Application of Computer Vision in Pipeline Inspection Robot

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Abstract

Industrial Structures such as pipes develop issues over time which are primarily due to ageing, corrosion, cracks, or other forms of mechanical defects which could potentially lead to leakages or further uncontrollable fatal occurrences. As a result, inspections of such industrial structures are therefore of extreme importance. While prevailing inspection techniques are usually sensor based, time-consuming and labour-intensive, the application of robotic systems significantly reduces the human effort required for the same level of inspection. In this paper, implementation of a vision-based approach and a suitable low-cost solution was developed for detecting defects in industrial structures such as pipelines and hollow cylindrical structures. The camera embedded in the robot is used to identify defects such as cracks, corrosion and blockage in real time through a systematic algorithm of dataset training (1500 datasets) representing these conditions. This paper also focuses on the modelling and analysis of the dataset training of a pipeline inspection robot. The machine vision system thus developed was capable of effectively detecting defects even in low light conditions with a mean average precision of 91%.

Keywords
Computer Vision, Inspection, Pipeline, Robot and SolidWorks

1. Introduction

Pipelines are the safest means by which oil, gases and other fluids such as chemicals are transported and distributed. however, structural issues often arise such as cracks and corrosion which causes progressive degradation and disintegration over time (Kiran et al., 2017). This progressive deterioration also increases the probability of failure (fatigue cracking). In an effort to prevent structural failure, companies are required to perform periodic inspections of all critical facilities (Kamsu-Foguem, 2016). Existing inspection method often involved physical evaluation by skilled personnel, high inspection cost (Oyekola, Mohamed, et al., 2019) for inspection of structures in high risk locations such as working at height, confined spaces, toxic environment etc. this therefore makes inspection a painful and enduring task which also affects work flow. Additionally, exact and solid assessment of pipelines are sometimes required for more stringent controls and escalated financial weight (Casal, 2017).

In an effort to find a solution of this existing inspection technology, companies now seek for solution which would not affect or interfere with regular operational run. Additionally, adequately dependable and accurate examination results can only be gotten by direct contact or access to the inspection surface and if this isn't plausible from an external perspective, there will need for internal inspection. Sometimes, physical access to these structures might not be possible due to sizing constraint. However, a pipe inspection robot is a welcome development in the field of robotics which provides answers for inaccessible pipeline systems (Oyekola, Lambrache, et al., 2019).

Robotics is a robust developing engineering fields as they provide solutions which surpasses human limitations such as fatigue, stress ability to function in toxic environments, tight spaces etc. (Lattanzi & Miller, 2017). The utilization of robot is more normal these days than at any other time and it is not, at this point only utilized by heavy production industries given that integrity threats form serious safety concerns which are often required to be addressed on time.

In mitigating these threats, there is a need for an internal inspection tool which is capable of incorporating relevant technologies and sensors in order to effectively detect these anomalies (Xie et al., 2018).

Robots versatile mechanical frameworks are discovering their way into a wide range of situations into which past frameworks couldn't venture. Portable robots have the ability to perform different investigation errands in a given domain without being settled to one area (Seeja et al., 2018). An ever-increasing number of versatile mechanical frameworks are supplanting difficult, hazardous, or bulky duties that were previously done by human workers. This is on the grounds that innovation, for example, robot vision, discernment, detecting and instrumentation keeps on enhancing with technology on a daily basis due to an exponential development in computing power especially on mobile computers.

In this paper, both the study of pipe inspection robots and design of such robots to inspect pipes, checking pipe integrity and detecting cracks is carried out. This study will also be useful for inspection of water pipelines, plumbing, sewer inspection, etc.

2. Literature review

Several robotic systems have been designed for the purpose of pipeline inspection. Some of the varieties such as Cartesian, round and hollow robot, polar robot, SCARA robot, articulated robot (Spielberg et al., 2017), and parallel robot can deal with unsafe chemicals as well as other unfriendly environment with minimal or no disturbance to data acquisition (Bhaumik, 2018). Furthermore, the pipe robots are characterized into three fundamental classes dependent on their motion component; non-wheel, tracked and wheel-based systems. These dynamic driving systems have been successfully implemented in pipeline inspection as seen in the study of (Nayak & Pradhan, 2014) (Tur & Garthwaite, 2010).

