Development of a Robot for Boiler Tube Inspection

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Abstract: The maintenance and inspection of large vertical or horizontal tubes in an autonomous manner is still an unsolved issue. Existing techniques can traverse various types of surfaces but cannot measure inner cracks in a long tube. However, most of these techniques are restricted by accuracy level, type of construction material and cost efficiency. This research is mainly focused on the studies of various types of design investigations related to the climbing robots for the inspections, and design and development of a new robot to solve the existing problem in measuring various pipes diameter in petroleum industries. Based on the existing prototypes, a new type of adhesion, locomotion, sensor mechanisms and a modernized design was accomplished. The importance of this work is to prevent hazardous failures, which probably can be determined through the on-site analyses of the tubes. At this point, it is a laborious, time-consuming and dangerous process, which is performed by the human being. Finally, a climbing robot based on duct fan is designed and developed as a prototype. The thrust force, provided by the fan, ensures that the robot is not falling while the DC motors generate the motion. The ultrasonic sensor is chosen for the defect detection. It generates a reference signal of a proper tube and compares it to the signals received from the defected tubes. The preliminary design and development of the robot are done in SolidWorks software together with the available components in the market.

1 INTRODUCTION

The aging issue of civil architecture consisting bridges, tunnels, and manufacturing communications that mainly apply metal structures, pipes, and tubes, has been a significant research topic of structural health monitoring (SHM). The failure of inspecting and anticipating the SHM of these constructions may contribute to severe tragedies, such as Santa Barbara oil spill (Kolpack,1969). Thus, obtaining the routine inspection data, and further investigation is an essential tool to figure out the sustainability of this infrastructure. Considering Kazakhstani plants, despite ongoing development in the robotics field, most of the methods used for inspection of metal structures are accomplished manually or even worse, left without any evaluation. The proposed solution for this issue is the robot which can be controlled remotely, which means that it reduces any risks associated with reaching difficult-to-access zones for plant workers. The electronic components of the robot should be able to detect the defects of the structural units. The regular inspection of the tubes and other structures is going to decrease the chance of failure occurrence on the plant. This preventive measure is not costly while it precludes high expenses from the system breakdown. It is very challenging and expensive to examine surfaces, which are difficultly accessible, such as vertical tubes in coal-fired electric plants. Present technology of manual inspection is time consuming, costly, and regularly needs the application of large scaffolds, influencing human safety issues. The solution for this is considered to be automated investigation process which can be provided by a robot. Even though a significant advancement in the robotics field, it is not still fully developed to work in the field. The robot should be able to move in a vertical and horizontal direction and be able to inspect the tube. It means that there should be a unique technique for the robot to climb up and down and specific sensors that will provide an appropriate assessment of pipelines conditions. The research focuses on creating an inexpensive prototype for external inspection of pipes and other structures. A robot based on Arduino board makes the inspection. The key working principle of the robot is that it uses ultrasonic sensor and camera to evaluate the health

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of the structure. The duct fan is applied to attach to the surfaces and move in vertical directions. There are two separate power sources for the Arduino and duct fan as the duct fan requires more voltage to work. The approximate cost for the prototype development is $300, and the size is 250 mm x 250 mm x 100 mm.

2 LITERATURE REVIEW

The most cost-effective and troublesome components of electric power, chemical, and operating plants, which cause large expenses during unscheduled breakdowns, adjustment work, are boilers. Every existence of cracked tubes contributes to an emergency shutdown of the whole plant. Thus, the regular inspection of boiler tubes is carried out to assure the operational safety and forbid the leakage of hazardous substances to nature. Generally, the investigation is performed manually or automatically (Vakhguelt, Kapayeva, and Bergander, 2017). A wall-climbing robot for the nuclear power plant is discussed by Briones, L. et al. (1994). A marine vessel inspection robot based on the magnet is designed and developed by Markus Eich and Thomas Vogele (2011). A fuzzy controlled based similar robot for pipe inspection is proposed by Huang, H. P., et al. (2010). Another paper discussed an automatic inspection of ship hull by a magnetic crawler using a camera (Annalisa et al., 2017).

