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# DEVELOPMENT OF MAGNETIC WHEELED BOILER TUBE INSPECTION ROBOT

M. F. Abdul Jalal*, K. S. Mohamed Sahari, A. Anuar

Centre for Advanced Mechatronics and Robotics, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Malaysia

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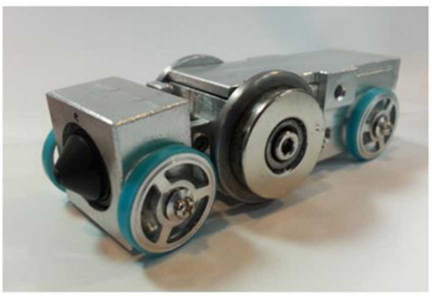
*Corresponding author
amfairuz@uniten.edu.my

**Graphical abstract**



**Abstract**

The periodical inspection of boiler header and tube is considered important to avoid power plant shutdown due to failures caused by degradation, creep, corrosion, thermo-mechanical loading and others. The boiler header inspection robots developed by our research center, namely "MK-02" and "LS-01", are only able to inspect the boiler header but unable to travel in and examine the boiler tube condition. This paper introduces a boiler tube inspection robot with magnetic wheeled which is able to inspect the inner surface of 45 mm ferromagnetic tube. The detailed design and analysis of Boiler Tube Inspection Robot "ND-01"are presented. The experimental results proved that the proposed system was able to work efficiently. With further research, the proposed design is expected to improve the inspection of boiler tube or small pipe efficiency.

*Keywords:* Boiler tube, in-pipe inspection robot, magnetic wheel



## 1.0 INTRODUCTION

Reliable and robust inspection system, especially the inspection of boiler header and tube for the variable dimension and configuration, has been identified as one major challenge on the inspection and maintenance for Tenaga Nasional Berhad (TNB) power plants. The periodical inspection of boiler header and tube is considered important to avoid power plant shutdown due to failures induced by degradation, creep, corrosion, thermo-mechanical loading and others.

The application of robots carrying sensing tools for in-pipe inspection offer an alternative in term of reliability and ease of operation compared to conventional methods. In our case, visual inspection is considered as the primary means of evaluation of surface conditions of boiler header and tube. Our research center had developed Boiler Header Inspection Robot "MK-02" (BHIR "MK-02"), the continuation of the first prototype, namely BHIR "LS-01". We developed BHIR "LS-01" in 2010 which functions as a carrier for an existing borescope to inspect the inner surface condition of the boiler header. Based on site testing, it was found that the length of the borescope is not sufficient, and it cannot be integrated into the developed robot [1]. Hence, an integrated image acquisition system is developed and embedded to BHIR "MK-02" in 2013 [2]. Both robot is designed to inspect boiler header but unable to travel in and examine the boiler tube inner surface condition.

The boiler headers and tubes operate under very high temperature and pressure loading during operation. Therefore, only a small opening for robot entry is allowed during inspection routine. The existing robots developed by our center, "MK-02" and "LS-01", enter the boiler header trough small entrance by cutting the boiler header nipple part or handheld nipple with the size ranging from 89 mm to 102 mm.

### 1.1 Locomotion

Numerous conceptual design and prototype of in-pipe inspection robots have been developed for the past few decades. The robot is designed either using a single or hybrid locomotion system. The locomotion selection is based on their design requirement and maneuverability in the pipe environments. The single locomotion is namely wheeled type, caterpillar type, snake type, legged type, inchworm type, screw type and pipe inspection gauge (PIG) type [3]. The hybrid locomotion system offer many advantages in term of adaptability, flexibility and maneuverability to navigate in a various pipe configuration albeit increasing the complexity of robot design and control strategy.

## 2.0 THE BOILER HEADER INSPECTION SYSTEM

### 2.1 Design Requirement

The detailed analysis of the requirements and constrains for the Boiler Tube Inspection Robot (BTIR) were carried out before the execution on the previous project, BHIR "LS-01" [1] and BHIR "MK-02" [2]. The design requirements for BTIR are extracted from raw data collected from several local power plants which are operated by TNB, Malaysia's utility company. As the result, following requirements were established:

- Able to travel in 45mm ferromagnetic tube
- Able to enter and exit the tube without any detached parts
- Able to traverse in the tube up to 2 m
- Carry camera for visual inspection

The geometrical studies on the requirements mentioned above were made in order to evaluate the permissible BTIR dimension to negotiate various tube arrangements.

