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Prototyping a piping inspection robot using a BeagleBone black board

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Résumé :

Dans le cadre d'un projet avec AREVA, un robot d'inspection de canalisation de 50 à 94 mm de diamètre a été développé. En utilisant des pattes, des moteurs à courant continu, des vis-écrous et des cartes électroniques, le robot imite la locomotion d'une chenille. Deux algorithmes peuvent être utilisés pour le contrôle de ce robot: le contrôle en position ou le contrôle en effort. Le premier est utilisé pour l'estimation de la position d'un robot lorsque l'environnement est connu mais nécessite des codeurs pour identifier la position des pattes. Dans le cas du contrôle en effort, l'algorithme permet au robot de se déplacer dans un environnement inconnu. En utilisant une carte électronique BeagleBone (BB) black, un algorithme de contrôle en effort est développé pour ce robot d'inspection. Comme le robot travaille à l'intérieur de tuyaux de diamètres inconnus, les sorties PWM de la BB black sont utilisées pour générer la tension nécessaire qui permettant le clamping du robot. En fixant ces seuils, la tension et le courant dans les moteurs peuvent être évalués pour détecter la fin des mouvements de clamping ou de repliement. Avec l'aide des ADC, la tension de sortie est affichée à l'utilisateur sur un ordinateur. Pour le bon fonctionnement du robot, les paramètres du moteur tels que la vitesse maximale, le sens de rotation et le courant nominal sont étalonnés au début des expériences. La tension de sortie et les courants consommés sont générés et tracés pour un cycle de locomotion du robot dans un tuyau droit de 74 mm de diamètre.

Abstract :

As a part of a project with AREVA, an inspection robot for 50-94 mm diameter range pipelines have been developed. By using leg mechanisms, DC motors, spindle drive, and control boards, the robot accomplishes the locomotion of a caterpillar. Two algorithms can be classified for the control of this robot via Displacement control algorithm and Force control algorithm. The former deals with the estimation of the position of a robot inside a known environment and it requires sensors for identifying position as well as for initiation procedures. In the case of force control, the algorithm is highly suitable for a robot that moves inside an unknown or closed environment. Using a BeagleBone (BB) black board, the force control algorithm is developed for the inspection robot under study. As the robot works inside

pipelines of unknown diameters, the reconfigurable pins of BB black are employed to apply a voltage in order to achieve the desired clamping force for having contact with pipeline walls. By setting threshold limits, the voltage and current supply to the motors can be cut-off at the end of clamping or retraction operations. With the help of ADC, the output voltage can be displayed to the user on a computer. For smooth functioning of the robot, the parameters of the motor such as the maximum velocity, direction of rotation and nominal current are calibrated prior to the start of experiments. The output voltage and currents of the motors are generated and plotted for a locomotion cycle of the robot inside a 74 mm diameter straight pipeline.

Keywords: Piping inspection robot, Caterpillar locomotion, Force control algorithm, BeagleBone (BB) black

1 Introduction

Piping inspection robots play a significant role for industries such as nuclear, sewage as they reduce human effort and impose lesser risks to human life. Such inspection robots employ one or more electronic boards for their control and movements when moving through various trajectories of pipelines. Some of the well-known devices are the Raspberry Pi [1], Arduino [2] and BeagleBone (BB) black [3]. The choice of these boards or micro-computers purely depends on the intended application. Leccese et al. [4] studied on the comparison of these three micro-computers. Arduino is usually used for programming with low-level C++ languages and it can also be used to create an interface between sensors. An interesting example is the vibro-impact capsule type inspection robot prototype of Yusupov et al. [5] where an Arduino board is used to propel the robot inside a Poly-vinyl chloride(PVC) test pipe. Raspberry Pi and BB Black, on the other hand, works efficiently for high-end programming languages such as Python and MATLAB. These micro-computers operate on Linux platform with access to the internet. Raspberry Pi is intended for applications with GUI and cannot be compatible for interfacing with external sensors. However, it has compatibility for camera interfacing which makes it efficient for moving inside dark pipelines. The robot of Abdellatif et al. [6] employs a Raspberry Pi for robot control and detection of cracks inside a dark environment. A bio-inspired caterpillar type robot was proposed by Henry et al. and Chablat et al. [7],[8]. This robot is capable of working inside pipelines having diameters between 50-94 mm. A prototype of this robot was developed at LS2N, France and the testing was carried out inside a transparent PVC pipe of 74 mm diameter and 2.5 m length. A BB black is utilized for the control and locomotion of this robot. This paper concentrates on the architecture of this robot and the results of voltage and currents induced on the motors during a locomotion cycle.

