.13**
Speed (Km/h)	**0.56**	**0.48**	**00.34**	**1.19**	**1.00**	**0.71**	**0.57**	**0.45**

4.3. Defect identification

The robot was tested using images which were not used in the training process as well as live field testing. In training the dataset, the training algorithm was set to perform 6000 iterations of the complete dataset, which is equivalent to 1000 iterations for one epoch.

The resulting accuracy of the model reached 91% average precision (figure 2a) which is much better when compared to the previous versions trained in the preceding versions of YOLO before YOLOv4. This makes detecting object, which is relatively small improved for crack identification. On the other hand, the detection system was more accurate in identifying corrosion which does not cover up an entire surface (see figure 2b).

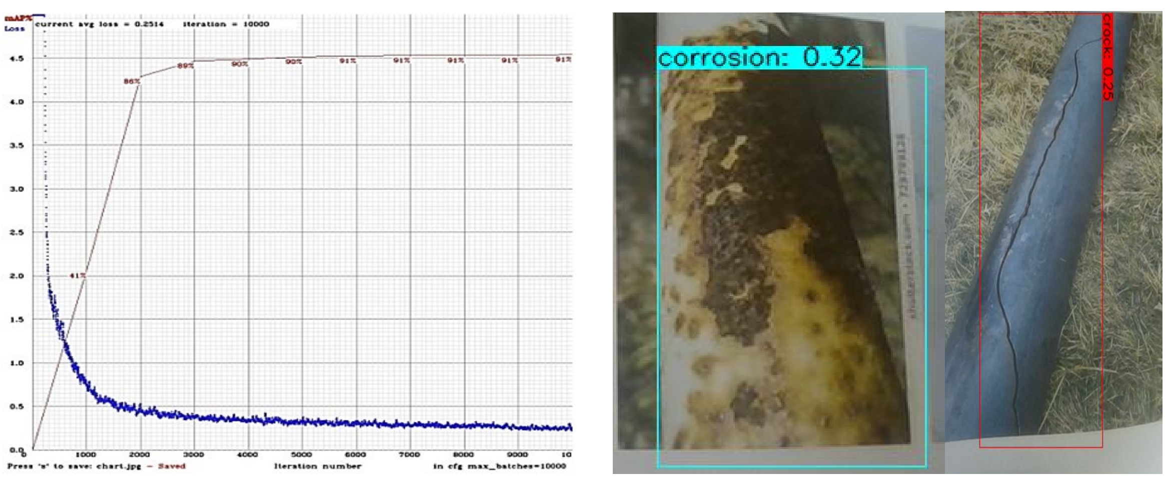

Figure 2. (a) Training iterations and precision (b) Sample detections

The major source of errors encountered was due to improper data annotation and arrangements for training even though there is no defined rule for image annotations. A more precise model will require annotation on the exact item to be identified with little or no interference from other background images and noise.

4.4. Magnetostatics analysis

For vertical robot navigation over ferromagnetic structures, the robot is expected to support both its weight as well as the total weight of additional payload without compromising adhesive force of attachment to the walls which are generated by the neodymium magnets attached to the tracks of the robot.

Design optimising of the required adhesive force was simulated using Electromagnetic Simulation Software by EMWORKS (EMS 2017) to determine the optimal magnet type, shape as well as other parameters based on an analysis of the magnetic flux variation under different conditions such as varying distance between magnets, air gaps etc. after which, validation experiments were done to determine the validity of the simulated results.

The effect of varying airgap on the magnetic/adhesion properties was simulation for varying airgap of up to 5mm while two magnets are kept at a constant distance of 20mm. The figure 3 below shows that a minimum airgap is tolerable to prevent slip and rollover of the robot.