### 2.2 Overall Characteristic

The major challenges in designing the BTIR are the overall size constraint, the ability to travel in bended tube and the required frictional force at the wheel for climbing the inclined tube. In order to fulfil those challenges and design requirements, the robot was designed into 2 separate module consist of front module to incorporated camera and main module for locomotion with a set of magnetic ring attached to the wheel rims. This robot "ND-01"has 2 degree of freedom which is forward and backward movement as well as tilting of the front module. The robot model and fabricated prototype are shown in Figure 1.

The front module can be tilted, a up to 30° as illustrated in Figure 2.

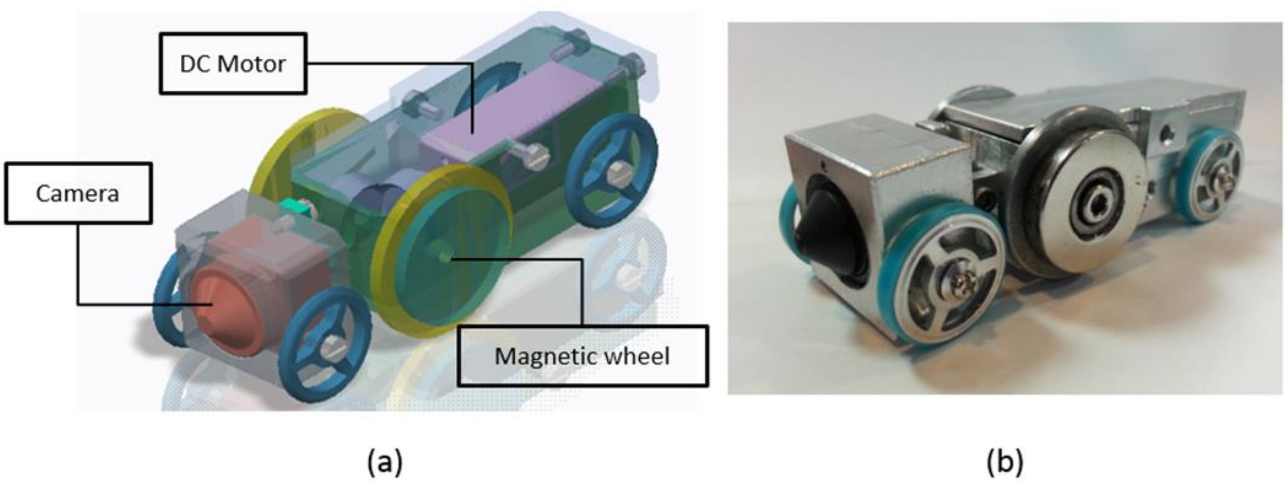



**Figure 1** (a) Prototype model (b) Fabricated prototype

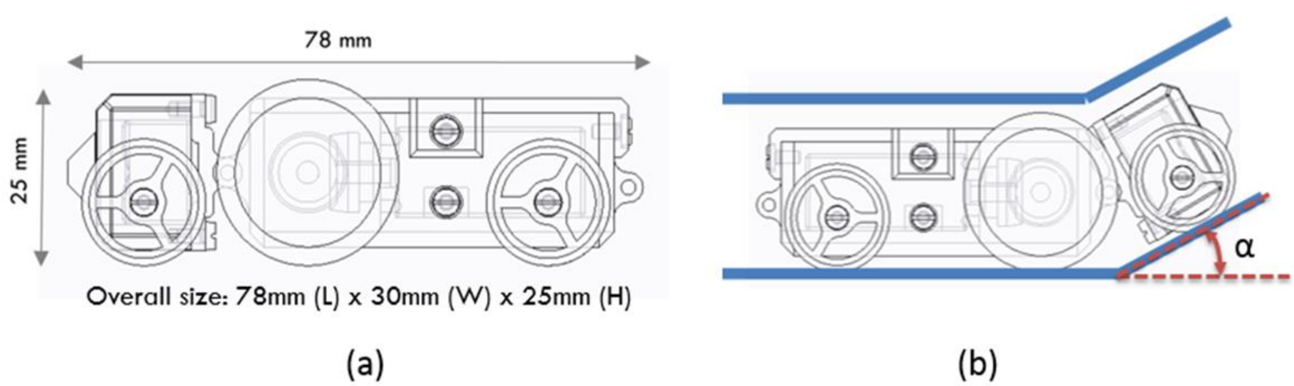



**Figure 2** (a) Overall dimension (b) Tilted angle a

### 2.3 Transmission

The size of motor must be as small as possible to align with size constraint. The robot "ND-01"is using single locomotion by installing micro metal gearmotor, 20 mm (W) x 20 mm (H), which provide advantages in term of its size and high torque capability. The gearmotor is a miniature DC motor with 29.86:1 metal gearbox and produces 9 kg-cm of torque. Since there are no tube branches, the robot was only designed for forward and backward movement.