2.1 Manual Type of Pipe Inspection and Its Limitations

Manual type of pipe inspection is very challenging and costly to investigate surfaces, which are problematically attainable, as well as vertical pipes in coal-fired electric plants. Present manual techniques are time-consuming and commonly need the utilization of vast scaffolds, which negatively affects human safety issues (Advanced Pipe Inspection, 2018).

2.2 Robot based Pipe Inspection and Its Limitations

2.2.1 Internal Pipe Inspection Robot

Immersed pipes, generally used for gas pipelines, cannot be investigated as conveniently as above-ground pipes due to the excavation and refilling effort involved. Namely, the ground must be excavated before the investigation to expose all sides of underground tubes located at depth. Then, the ground must be backfilled after finishing the analysis. All this work consumes a sufficient amount of time beyond the time needed for the specific investigation. The internal inspection robot proposes the community the advantages that less time and less operational cost are needed for the work. Thus, interior surface inspection technologies are rapidly being developed. However, there are several problems with the interior surface investigation performance of robots. Various limitations are reported in the following paragraph (Kawaguchi et al., 1995).

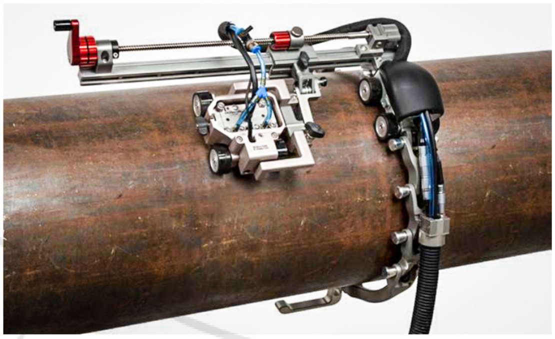

Figure 1: Manual inspection.

Problem 1: Robots operate in the most of the cross-section of the pipe. Objects are standing in tubes, as the plug valves, are challenging to handle for robots. Robots usually cannot be driven through pipes of certain types of diameters connected using reducers or go through narrow paths, as valve position.

Problem 2: One of the most significant limitations is that the supply, such as gas, hot water, which is transferred through the conduits, is needed to be switched off during pipe investigation. The interruption not only adversely affects the economics but also poses the risk of explosions due to the interior of the tube is exposed to outside air.

2.2.2 External Pipe Inspection Robot

External climbing robots became more and more significant in the engineering industry over the last twenty years. The area of utilization of these robots increases with their capability to traverse on different surfaces and to operate faster and more detailed. Currently, climbing robots are examined to support the investigation, maintenance and building tasks everywhere due to new locomotion types and adhesion principles. One of the main aspects is safety, which considers the ability of robots to inspect dangerous constructions of human beings

(Schmidt and Berns, 2018). To perform the requested tasks, climbing robots as all other technical systems have to accomplish several fulfilments which depend on the area of application. However, commonly accepted requirements can be figured applicable for practically all climbing robots in the range of investigation and support:

a) Velocity and Mobility: The robot velocity and its capability to move are two principal features in this area. Based on the size of the piping construction it might be obligatory to reach relatively high speed even in vertical or horizontal direction. Furthermore, it might be required to precisely manipulate and position the system sidewards to investigate and measure existing defects in the whole area of the structure in 360º.

b) Payload: Based on the sensor type, locomotion, as well as adhesion mechanisms, the vehicle needs to be able to carry a payload of various weights.

c) Reliability and safety: Another significant non-functional aspect is the robustness of the system. If the tube-climbing robot fails during investigation task, it would not be applicable in practice. Thus, the reliability and safety requirements consist of robust hardware, more advantageous controllers and approaches to identify and take care of dangerous situations and to rescue from them. Entirely, it might be designated by rules to protect the robot within a cable or wire to defeat the risk of a drop-off that could hurt persons and destroy the system.

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d) Usability: Each of the abovementioned criteria is significantly essential; however, this is only the basis of the universal operability of the system. To carry a vehicle system into operation, it has to be more forceful, more efficient and less unsafe than conventional methods, e.g., regarding inspection systems. Moreover, it must be able to carry different payloads (e.g., sensors or camera) depending on the desired response, high mortality parts need to be quickly replaceable, and the process must be faster and less complicated compared to actual technologies or methods.