2.1. Existing Inspection Robot

Practical inspection robots have been developed and studied by various researchers which employs a variety of functional mechanism (figure 1). An example of such is seen in the model developed by Oya et al which features a wheeled based steerable robot which is based of passive pressure applied to the internal walls of the pipes for movement (Oya & Okada, 2005). Bradbeer model on the other hand was based on a legged system which was activated and controlled via a pneumatic actuator to aid robot positioning as well as navigation (Bradbeer et al., 1997). As stated by Amr, robots which are based on the actuated legged principle for locomotion allow for a wider range and possibility of motion due to the large degree of freedom associated with multi legged systems. The shortcoming to this method however is the complexity of control well as large number of required actuators (Bekhit et al., 2012).

Choi et al (Choi et al., 2010) design, was based on the use of an inchworm locomotion mechanism which allows sliding motion as well as pipe gripping, translational as well as rotational functionalities of the robot. This mechanism could only be used for external inspection in this case but other studies have successfully been able to modify this mechanism for internal inspection requirements (Anthierens et al., 1999) (Fang et al., 2018; Hayashi et al., 2020; Ikeuchi et al., 2012; Kusunose et al., 2020; Ogai & Bhattacharya, 2018; Takagi et al., 2019). Ankit and Pradhan (Nayak & Pradhan, 2014) developed a screw type mechanism for their pipe inspection robot which is composed of a stator and a rotor that has elastic arms mounted with wheels attached to it; they proposed that better choice of the locomotion mechanism of an internal pipeline inspection robot is the screw type due to the fact that it has many advantages compared to other mechanism.

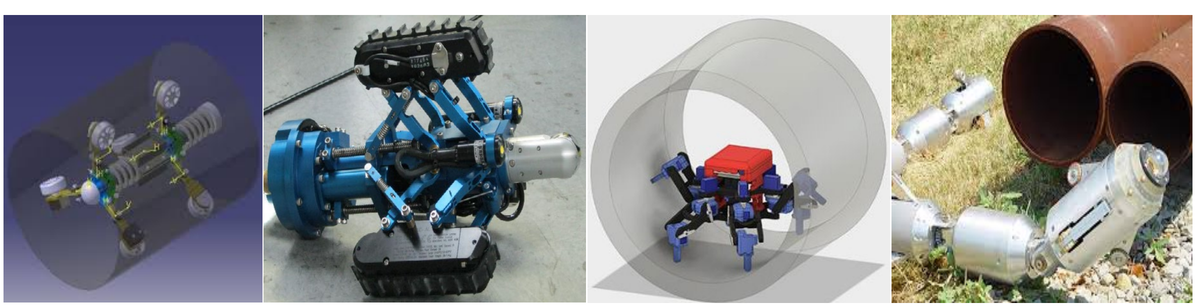


Figure 1. Various locomotive mechanism applied in pipeline inspection

Of all the various robotic designs implemented in industrial use such as in petrochemical, water supply and liquid supply industries, there remains some reservation on the optimum mechanism to be implemented such as vision, dynamics and control, etc. the literatures above further proved that the most common pipeline robots were under three broad categories which are the wheeled, caterpillar and the non-wheeled locomotive configuration systems. The choice of preference however depends on a number of factors such as speed control, adaptability, frictional force required for adhesion, ease of deployment etc. A comparison of various inspection mechanism is shown below.

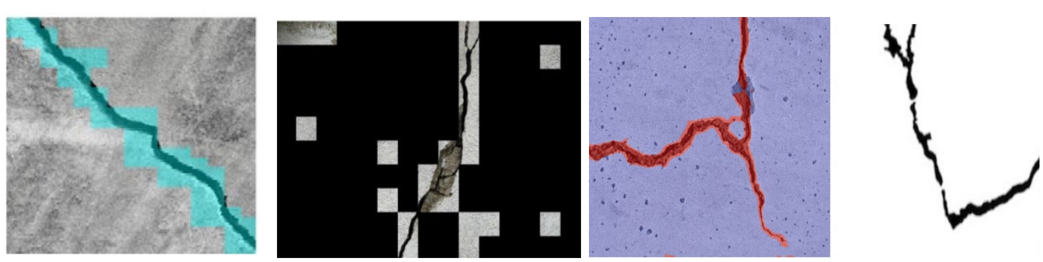
Table 1. Mechanism of pipeline robots' locomotive systems

	Wheeled	**Screw**	**Tracked**	**Legged**	**Worm**	**Snake**
Climbing	Moderate	High	Moderate	High	Moderate	Moderate
Steering Control	Moderate	Moderate	Moderate	High	Moderate	Moderate
Flexibility	Low	Moderate	Low	Low	High	High
Motion	Moderate	High	Moderate	High	High	Moderate
Actuators Required	Moderate	Low	Low	High	High	High
Control	Moderate	Moderate	Moderate	Low	Low	Low
Pipes Adaptability	Low	Moderate	Moderate	High	Moderate	High
Stability	Low	High	Moderate	Moderate	Moderate	Moderate

The table above showed that in the selection of locomotive mechanism, the screw adhesion system seemed to be on the average more adaptable and easier to implement than other mechanisms. For this reason, A passive screw adhesion and locomotion system have been adapted in this design.