In general, two algorithms can be classified for the control of a robot namely Displacement control and Force control. The former is used for a robot that works in an open environment and moves through a known distance. Since the diameter of any instance of a locomotion step is unknown, the force control algorithm is employed where through voltage control, the necessary force is applied to the motors in order to clamp the robot legs with pipeline walls. DC motors and spindle drives provided by Maxon is used in this robot to accomplish the caterpillar locomotion. The outline of the paper is as follows. In the first section, the locomotion procedure and the electronic architecture for the prototype is presented. Followed by that, the force control algorithm is exploited. The results of voltage induced on the motors during a locomotion cycle are then presented. Finally, the paper ends with conclusions and future works.

2 Assembly of the robot

2.1 Locomotion principle and architecture

The robot proposed in [7],[8] mimicks the locomotion of a caterpillar. The general motion of a caterpillar comprises of a front and rear elongation module and a central blocking module. Anthierens et al. [9] developed a similar inchworm type electro-pneumatic robot that uses bellows to accomplish this locomotion. However, inside nuclear power plant pipelines there exists dust particles and deposits which limits the use of bellows and it is complex to apply a force control algorithm for systems using bellows. Electrical actuators are thus used in the robot to accomplish the caterpillar locomotion which is accomplished in six steps [8]. The outline of the robot inside a pipeline of radius r is shown in Figure 1.

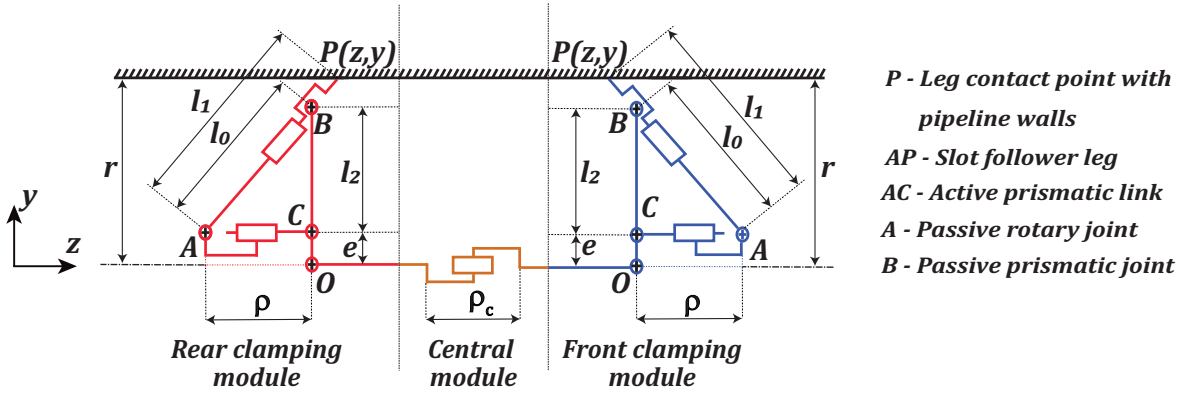


Figure 1: Outline of the robot inside a pipeline of radius r

A slot-follower leg mechanism is used in the front and rear modules to have contact with pipeline walls during locomotion. In Figure 1, AP represents the slot-follower leg. O is the reference point for the leg mechanism. AC represents the active prismatic link which has a stroke length of ρ . The leg is hinged at B in order to slide and have contact with pipeline walls. The stroke length of the central module is represented by ρ_c . A Maxon EC motor (brushless DC motor) coupled with a Maxon spindle drive is used to accomplish the clamping and elongation processes. The specifications of the motor and spindle drive are provided below in Tables 1-2.