By the performing task, a robot developer has to determine which fulfilments have to be executed and select applicable locomotion and adhesion mechanisms.

2.3 Locomotion Types

a) Arms and Legs: The most general principle of locomotion in the sphere of designing climbing robots is the application of arms or legs. Based on the specific type of task, climbing robots have been constructed with the specified amount of limbs of different degrees of freedom. The principal advantage of this principle is high adaptability of a robot to the surface structure. Every leg is designed with adhesive components which allows an examination of the foothold for the chosen attraction forces. However, a significant amount of degrees of freedom contributes to a complex mechanical structure and control system. Also, this leads to more considerable weight and greater torques. Principally, the speed of these machines is sufficiently low in consideration of other locomotion mechanisms.

b) Wheels and Chains: For the operation on a relatively smooth area, dozens of climbing robots exist applying wheels or chain-driven locomotion. In contrast to the legged systems, the adhesion and locomotion components are decoupled in many cases as used in different wheeled and tracked machines. Another set of systems combine locomotion and adhesion systems in the form of electro adhesive or sticky tracks, tracks equipped with suction cups or by magnetic wheels. The significant advantage of wheeled or tracked locomotion is the high speed, continuous movement and the more straightforward mechanical design and control elements. Nevertheless, these robots cannot handle more substantial steps or obstacles, so they are less adaptable to the surface characteristics and are revealed to slip effects.

c) Sliding Frame: Particularly in combination with pneumatic or magnetic adhesive systems sliding frames are generally known. These principles present a simple mechanical construction with two frames which can move in a linear or rotational road against each other. Mainly, each frame is equipped with a group of attach points like suction cups or magnets and keeps the robot at the wall while the second frame is ascended and moved in the desired direction. It allows easy control of robot movement in combination with reliable adhesion since the method can test its foot points before lifting the second frame. The disadvantages of this principle are a low speed compared to wheeled or tracked robots, a discontinuous movement due to the stick-move-stick-move cycle and comparably large size. Wires and rails: Rails and wires are widely used for robot locomotion in some fixed operation types. The essential advantage of these motion principles is that the system is attached and cannot fall away since the adhesion system only has to arrange the machine at the construction while the wires carry the weight of the vehicle and additional payload. It allows a much simpler robot structure, but, of course, requires remote control and equipment limiting the robot to this particular setup.

2.4 Adhesion Principles

Similar to the type of locomotion. Also, the adhesion mechanism has to be determined based on the intended goal. This part explains various adhesion principles, which include the following methods.

a) Magnetic Adhesion: This fundamental technique for climbing robots includes electromagnets and permanent magnets, which are placed on the surface or held at a specific distance. This method is very reliable on ferromagnetic structures, and it can produce high adhesion forces on a limited surface area. Some examples are given in **Fig.2**.

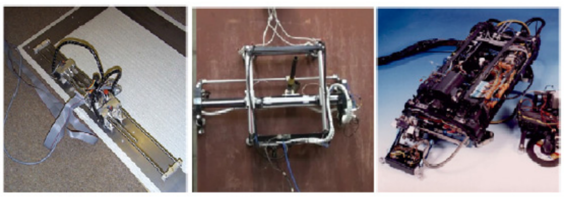

Figure 2: Magnetic robots (Schmidt and Berns, 2018).

b) Pneumatic Adhesion: The second principle is the pneumatic or negative pressure adhesion technique, which is categorized by three distinct types: passive suction cups, suction chambers, and vortex or thrust systems. Pneumatic adhesion types of robots are shown in **Fig.3**.

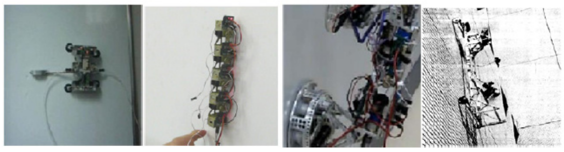

Figure 3: Pneumatic adhesion robots.