2.2. Computer Aided Inspection

Traditionally, inspection for defects and quality control has been carried out by humans, especially skilful and experienced individuals. However, according to Mayuri and Ramesh (Shinde, 2016), this has a high probability of error occurrence, longer lead-time and less effectiveness in radioactive or toxic environment compared to computer aided inspection. Neethu and Anoop, stated that based on the functionality of computer version, most of its applications are categorized into three main groups; inspection, sorting and finally gauging (N.J. & B.K., 2015). Furthermore, C.Zimmerman (Czimmermann et al., 2020) concluded that apart from numerous techniques employed in computer version aid especially in terms of artificial image processing, Neural Network is deemed the most powerful technique but it requires datasets to be labelled. Recently, Sacco et al (Sacco et al., 2018) confirmed that Neutral Network or Convolution Neutral Network requires a larger training dataset, at least more than 300 samples would increase its efficiency. Nevertheless, an algorithm developed by Wang enables the Faster Region-based Convolution Neutral Network to operate at a faster speed and even detect defects that's are geometrically small; the new development is rated as 78% in terms of detection and 81% identification (Lu et al., 2018). For the most part, sample segregation or segmentation as well as detection abilities have been used in identifying objects as in figure 2



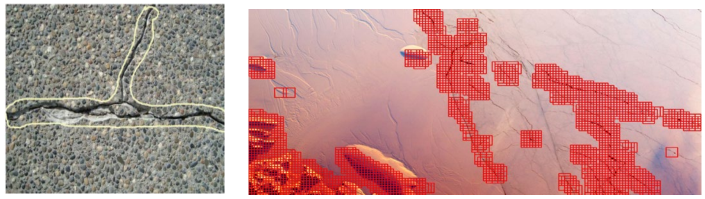


Figure 2. Sample crack segmentations and detection

3. Materials and Methods

The design and analysis of the pipe inspection robots heavy relies on results gotten from computer aided condition simulation using SolidWorks. The model of pipeline inspection robot in this paper is based on a passive adhesion and locomotion mechanism which utilizes springs for attachment to the internal surface of pipeline structures. The robot utilized three separate geared motor which independently controls the three mounted tracked wheels specifically chosen for ease of traversing pipeline bends and for control of tilt angle (figure 3). The three-degree of freedom provided by the geared actuators increased mobility which is supported by the springs mounted on each of the independent tracks. While the robots pitch varies based on the angle at which the wheel is tilted, the major kinematic assumptions however are that all three wheels mains in continuous contact with the pipes surface, negligible friction between tracks and hub also, it is assumed that the pipe walls is not deformable.

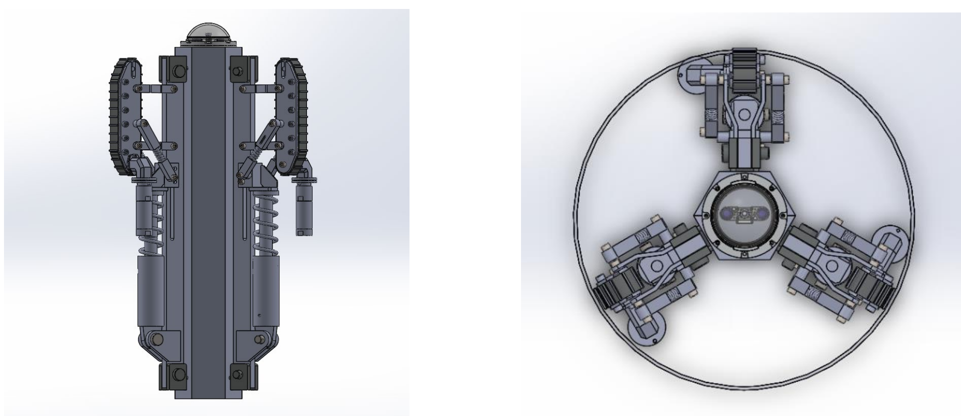


Figure 3. Side and top view of the robot

The designed platform showed in the figure above enables the robot acquire the necessary stability and rigidity associated with moderate speed navigation. While the slime line chassis or hub mount was designed to reduce drag, force exerted by fluids which will be flowing through the pipes. It also helps in effective distribution of robot mass towards the circular track array.