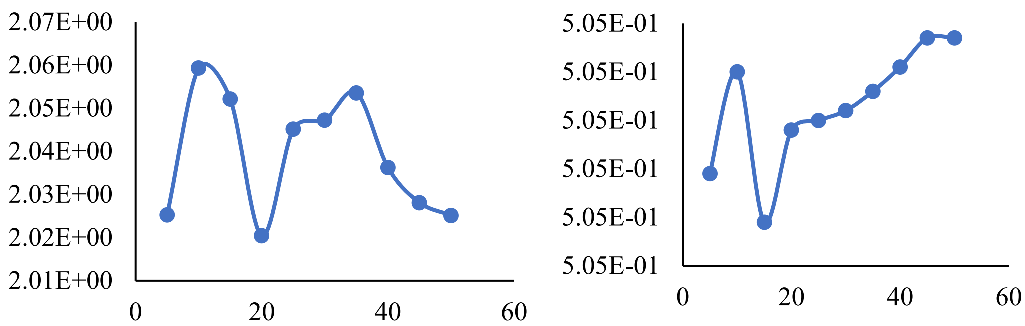

Figure 3. varying air gap (a) Maximum flux density (b) Magnetic energy

The effect of the inter-magnet distance on the adhesion force of the robot was varied from 5 mm to 50 mm at a fixed air gap of 5 mm. The field intensity using the different magnets arrangements shows that maximum field intensity is observed at 12 mm which declines and oscillates in a repeated pattern. Similarly, the maximum magnetic force density is also observed at a distance of 10 mm between magnets, as seen in figure 4 below. The result of this simulation shows that the optimum magnet distance is between 10 mm to 15 mm.

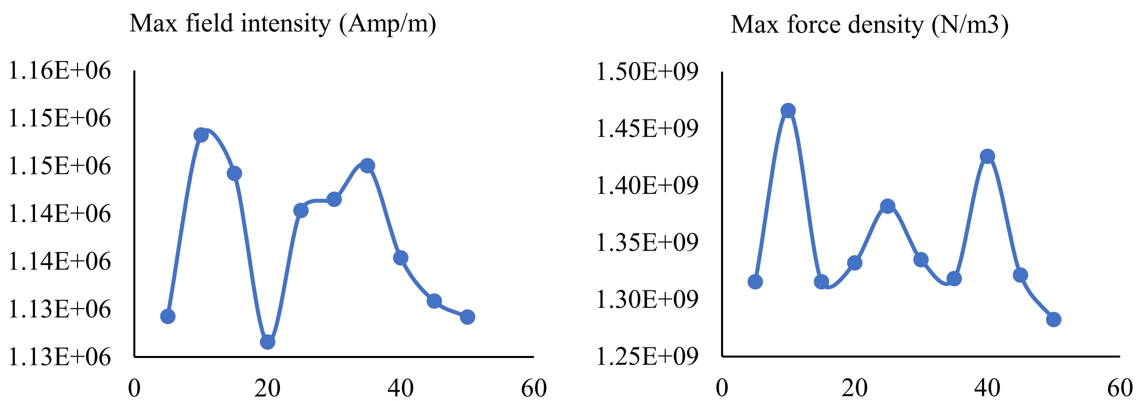

Figure 4. varying magnet distance (a) Field intensity (b) Force density

The thickness of the magnet, as well as magnet width and yoke thickness, also affect the resultant adhesive force which is desired. While keeping other factors constant and varying the magnet width, this increases the weight of the magnet's unit. The result shows that the energy density of the magnet increases with increasing width up to 20 mm before it peaks and subsequently decreases.

Similarly, the yoke thickness effect on the magnetic force shows an increase in adhesion force with increasing yoke thickness as well as a reduced flux leakage. However, after optimum thickness is observed, a corresponding loss of adhesion on the steel plate with a thickness greater than 20mm is observed. Figure 5 below.