There are three sources of force included in the calculation for finding the required force and torque for travelling up the inclined and bended tube. The forces are namely the gravitational force due to weight of both modules, frictional force at the contact point between magnetic wheel and tube surface, and drag force due to frictional sliding effect between the cable and tube surface. Figure 3 shows the robot "ND-01" in boiler tube and the simplified free-body diagram.

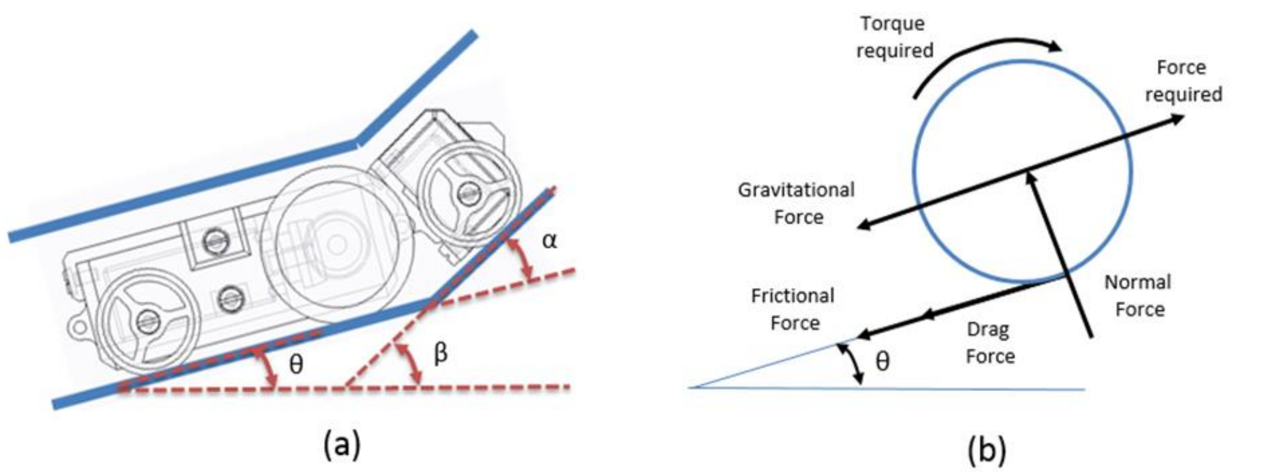



**Figure 3** (a) BTIR "ND-01" in boiler tube (b) The simplified free-body diagram

The equations of the forces required Freq to overcome the gravitational force, frictional force and drag force are illustrated below:

$$F_{req} = F_{gra} + F_{fric} + F_{drag} \tag{1}$$

$$\beta = \alpha + \theta \tag{2}$$

$$F_{gra} = (m_{main} + m_{cable}) g \sin\theta + m_{front} g \sin\beta \tag{3}$$

$$F_{fric} = \mu_{rolling} \left( (m_{main} + m_{cable}) g \cos\theta + F_{mag} + m_{front} g \cos\beta \right) \tag{4}$$

$$F_{drag} = \mu_{sliding} m_{cable} g \cos\theta \tag{5}$$

The gravitational force that acts on the BTIR is consists of the weight of the BTIR itself (main and front module) and cable (safety and fiber optic cable). The equation for the gravitational force with inclined angle and is shown in Equation 3. The gravitational force component is roughly estimated during the preliminary stage. The estimated BTIR weight is extracted from conceptual 3D model. Later the design is optimized via analysis using actual weight values of the BTIR and cable; 0.9N and 3N respectively. The cable weight is assumed as concentrated instead of distributed loading. The robot experiences drag force due to sliding effect of the cable on the rough tube surface as shown in Equation 5.