3.1. Image Processing

This paper involves the use of automated image processing to identify defects within pipelines and hollow cylinders. This was achieved using convolutional neutral network to our training datasets. For higher efficiency in defect recognition, a lot of sample data set is required and this was gathered mostly from the internet and from physical visits to industries with the purpose of obtaining practical images of the target defects. Furthermore, labelimg tool was used in annotating all the acquired data set which utilizes a coloured box to indicate the defects within a pipeline. The whole process of object detection using images processing involves an input (dataset), labelling, training and output (object detection) as shown in figure 4 below.

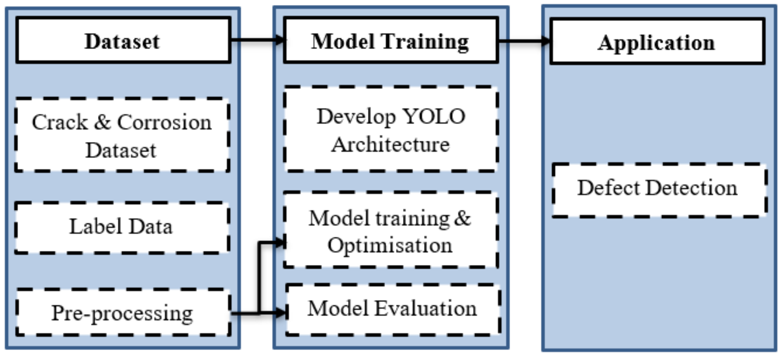


Figure 4. Implemented YOLOv3-Lite algorithm.

3.1.1. Input (Dataset)

The input or dataset contains about 1500 images of defects that can be found on interior surface of pipelines. It is also known as training dataset or training samples. The images that fit the requirements of our dataset were all downloaded from multiple research site. One of the main requirements is that the image file must be in just ".jpg", given that our training module recognize this image format only.

3.1.2. labelling

Labelling is the process that involves indicating a particular object from all the images in the dataset. This process was completed using "Labelimg" which allows importation and annotation of dataset. The object of interest can be annotated and labelled accordingly as shown in figure 5 below. After labelling the whole dataset, the labelled changes were saved in the same folder as the dataset as .txt file containing information about the class and the position of the object.

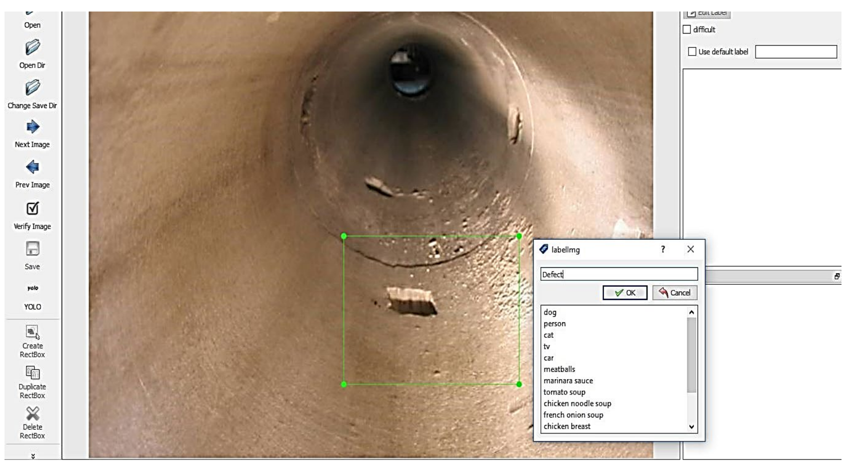


Figure 5. Dataset annotation using Labelimg

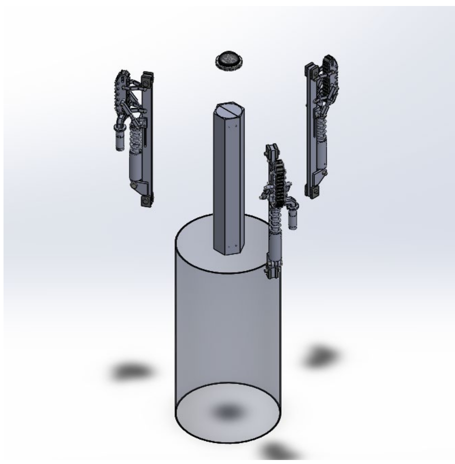
3.1.3. Training

In training the model to recognise defects, the Single Shot Detection (SSD) model was adopted. It is an open-source variety of the COCO-weighted models and it conveniently balances speed and performance during real time inspection with assistance from a GPU enabled computer. GPU's are very expensive; hence the model training was done on Google Collaboratory (Colab) which is a service provided by the Google offering free GPU for a 12-hour period plus a python editor which enabled uploading of training module (yoloV3) onto Colab with enabled GPU.