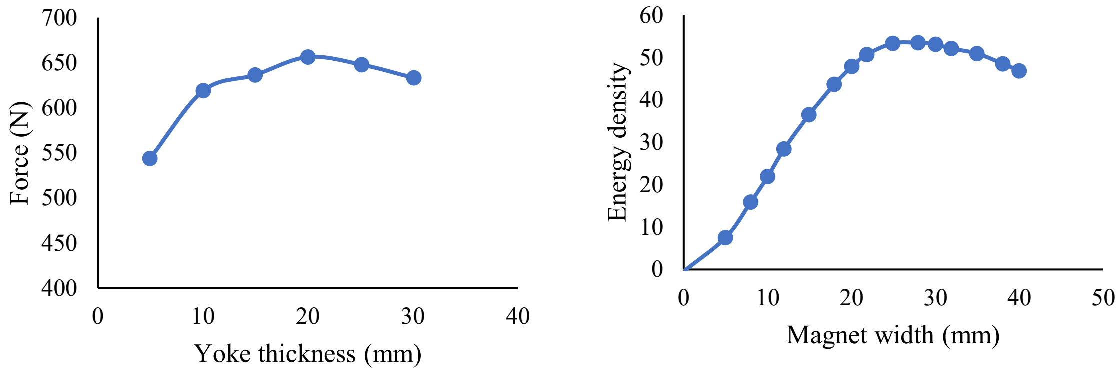

Figure 5. Effect of yoke thickness and magnet width on adhesion

5. Conclusion & future work

This thesis synopsis contains the design and construction of a climbing robot for utilisation in ferromagnetic industrial environments. In achieving this aim, a set of model parameters with respect to the design variables was parameterized and used to derive a nominal design of the robot based on commercially available and accessible parts partially affected by Coronavirus pandemic. This nominal design was then used to derive a functional model while adhering to key parameters such as necessary magnetic induced adhesive force, robot speed, robot arm control etc. which were subsequently validated experimentally and by the aid of computer-aided simulation.

The six degrees of freedom robot arm installed introduced flexibility necessary to undertake some inspection and maintenance tasks therefore, the Denavit-Hartenberg's convention was used to analyse the robot arm and joints parameters. Additionally, the design of the robot was done with the consideration of future modifications to allow for use in other unrelated tasks such as retrieval, pipeline inspections, search and rescue etc. therefore due consideration was given towards ease of dismantling and parts modification or replacement.

The main onboard computer used was a raspberry pi 4B due to its high level of autonomy as well as advanced processing speed as its utilised a 4GB LPDDR4 RAM required for image and video processing. This connected the servo controller, LN298N motor driver, camera as well as the charging module and another necessary component for full functionality.

The defect identification system was achieved using an installed adjustable focus wide-angle fisheye lens camera mounted in front of the robot and controlled on a mounted pan and tilt mount. The trained model is based on open-sourced images of defects available online as well as from site visits, and the confidence threshold of the model was set at 25% for optimised detection.

Furthermore, choice of selecting the tracks system for the implementation of the permanent magnet adhesion base was based on consideration of factors such as power consumption, payload capacity, environment of operation as well as other variables. This system offered the flexibility and portability required for easy control by any operator even though when changing direction, there is a possibility of damage to structural coatings. From the validation test done, the robot was successfully able to navigate over small obstacles such as weld beams, joints, bolt and nuts etc. without compromising adhesive force needed to keep the robot firmly on the surface of the inspected structure. Furthermore, the static and dynamic forces were analysed under different working conditions to aid in the proper selections of magnets as well as determining the minimum forces required to prevent rollover, sliding down and rotating failure modes usually associated with climbing robots

Given the time limitation for this study, depth of knowledge as well as restrictions placed by the current pandemic, future improvements include but not limited to areas such as the prototype model development (chassis, hardware etc.) as well as electronic component and software optimisation.

References

Albitar, H., Ananiev, A., & Kalaykov, I. (2013). New concept of in-water surface cleaning robot. 2013 IEEE International Conference on Mechatronics and Automation, IEEE ICMA 2013. https://doi.org/10.1109/ICMA.2013.6618150

Armada, M. A., de González Santos, P., Berns, K., Braun, T., Hillenbrand, C., & Luksch, T. (2005). Developing Climbing Robots for Education. In Climbing and Walking Robots. https://doi.org/10.1007/3-540-29461-9_96

Armada, M., Prieto, M., Akinfiev, T., Fernández, R., Santos, P. G. de, García, E., Montes, H., Nabulsi, S., Ponticelli, R., Sarriá, J., Estremera, J., Ros, S., Grieco, J., & Fernández, G. (2005). On the design and development of climbing and walking robots for the maritime industries. Journal of Maritime Research.