Table 1 demonstrates the evaluation procedure of the sensors discussed. Laser sensor has the highest range and lowest percentage of error. However, it costs correspondingly high. Also, it cannot penetrate layers of the boiler tube. Infrared sensor has a small range of operation and error, but this sensor depends on the reflection characteristics of the object. Ultrasonic sensor has a preferable range of working and error. However, the received signal may be fluctuated depending on environmental conditions. Thermosensors are installed in these sensors to compensate for the fluctuating. Overall, by evaluating all type of sensors, it is decided to use the ultrasonic sensor in the research due to its ability to work under required conditions, cost-effectiveness and a low percentage of error.

Table 1. Evaluation of sensors.

Sensors	**Range(m)**	**Error (%)**	**Limitations**	**Cost ($)**
Ultrasonic	0.2-10	2.2 – 3.4.	Depend on environmental conditions	2-20
Infrared	0.1-0.8	0.5-5.3	Depend on reflection parameter of the object	2-20
Laser	0.2<	0.50%	Cannot penetrate layers of tube	50-150

3 DESIGNS AND MODELING

3.1 The Concept

As it was mentioned above the primary goal of the research is to design a robot for boiler coal-fired tube plants, which satisfies specific objectives, namely,

a) Move vertically and circular directions
b) Crack detection
c) Decrease time of inspection
d) Improve cost-resource efficiency

First of all, to make robot's movement towards the corresponding directions, the principle of inspection is specified. Because inside inspection requires specific conditions, such as stopping production and specific dimension of the robot for different tube sizes, which are expensive and time-consuming, outside inspection method is chosen. Consequently, to perform outside inspection, adhesion principle, specifically duct fan-based, is the most appropriate method. Thrust force, which is created by duct fan, is crucially needed to move vertically up and circular directions. Secondly, because in recent industry inspections in tube plants are mostly performed by professionals manually, the development of this robot automates the investigation procedures, which in turn leads to significant reduction of time consumption. As it was mentioned above, the main time-consuming element of the manual inspection is the human factor. Generally, reduction of productivity and existence of errors make the human resources time-consuming component. In contrast, fully automated robots with a certain amount of sensors can perform inspections at any time and conditions without disruption of productivity. Additionally, automation of inspections leads to decreasing and elimination of errors. The climbing robot works with a certain amount of sensors to inspect tubes for cracks and defects to achieve the third goal. Selection of sensors with appropriate performance is an essential part of tube inspection. Ultrasonic sensors are selected because of its working range, low percentage of error and cost-effectiveness. Additionally, as the robot inspects only outer diameter of a tube, a camera can be used as an alternative solution.

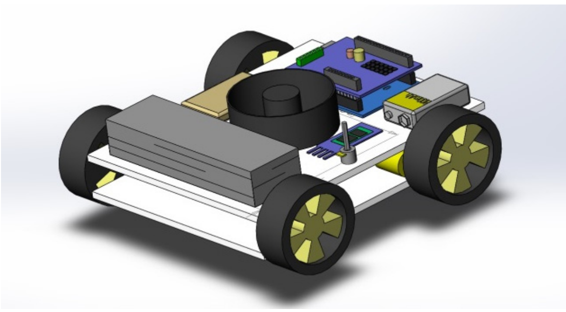

Figure 4: Final 3D Model.

Lastly, the implementation of climbing robots in industry significantly reduces cost and improves resource efficiency. In addition to the low cost of components, robots do not require extra usage of apparatus during the inspection. Furthermore, robots can be reused for next inspections until it breaks. However, it can be solved not by purchasing a new robot, but replacing a broken component, because the construction of robot is simple. **Figure 4** shows the final CAD model.

4 MATERIAL SELECTIONS

4.1 Components

The primary objective of this part of the paper is to determine and describe the fundamental components and their characteristics. Due to the chosen design, electrical, mechanical and control components can be designated. Tables 2 shows the critical components incorporated into this research.

Table 2: Components.