For the offline training, the file location containing the tf.records and other necessary files can be trained with a CPU or GPU enabled system. The files were extracted before the training initiated before checkpoints files were saved and locally backed up for subsequent evaluation. In testing the detection model, the camera was connected to the robot onboard computer (Raspberry Pi 4B). The model predictions of defects are then superimposed on the streaming video output which can be viewed from the operating station wirelessly.

3.2. Design and assembly

The design of the robot was entirely based on the use of SolidWorks 2018 Computer Aided Design software. This helped in analysis and simulation of operating conditions as well as analysing the possibilities of adapting different configuration setting for varying pipe sizes. The results of the conducted simulation ascertain the adaptability of the robot to pipes of various dimensions ranging from 150mm to 500mm. In the consideration of robot movement across pipe changing planes such as bends and joints, the robot wheels are designed such that the independently controlled tracks press against the internal surface of the pipe thereby providing sufficient grip and control in situations where a change of pipe diameter may be encountered (See figure 6 below). Additionally, the passive springs implemented in each wheel assembly helps in providing necessary tension to the surface which prevents slipping. This also ensures a wide conformity to industrial pipelines as well as flexibility.



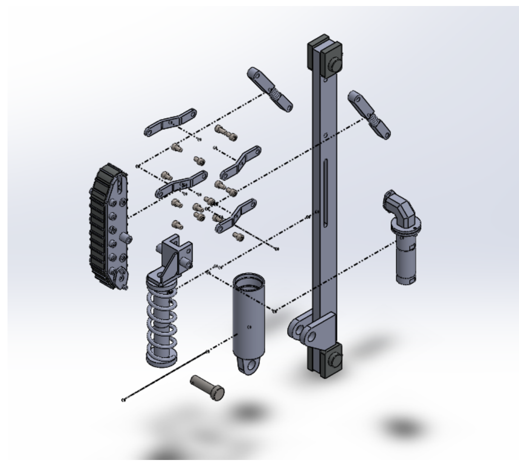


Figure 6. Exploded view of the robot (b) Arm assembly

The preferred material selected for the track was soft PLA. Although this is not the standard rubber, it shares similar properties and can be 3D printed without shrinking. The track design ensured for a larger area of contact with surface of the pipe. The threaded grooves displace fluid from the surfaces in contact to allow for increased friction which is desired in vertical and inclined movements. The sliding joints and linear actuators are made of cast stainless steel to avoid corrosion and is a prominent feature for this part.

4. Analysis & Discussion

In determining the optimal spring tension and stiffness, considerations of both vertical and horizontal scenarios were considered. In vertical orientation, the total wheel force amounts to the summation of the resultant horizontal component of the weigh and frictional force which occurs at the interface of the robot tracks and the internal pipe surface. An estimates robot weight of 5 Kg was used for simulation of forces. Spring stiffness (K) is given as;

$$k = \frac{spring\ force}{\max spring\ elongation} \quad (1)$$

While the spring proportion was estimated with shear stress of

$$\tau = \frac{8 \times F \times C}{\pi \times 4r^2} \quad (2)$$

Further analysis of the robot parts was carried out on SolidWorks simulation using the following specifications:

- Max Pipe Diameter = 500mm (20inches)
- Spring Tension on the Pipe wall = 3200N
- Compressive Force on the Linear Actuators due to spring Tension = 3200N

- Thickness of Pipeline = 5mm

For proper analysis, the model was simulated based on the assumptions that the robot will be used when there is little or no fluid in the pipeline, and the model is best suited for the inspection of straight pipes with capability of vertical movement without slipping from the surface. For these reasons, the study was carried out to determine the effect of the suspension tension on stress and deformation of the pipe wall as well as the effect of the suspension tension on the durability of the motor arm assembly.