Asbeck, A., Dastoor, S., Parness, A., Fullerton, L., Esparza, N., Soto, D., Heyneman, B., & Cutkosky, M. (2009). Climbing rough vertical surfaces with hierarchical directional adhesion. Proceedings - IEEE International Conference on Robotics and Automation. https://doi.org/10.1109/ROBOT.2009.5152864

AZAIZ, R. (2010). UNIFIER – UNIFIED ROBOTIC SYSTEM TO SERVICE SOLAR POWER PLANTS. https://doi.org/10.1142/9789812835772_0136

Bahr, B., Li, Y., & Najafi, M. (1996). Design and suction cup analysis of a wall climbing robot. Computers and Electrical Engineering. https://doi.org/10.1016/0045-7906(95)00039-9

Balaguer, C., Gimenez, A., & Jordon, A. (2005). Climbing robots' mobility for inspection and maintenance of 3D complex environments. Autonomous Robots. https://doi.org/10.1007/s10514-005-0723-0

Boscariol, P., Henrey, M. A., Li, Y., & Menon, C. (2013). Optimal Gait for Bioinspired Climbing Robots Using Dry Adhesion: A Quasi-Static Investigation. Journal of Bionic Engineering. https://doi.org/10.1016/S1672-6529(13)60193-6

Carlo, M., & Metin, S. (2006). A Biomimetic Climbing Robot Based on the Gecko. Journal of Bionic Engineering. https://doi.org/10.1016/S1672-6529(06)60015-2

Chang, J. I., & Lin, C. C. (2006). A study of storage tank accidents. Journal of Loss Prevention in the Process Industries, 19(1), 51–59. https://doi.org/10.1016/j.jlp.2005.05.015

Chen, R., Liu, R., & Shen, H. (2013). Design of a double-tracked wall climbing robot based on electrostatic adhesion mechanism. Proceedings of IEEE Workshop on Advanced Robotics and Its Social Impacts, ARSO. https://doi.org/10.1109/ARSO.2013.6705531

Cor-Pro Systems. (2013). Case Study: How Corrosion's Economic Impact Across Multiple Industries - Cor Pro. http://www.cor-pro.com/case-study-corrosions-economic-impact-across-multiple-industries/

Daltorio, K. A., Wei, T. E., Horchler, A. D., Southard, L., Wile, G. D., Quinn, R. D., Gorb, S. N., & Ritzmann, R. E. (2009). Mini-whegsTM climbs steep surfaces using insect-inspired attachment mechanisms. International Journal of Robotics Research. https://doi.org/10.1177/0278364908095334

Elkmann, N., Felsch, T., Sack, M., Saenz, J., & Hortig, J. (2002). Innovative service robot systems for facade cleaning of difficult-to-access areas. IEEE International Conference on Intelligent Robots and Systems. https://doi.org/10.1109/IRDS.2002.1041481

Elsevier's R&D Solutions for Oil and Gas. (2018). Don't let corrosion put holes in your net gains.

Faíña, A., Souto, D., Deibe, A., López-Peña, F., Duro, R. J., & Fernández, X. (2009). Development of a climbing robot for grit blasting operations in shipyards. Proceedings - IEEE International Conference on Robotics and Automation. https://doi.org/10.1109/ROBOT.2009.5152584

Francke, J. (2012). A review of selected ground penetrating radar applications to mineral resource evaluations. Journal of Applied Geophysics. https://doi.org/10.1016/j.jappgeo.2011.09.020

Guo, W., Zhong, M., Li, M. T., & Li, Y. (2008). Design of a six legged wall-climbing robot. Proceedings of IEEE Workshop on Advanced Robotics and Its Social Impacts, ARSO. https://doi.org/10.1109/ARSO.2008.4653597

H. Koch, G., P. H. Brongers, M., G. Thompson, N., P. Virmani, Y., & H. Payer, J. (2001). CORROSION COSTS AND PREVENTIVE STRATEGIES Publication No . FHWA-RD-01-156. Corrosion.

Hongjun, C., Weihua, S., Ning, X., & Jindong, T. (2005). Motion control of a micro biped robot for nondestructive structure inspection. Proceedings - IEEE International Conference on Robotics and Automation. https://doi.org/10.1109/ROBOT.2005.1570164

Huang, H., Li, D., Xue, Z., Chen, X. L., Liu, S., Leng, J., & Wei, Y. (2017). Design and performance analysis of a tracked wall-climbing robot for ship inspection in shipbuilding. Ocean Engineering, 131(March), 224–230. https://doi.org/10.1016/j.oceaneng.2017.01.003