Table 1: Specifications of the Maxon EC-motor (Part No. 283828) [10]

| Parameters | Value |
|---------------------------|------------|
| Nominal voltage | 12 V |
| Nominal current (I_c) | 0.456 A |
| No load speed | 13500 rpm |
| No load current (I_n) | 60.2 mA |
| Nominal speed | 5840 rpm |
| Efficiency (η_m) | 54 % |
| Torque constant (K_T) | 7.82 mNm/A |
| Speed constant (N_v) | 1220 rpm/V |

For the control of motors, three ESCON 36/3 servo controllers offered by Maxon [10] are used, with one controller for each motor. This controller ensures speed and torque control of the motor units. Using the motor units, spindle drive, coupling screws and standards fasteners such as circlips, studs, nuts and bolts,

Table 2: Specifications of the Maxon Spindle drive (Part No. 424749) [10]

| Parameters | Value |
|--|----------------------|
| Spindle screw diameter and pitch (p) | $\phi 5 \times 2$ mm |
| Reduction ratio (G) | 455:1 |
| Max. static axial load | 500 N |
| Max. spindle length | 102 mm |
| Efficiency (η_s) | 63 % |

the entire robot can be assembled. A 3D model of the robot is also realized using CATIA software[†].

2.2 Interfacing with BB black and ESCON controllers

For the command and control of the robot, a BeagleBone (BB) black micro-computer is used. The BB black offers 92 pins which comprise of the Pulse-Width modulation (PWM), General-Purpose Input/Output (GPIO), Analog to Digital converters (ADC) and reconfigurable digital ports [11]. Each Maxon motor is interfaced with the BB black through their ESCON 36/3 servo controller by three pins. One pin is connected to the PWM which is used to operate a motor on a duty cycle in a particular direction. The other pin is connected to a GPIO which is used to enable or disable the motor functioning in a boolean way. The third pin is connected to the ADC to read the motor voltage. The PWM of the BB provides a maximum voltage of 3.3 V and it is used to operate the motors with control over the speed. For the idle stage, 50% duty cycle is set as a reference where the current is 0 A. For the safe running of motors, 80% of the duty cycle of the PWM is only used. At 80% duty cycle the motor performs either clamping or retraction operation with clockwise rotation and at 20% duty cycle the motor performs de-clamping or elongation operation with anti-clockwise rotation. The interfacing between BB black and one set of EC motor and its controller is provided in Figure 2.

In Figure 2, the **J2** cable of each ESCON controller is connected to its EC motor unit. The **J1** cable of each controller is connected to a power source of 12 V. The cables **J5** and **J6** are connected to the PWM, GPIO and ADC pins of BB black. The PWM, GPIO and ADC pin address on BB black for each motor and its servo controller is listed below in Table 3.

Table 3: BB black pin address for each motor and its servo controller

| Motor | PWM (duty cycle) | GPIO (Enable/Disable) | ADC (Results) |
|---------|------------------|-----------------------|----------------|
| Motor-1 | P9_14 (DigIN 1) | GPIO_14 (DigIN 2) | AIN0 (AnOUT 1) |
| Motor-2 | P8_13 (DigIN 1) | GPIO_47 (DigIN 2) | AIN1 (AnOUT 1) |
| Motor-3 | P9_31 (DigIN 1) | GPIO_68 (DigIN 2) | AIN2 (AnOUT 1) |

Before the start of experiments, the DC motors and ESCON controllers are calibrated in a computer through a USB cable through port **J7** as per the specifications mentioned in Tables 1-2. The output voltages from PWM which are generally analog is passed to the ADC to display the outputs to the user. The ADC of BB black, however, supports a maximum voltage of 1.8 V. Thus, the output analog voltage before passing to ADC of BB black is calibrated in the ESCON software in accordance with the nominal current of the motor. The BB black also offers Enhanced Quadrature Encoder Pulse (eQEP) pins which can be used to determine the position/displacement of robot at any instance of locomotion. However, this feature is not included in the current control loop of the robot. The control methodology for the

[†]3D model of the robot in CATIA and simulation available in -
<https://www.youtube.com/watch?v=7z6-by83mtw>