The degree of freedom accompanying the selected configuration is indicated (figure 7) below (Kumar et al., 2019):

$$Total\ Degree\ of\ freedom\ =\ rigid\ body\ freedom - joint\ constraint \tag{3}$$

$$Dof = m(N-1) - \sum_{i=1}^{j} c_i = m(N-1-J) + \sum_{i=1}^{j} f_i \tag{4}$$

Where N is the number of bodies including the ground, J is the number of joints and m is six for spatial bodies and 3 for planer bodies

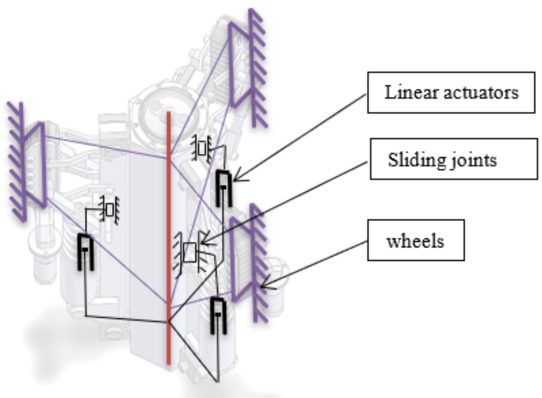


Figure 7. Robot's links and joints schematic

The motor assembly arm (figure 8b) is made of carbon stainless steel because of its anti-corrosion property. This part of the robot is exposed to the internal environment of the pipeline and it is assumed that fluid substances will still be present within the pipeline in small quantities even after been drained for inspection.

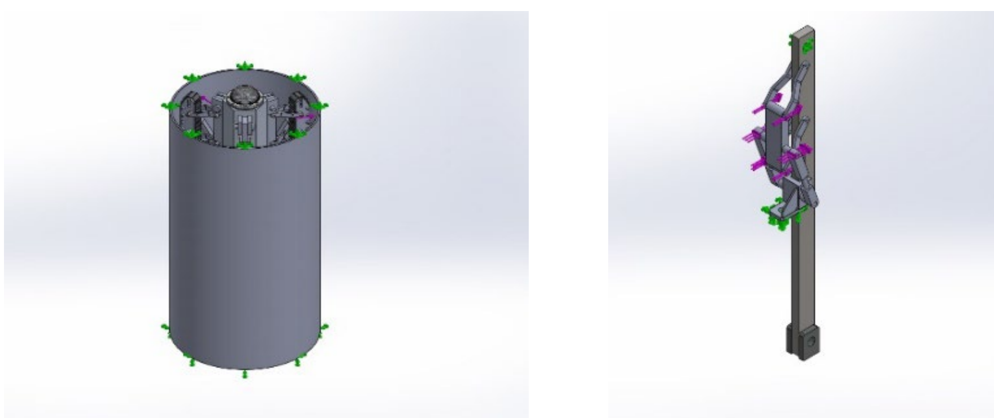


Figure 8. Simulation of forces exerted on the pipeline wall (b) Motor Assembly support Arm

4.1. Stress Analysis on the Pipe Wall

As shown in the figure 9 below, a force of 3200N was applied along the pipe wall and the result was a max von Mises Stress of 0.083MPa and a max displacement of 0.00009746mm. Uniform probing of the part surface was carried out and the result which represents the nodal stress and displacement respectively is subsequently plotted in figure 9 & 10