Kalra, L. P., Gu, J., & Meng, M. (2006). A wall climbing robot for oil tank inspection. 2006 IEEE International Conference on Robotics and Biomimetics, ROBIO 2006. https://doi.org/10.1109/ROBIO.2006.340155

Kennell, G. F., Evitts, R. W., & Heppner, K. L. (2008). A critical crevice solution and IR drop crevice corrosion model. Corrosion Science. https://doi.org/10.1016/j.corsci.2008.02.020

Koh, K. H., Kuppan Chetty, R. M., & Ponnambalam, S. G. (2011). Modeling and simulation of electrostatic adhesion for wall climbing robot. 2011 IEEE International Conference on Robotics and Biomimetics, ROBIO 2011. https://doi.org/10.1109/ROBIO.2011.6181590

Lee, D. G., Oh, S., & Son, H. Il. (2016). Maintenance Robot for 5-MW Offshore Wind Turbines and its Control. IEEE/ASME Transactions on Mechatronics. https://doi.org/10.1109/TMECH.2016.2574711

Liu, Y., Sun, S., Wu, X., & Mei, T. (2013). A leg-wheel wall-climbing robot utilizing bio-inspired spine feet. 2013 IEEE International Conference on Robotics and Biomimetics, ROBIO 2013. https://doi.org/10.1109/ROBIO.2013.6739732

Luk, B. L., White, T. S., Cooke, D. S., Hewer, N. D., Hazel, G., Chen, S., Centre, B., & Gl, G. (2001). Climbing Service Robot for Duct Inspection and Maintenance Applications in a Nuclear Reactor. International Symposium on Robotics.

Miller, J. (2004). Robotic systems for inspection and surveillance of civil structures. May.

Mondal, S., Sattar, T. P., & Bridge, B. (2002). TOFD inspection of V-groove butt welds on the hull of a container ship with a magnetically adhering wall climbing robot. 5th International Conference on Climbing and Walking Robots and Their Supporting Technologies (CLAWAR 2002).

Padrón, V. M., Giménez, A., Balaguer, C., Abderrahim, M., & Pastor, J. M. (2002). A climbing autonomous robot for inspection applications in 3D complex environments. Robotica. https://doi.org/10.1017/s0263574799002258

Papavinasam, S. (2013). Corrosion Control in the Oil and Gas Industry. In Corrosion Control in the Oil and Gas Industry. https://doi.org/10.1016/C2011-0-04629-X

Perelli, A., De Marchi, L., Marzani, A., & Freear, S. (2013). Compressive Sensing for Damage Detection in Composite Aircraft Wings. Structural Health Monitoring 2013, Vols 1 and 2.

Ratnayake, R. M. C. (2012). Modelling of asset integrity management process: a case study for computing operational integrity preference weights. International Journal of Computational Systems Engineering. https://doi.org/10.1504/ijcsyse.2012.044738

Saiigdeok Park, Hee Don Jeong, & Zhong Soo Lim. (2004). Design of a mobile robot system for automatic integrity evaluation of large size reservoirs and pipelines in industrial fields. https://doi.org/10.1109/iros.2003.1249265

Sánchez, J., Vázquez, F., & Paz, E. (2006). Machine vision guidance system for a modular climbing robot used in shipbuilding. Proceedings of the 8th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, CLAWAR 2005. https://doi.org/10.1007/3-540-26415-9-107

Sattar, T. P., Rodriguez, H. L., & Bridge, B. (2009). Climbing ring robot for inspection of offshore wind turbines. Industrial Robot. https://doi.org/10.1108/01439910910957075

Schmidt, D., Hillenbrand, C., & Berns, K. (2011). Omnidirectional locomotion and traction control of the wheel-driven, wall-climbing robot, CROMSCI. Robotica. https://doi.org/10.1017/S0263574711000294

Seo, T. W., & Sitti, M. (2011). Under-actuated tank-like climbing robot with various transitioning capabilities. Proceedings - IEEE International Conference on Robotics and Automation. https://doi.org/10.1109/ICRA.2011.5979533

Shen, W., Gu, J., & Shen, Y. (2015). Permanent Magnetic System Design for the Wall-Climbing Robot. Applied Bionics and Biomechanics. https://doi.org/10.1155/2006/143256