Number	Components	Quantity
1	Arduino	1
2	Duct fan	1
3	ESC	1
4	Battery for duct fan	1
5	Battery for Arduino	1
6	Bluetooth module	1
7	Ultrasonic sensor	1
8	H-bridge	1
9	DC Motors	2
10	Wheels	4
11	Potentiometer	1

4.2 DC Motor Selection

It is needed to determine the angular speed and required torque to select the appropriate motor to drive the robot. Then compare results with the technical specifications of the selected motor. **Figure 5**. shows the incorporated DC motor to this development and Eqns. (1) to (3) describe the motor's specification determination.

$$\omega = V/r \tag{1}$$

$$T = r * F \tag{2}$$

$$F = \mu * N = \mu * F_{th} \tag{3}$$

Where: ω = angular velocity; V=desired speed (assumed 10cm/s); r=radius of wheels (3cm); T=torque; m=mass;

$$\omega = \frac{\frac{0.1m}{s}}{0.03m} = \frac{3.3rad}{s}\ or\ 32rpm$$

$$F = 0.6 * 15.5 = 9.3\ N$$

$$T = 0.03\ m * 9.3\ N = 0.279\ Nm\ or\ 2.85\ k * cm$$

Based on equations 5 and 6, the applicable type of DC motor with the ω = 32 rpm or 3.3 rad/s and T = 0.279 $Nm\ or$ 2.85 $kg * cm$ are selected.

Figure 5: DC Motor.

5 RESULTS AND DISCUSSIONS

5.1 Prototype

At the beginning of the research, the 3D model of the robot was created in Solidworks. Then, according to the design, the prototype was started to construct. However, there were significant changes in the design to improve the performance of the robot. Since the main objectives of the construction were to decrease the weight of the robot, excessed materials were removed, and lighter materials were selected. For example, at the beginning metallic frame (**Fig. 6**) with appropriate locomotion were ordered, but due to the weight of the robot, it was not used.

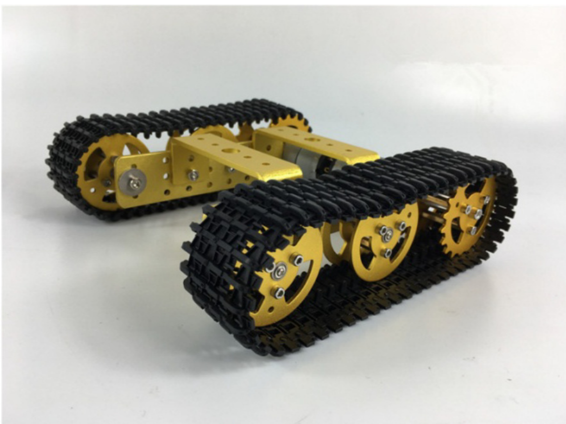

Figure 6: Metallic frame.

Another objective was to increase adhesion. For that purpose, several types of locomotion were considered. At the beginning of the research the locomotion with caterpillar belt was considered, as it has the larger contacted surface area, consequently has greater adhesion.

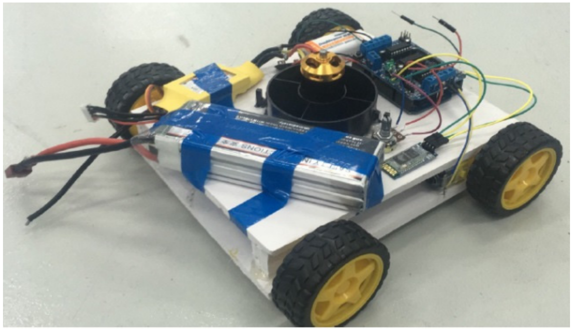

Figure 7: Final prototype-side view.

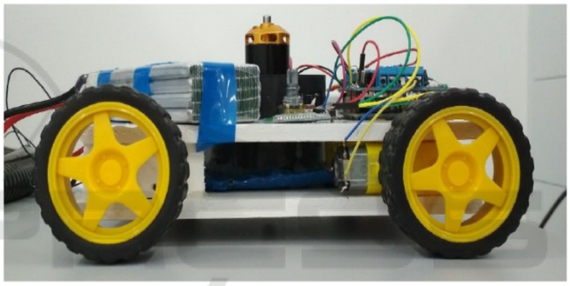

Figure 8: Final prototype-top view.