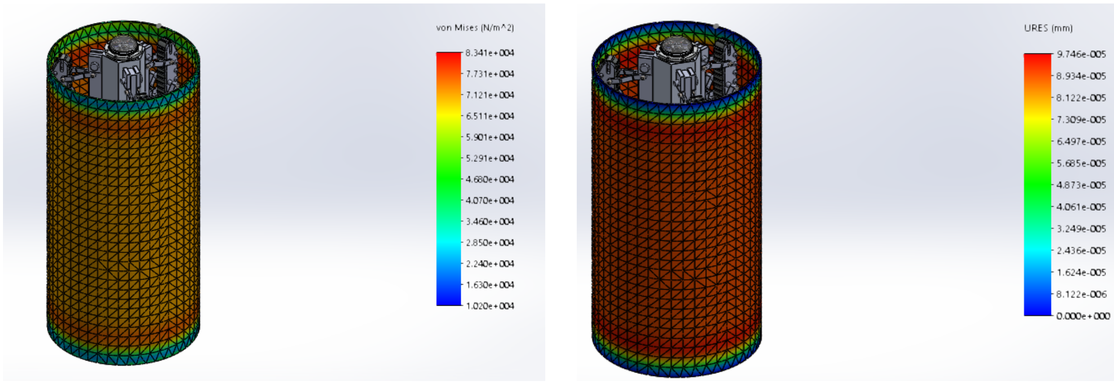


Figure 9. (a) Pipeline wall: Von Mises stress (b) Static Displacement

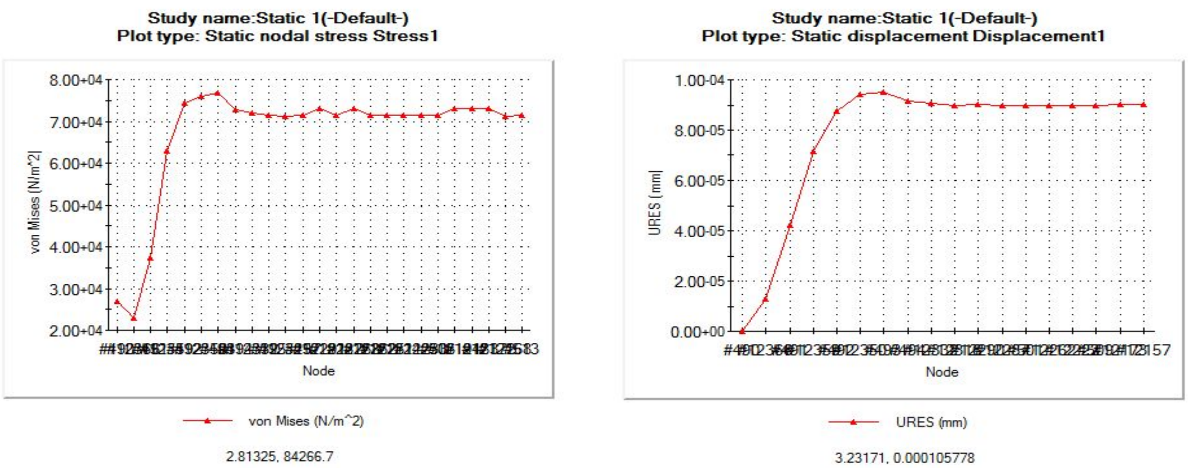


Figure 10. (a) Nodal stress distribution along pipe wall (b)Static Displacement

The pipeline averages around the Von Mises stress of 0.07MPa which is negligible and poses no threat because it is far lower than the Ultimate Tensile Strength of the material (which is 400MPa) and also produces an average displacement of 0.00008mm which is negligible.

4.2. Stress Analysis on the Motor Assembly Support Arm

This is the part that distributes the weight of the robot and aids in providing support for transmitting the tensile force from the spring. It is important to analyse this part to determine its ability to withstand tension from the spring suspension

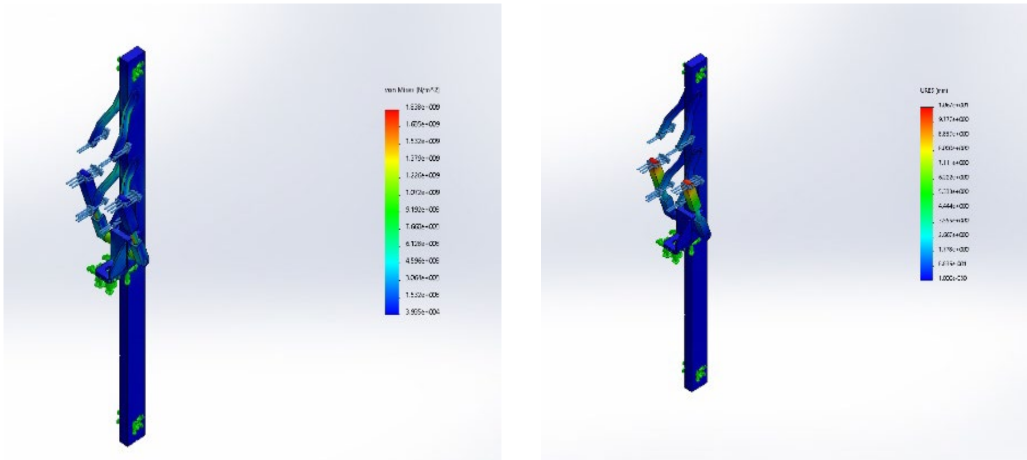


Figure 11. (a) Motor Assembly Linkage Arm: Von Mises stress (b) Static Displacement

As shown in the figure11 above, a force of 3200N was used to simulate the force acting on the arm and the result was a max Von Mises Stress of 170 MPa and a max displacement of 0.387556mm. The following nodal stress and displacement were visualized respectively on nodes located along the arm and represented in the figure below.