The main parameter that determine the overall functionality in term of motor and magnet selection for this robot "ND-01"is the magnet attraction force. The magnetic wheel increases the wheel traction and attaches the robot to the ferromagnetic pipe surface. The magnetic wheel enables the robot to transverse in inclined tube arrangement by exerting enough normal force albeit indirectly increase the frictional force (refer Equation 4).The attraction force between the wheel to the surface is estimated from the simulation result done in FEMM 4.2.

### 2.4 Magnetic Wheels

Due to size constraint, the compromise between the required magnet attraction force value and the permissible magnet diameter is deemed necessary. The Neodymium (NdFeB) magnet ring was used and attached to the inspection robot wheel rims which are made of stainless steel. This rare-earth magnet type offer advantage in term of high strength to size ratio. The wheel rims is fasten to the driveshaft using screw to accommodate ease of maintenance and part replacement.

The magnetic attraction force between magnetic wheel and ferromagnetic is influenced by the magnetic poles arrangement and the magnetic poles angle during the navigation. The magnetic flux plots during the travelling are shown in Figure 4. The attraction force reaches maximum value when the magnetic field direction is perpendicular and minimum value when the field direction is parallel to the tube surface. The magnetic attraction force fluctuates between 1.1 N to 1.4 N.

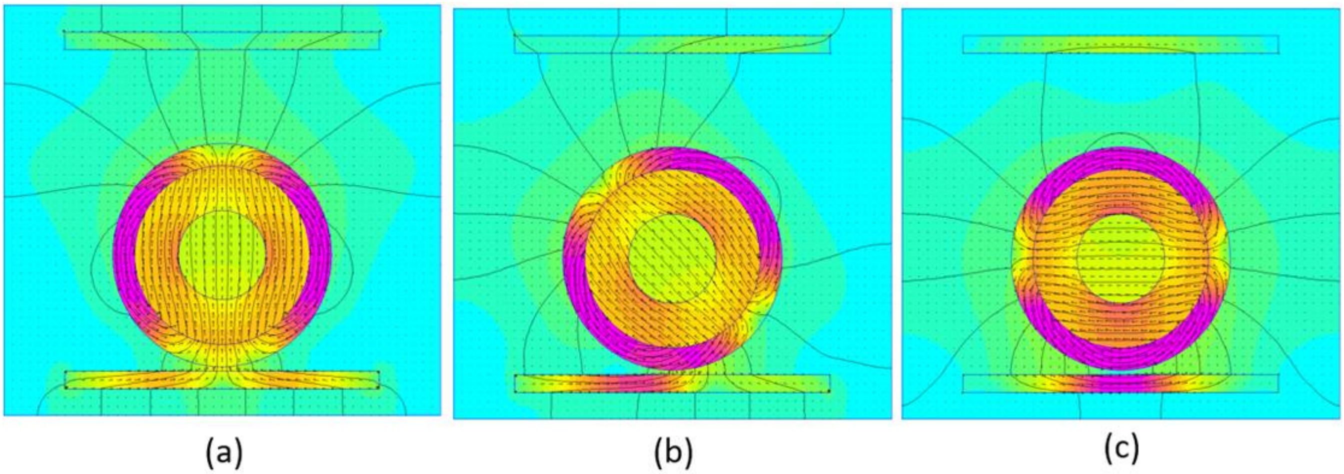



**Figure 4** Magnetic flux field representation during travelling at angle of (a) 90° (b) 135° (c) 180°

The effect on the magnetic poles arrangement was investigated to find the best possible option to maximize the attraction force between the wheels to the tube surface. The unlike poles arrangement offers 3.03N magnet attraction force, which is only 2 percent higher than like poles. The result show that there is no significance difference in term of magnet attraction force between both poles arrangement. However, the like poles arrangement induced neutral zone between both magnets. This solution is important for critical cases to reduce disturbances to motor and camera functionality, demonstrated Figure 5.