However, due to the delivery problem of the procurement other types were considered. Therefore, the locomotion with two driver and one guide wheels were considered to decrease the weight of the robot. However, by decreasing the weight of the robot, adhesion was also decreased. As a result, it was decided to use 4 wheels, specifically two drivers and 2 driven wheels with two-sided tape to increase adhesion. However, after the two-sided testing tape was removed, it glued the robot to the wall. Another method to increase the adhesion is to decrease the clearance between the robot and the surface of the tube. To achieve that several objective types of the frame were constructed. From **Fig. 7** it can be seen that air suction area was decreased, but it did not affect. Then, it was decided to decrease the full clearance between the frame and the surface of the tube, as can be seen in **Fig. 8**. There were two primary objectives while assembling all above-discussed components. First of all, it is needed to make the robot move by controlling it through Bluetooth module. It is required to connect the motors to accomplish this task. Bluetooth module and power supply to the Arduino. The Bluetooth module is used. Thus, writing program is not necessary. Secondly, it is required to build the connection to make the robot climb vertically up and move circular direction on the tube. To achieve this objective duct fan system is added. First of all, duct fan is connected to an ESC, which is connected to Arduino and power supply, simultaneously.

5.2 Testing

Testing was performed to regulate the components and optimize the performance of the robot. For instance, the direction of the motors was determined during the testing. Also, required the rotational speed of the duct fan was regulated at appropriate power to save the power of the battery. During the test, an electrical component was damaged and burned. **Table 3** highlights the advantages of duct fan used to develop this robot.

Table 3: Comparing with other methods.

Robot type	Main Advantage	Main Disadvantage
Duct Fan	**The simple and cheap mechanism, easy to build a prototype.**	**Needs design modifications to work on pipeline inspection**
Manual Inspection	High accuracy	Cost, more extended time consumption, the human factor
Magnetic crawler	Can be used on iron surfaces which works in the case of this research	Can shear off due to obstacles and heavy because of the magnets.
Suction mechanism	The simple mechanism can be applied to irregular surfaces	Does not suit size limitations
Flight robot	Fast	Risk of breakdown

5.3 Working Principles

Cr-Mo tubes are used in Coal-Fired Electric plants in Kazakhstan. About 80% of electricity in Kazakhstan is produced from coal (Kegoc, 2018). Therefore, coal-fired plants are significant for energy supply for the country. Chromium-Molybdenum is a type of 41xx steel which is used in high temperatures and pressures operating conditions. Even if it is the most appropriate material for boiler tubes, it has some defects after operating for a specified period. A failure of one tube may cause many problems in the manufacturing process. Orr et al. (1978) present a study of Chromium-Molybdenum steels failure modes. They discuss various factors affecting the defects emergence. The most important factor while studying Cr-Mo boiler tubes is the diameter of the tubes because it makes a significant impact on size limitation. The catalogues show that the tube diameter may vary from 31.8mm to about 50cm. According to Viswanathan (2005), the main steam pipes are about 50cm in diameter. Therefore, the robot should not exceed this diameter and be as small as it is possible. Apart from that, the robot can be found useful in a lot of other inspection processes. For instance, if there is a need to check something under the bridge, the robot can cope with it, as the thrust force should be able to keep it upside down. Therefore, this type of technique can be applied in many fields where defect detecting plays an important role. The main limitation for the prototype is the curvature of the surface: it is too high, the model is not capable of holding on the space.

6 CONCLUSIONS

This research contributes to the field of tube inspection in petroleum industries. There were two main challenges: i) decide on tube climbing technology, and ii) suggest a sensor system for defect identification. For the first challenge, duct fan based method was selected due to its effectiveness, cost, and simplicity. It has enough trust force to hold itself to the surface on a vertical wall. The cost of the prototype does not exceed $300. Concerning the second problem, the external inspection, which is also significant to perform, is possible to accomplish with the presented prototype. It uses the ultrasonic sensor to measure the distance until the surface. The reference signal shows the distance when the exterior part is proper, i.e., without any defect. If the signal differs from the reference, it can be concluded that that the surface has a defect. Moreover, one more proposed alternative is to use the camera and check the structure by observing the image of it. Another area of application is various structures that are subjected to risk of failures such as bridges, tunnels, tanks, ships, walls, windows and ventilation systems. Since the robot can work with the camera, it can check any surface with appropriate curvature for the defects. As some areas to inspect manually can be challenging to reach, a robot should substitute the human in those difficult to reach zones. In conclusion, the key objectives of this research are achieved; the prototype with the electronic and mechanical components is built and tested. The preliminary results of this work provide an excellent framework for the future advancement in this field.

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