Shores, B. E., & Minor, M. A. (2005). Design, kinematic analysis, and quasi-steady control of a morphic rolling disk biped climbing robot. Proceedings - IEEE International Conference on Robotics and Automation. https://doi.org/10.1109/ROBOT.2005.1570525

Speight, J. G. (2014). Oil and Gas Corrosion Prevention: From Surface Facilities to Refineries. In Oil and Gas Corrosion Prevention: From Surface Facilities to Refineries. https://doi.org/10.1016/C2013-0-18548-0

Tâche, F., Fischer, W., Caprari, G., Siegwart, R., Moser, R., & Mondada, F. (2009). Magnebike: A magnetic wheeled robot with high mobility for inspecting complex-shaped structures. Journal of Field Robotics. https://doi.org/10.1002/rob.20296

TERENCE BELL. (2019). What Is Metal Corrosion and Why Does It Occur? https://www.thebalance.com/what-is-corrosion-2339700

Unver, O., Uneri, A., Aydemir, A., & Sitti, M. (2006). Geckobot: A gecko inspired climbing robot using elastomer adhesives. Proceedings - IEEE International Conference on Robotics and Automation. https://doi.org/10.1109/ROBOT.2006.1642050

Wang, C. S., Li, H. J., & Wang, R. Q. (2010). Study of the wall-climbing robot for hull painting. 2010 International Conference on E-Product E-Service and E-Entertainment, ICEEE2010. https://doi.org/10.1109/ICEEE.2010.5660986

Wang, M., Qi, Y., Jiang, W., Li, S., Cheng, H., Bao, J., & Lu, L. (2013). Research on omni-directional moving adsorption mechanism and its application in wall-climbing robot. 2013 IEEE 3rd International Conference on Information Science and Technology, ICIST 2013. https://doi.org/10.1109/ICIST.2013.6747539

Wang, W., Zhang, H. X., Yu, W. P., Zong, G. H., & Zhang, J. W. (2007). F & A compensating variable bang-bang control algorithm for pneumatic driving glass-wall cleaning robot. IEEE International Conference on Intelligent Robots and Systems. https://doi.org/10.1109/IROS.2007.4398957

Wang, Z. H., Bao, G. J., Zhang, L. Bin, & Yang, Q. H. (2009). Development and control of flexible pneumatic wall-climbing robot. Journal of Central South University of Technology (English Edition). https://doi.org/10.1007/s11771-009-0160-x

Wu, S., Wu, L., & Liu, T. (2011). Design of a sliding wall climbing robot with a novel negative adsorption device. URAI 2011 - 2011 8th International Conference on Ubiquitous Robots and Ambient Intelligence. https://doi.org/10.1109/URAI.2011.6145940

Xiao, J., & Sadegh, A. (2012). City-Climber: A New Generation Wall-Climbing Robots. In Climbing and Walking Robots: towards New Applications. https://doi.org/10.5772/5090

YI, Z. (2010). Dynamic Modeling and Analysis on a New Type Wall-climbing Robot for Ship Wall Rust Removal. Journal of Mechanical Engineering. https://doi.org/10.3901/jme.2010.15.023

Yoshida, Y., & Ma, S. (2011). A wall-climbing robot without any active suction mechanisms. 2011 IEEE International Conference on Robotics and Biomimetics, ROBIO 2011. https://doi.org/10.1109/ROBIO.2011.6181587

Yunovich, M., Thompson, N. G., Balvanyos, T., Lave, L. (2001). Corrosion Costs and Preventative Strategies in the United States (FHWA-RD-01-156). In FHWA.

Zhao, Y., Fu, Z., Cao, Q., & Wang, Y. (2004). Development and applications of wall-climbing robots with a single suction cup. Robotica. https://doi.org/10.1017/s0263574704000517

Biography

Peter Oyekola is a graduate student at the Papua New Guinea University of Technology, Lae Morobe in the department of Mechanical Engineering. He completed his Bachelor’s Degree in Mechanical Engineering from Bells University if Technology Nigeria where he was a recipient of the Chevron undergraduate scholarship for the entire duration of his study. Similarly, he is currently sponsored by the Queen Elizabeth Commonwealth Scholarship for his Master’s degree program where he focuses on research areas such as automation, Structural Health Monitoring, Robotic, and design for manufacture.