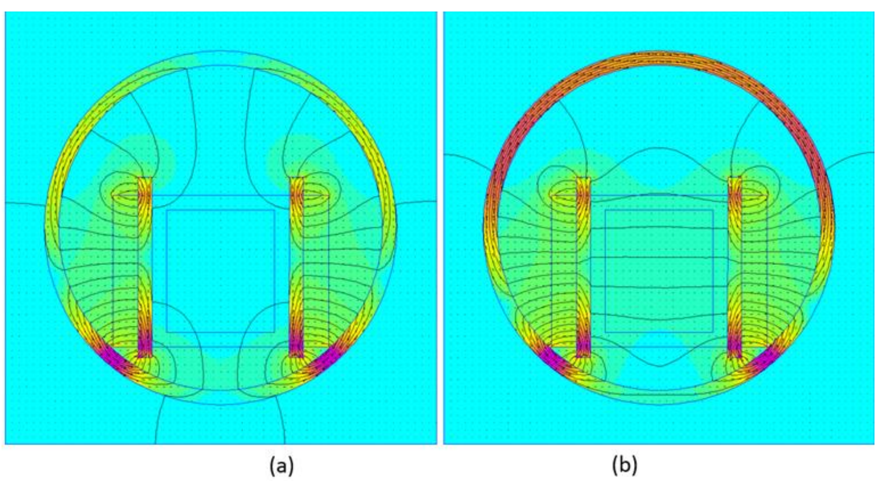



**Figure 5** Magnetic flux field representation according to magnet poles (a) unlike poles (b) like poles

As mentioned earlier, the total weight values of the BTIR including weight of front module with camera, main module for transmission and cables is 3.9N. The minimum magnet attraction force using unlike poles arrangement during the navigation is 4.43N magnet attraction force, which is slightly above the required value. The inspection robot is expected able to avoid sliding during traversing vertical tube. However, current inspection routine at the thermal plant only inspect horizontal and inclined tube arrangement, which contributes less pull force to trigger the sliding effect. Thus, current inspection robot "ND-01"is able to sustain its total weight during travelling up or stay stationary in inclined tube without unintended backward movement.

### 2.5 Test on Maneuverability

The maneuverability of "ND-01" are assessed through 3 tests as, namely:

- To test the robot ability to transverse forward and backward on metal plate as shown in Figure 6.

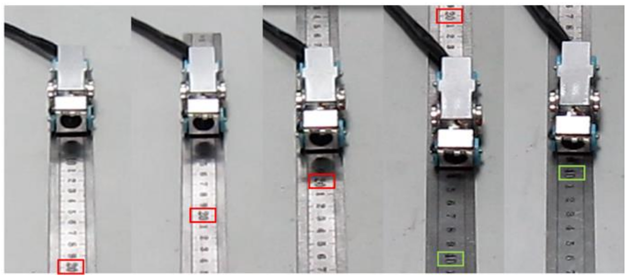


**Figure 6** Robot prototype on horizontal metal plate

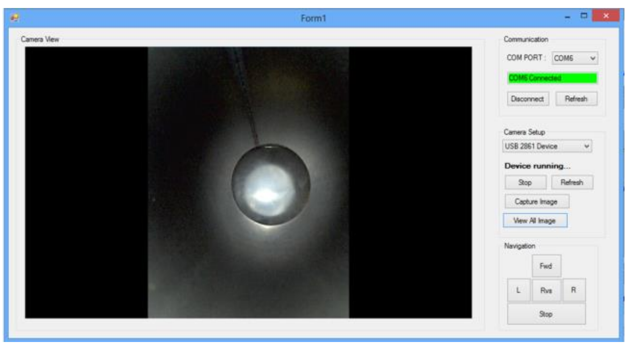



**Figure 7** Robot prototype on vertical metal plate

- To test the image coverage in tube as shown on Figure 8.

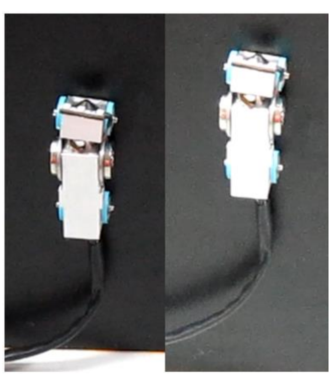


**Figure 8** Image coverage in tube

## 3.0 CONCLUSION

A working prototype of boiler tube inspection robot "ND-01"is tested and proven to be working to do inspection routine. The main challenges to develop this inspection robot are the selection of the smallest possible motor, miniaturization of the transmission system and maintaining traction between wheel and surface. The application of magnet attached to the wheels provide additional traction albeit increasing the load to the motor.

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