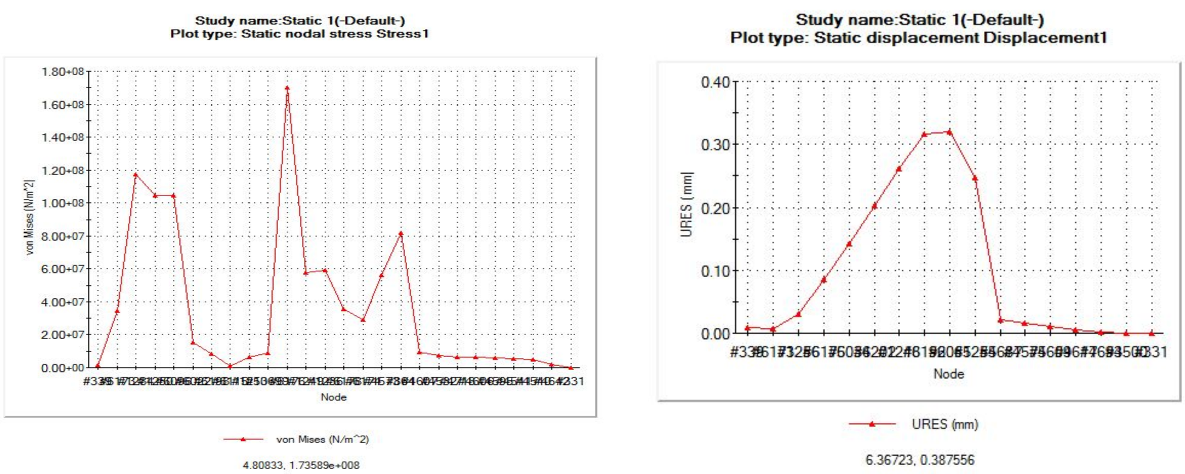


Figure 12. (a) Stress distribution at varying nodal points along the motor assembly support arm (b)Static displacement

According to the values in Fig 12(a), the max Von Mises stress of 170MPa poses no threat as it is lower than the Ultimate Tensile Strength of the material (which is 515MPa) and the displacement value in Fig 12(b) peaks at 0.387556mm which is negligible. A summary of the stresses analysed is shown in table 2.

Table 2. Summary of stresses analysed in the simulation study

Name	Pipeline		Motor Arm Support	
	Min	Max	Min	Max
Von Mises Stress (MPa)	0.0102	0.08341	0.03935	170.00
1st Principal Stress (MPa)	-0.01083	0.09605	-3.127	19.77
3rd Principal Stress (MPa)	-0.05546	0.02906	-19.260	3.662
Displacement (mm)	0.0000	0.00009746	0.000	0.387556

4.3. Machine Vision System

The elements comprising the vision system are the camera, lens, onboard computer, waterproof enclosure as well as the pan and tilt mount. The camera sits inside the clear waterproof containment box which provides a wide range of view about the horizontal and vertical axis (figure 13). The camera is connected to the onboard computer (raspberry pi 4B) through the use of flex cables which offers flexibility of movement with a limitation of affordable distance between the camera and the computer.

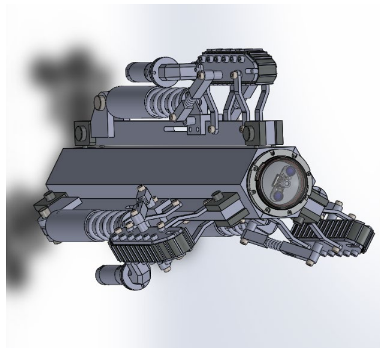


Figure 13. Final CAD assembly

From the arrangement described, it is seen that the object detection occurs in two phases which are the image pre-processing and the actual defect detection. In the pre-processing stage, the structure is inspected in other to identify defects of the nature of cracks and corrosion which complies with the models training data. After this stage, the final step involves creating the bounding boxes around the identified defects found on the inspected surface as shown in figure 14. This methodology can be applied even in situations where there is no prevailing information about the defect in the operating environment and can therefore be used for inspection in both industrial and non-industrial applications.

Figure 14. Real time defect detection output

5. Conclusion

This paper discussed the details surrounding the development and application of computer vision system used in inspection and automatic defect identification. The system design is based on defined requirements and operating conditions where the inspection is to be performed. The whole system is mounted on a mobile tracked robot which aids in inspection of industrial structure such as pipelines and hollow cylindrical structures. The key elements required were the camera, lenses, locomotive system and the processing platform.

Based on the above results, it can be deduced that the new design choices introduced in the mechanical design of the vertical climbing mechanism of the robot for crack inspection is appropriate as per specifications and can be proceeded further with the analysis of crack image inspection using the camera. It is also deduced that the further analysis can be done on this to improve the accuracy of crack image identification and is left for future work.

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