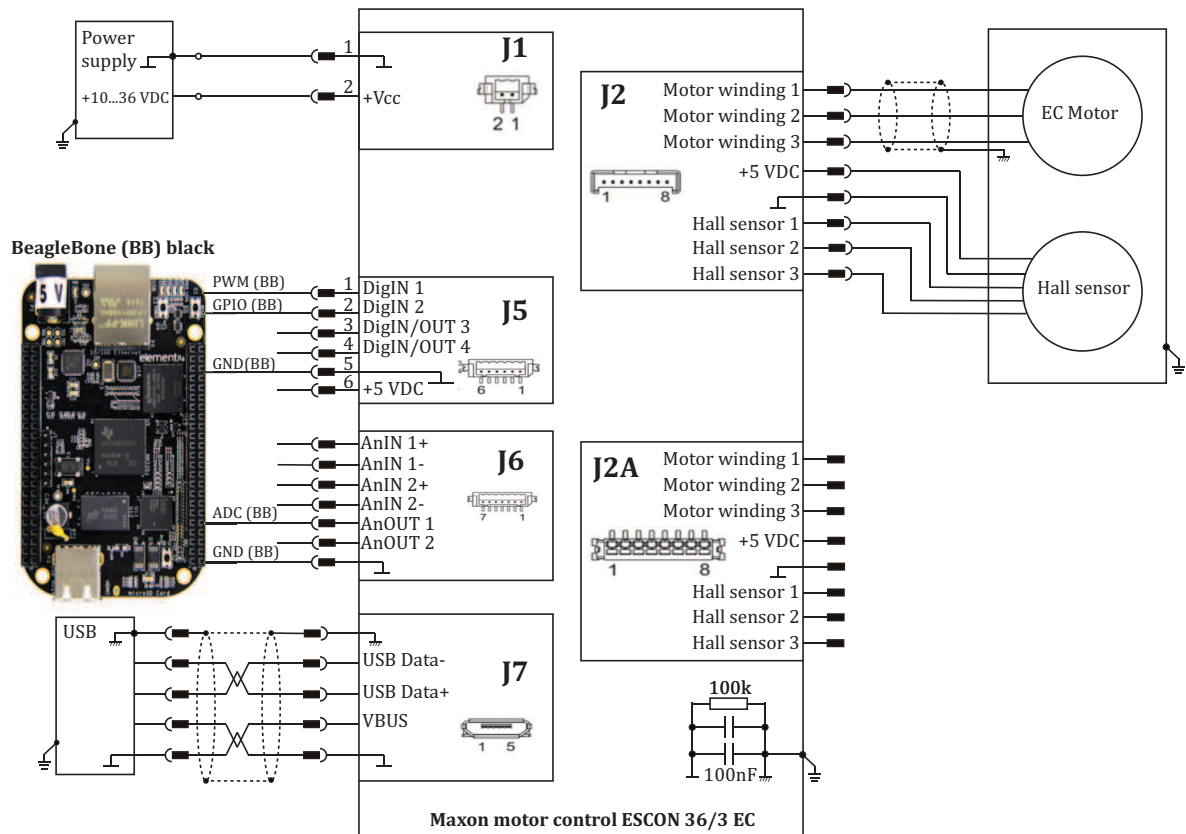


Figure 2: Layout of the interface between BB black to one EC-motor and its servo controller

locomotion will be explained in the next section.

3 Control methodology- Force control algorithm

In the real world application, the robot under study will be implemented for inspection inside dark pipelines with no visual information about its current position. A force control algorithm is employed which is used to control the locomotion of robot inside an environment of unknown size. By applying the necessary clamping force from the power source to the motors, the robot can adapt its legs and clamp itself to pipeline walls. Initially, interfacing between BB black and each motor as well as its servo controller is done as per Figure 2. The BB black is connected to a computer and this board operates on Debian OS 7.9. The activation of pins [‡] specified in Table 3 are done using the linux terminal of BB black micro-computer. When a PWM duty cycle is applied to the motor, the spindle drive enables the leg mechanisms to clamp or de-clamp or allow the central motor to elongate or retract. The motors rotate at a constant speed during its duty cycles. A simpler form of the pseudo-code for one forward motion is provided in Algorithm 1 in Appendix. At the end of one loop cycle, the robot remains in an over-constrained posture wherein both the leg mechanisms are clamped with the walls of the pipeline. The prototype of the robot developed at LS2N, France is depicted in Figure 3.

In Figure 3, *A* represents the working of robot inside a test pipe and in *B*, the side view of the robot is shown. In *C*, the ESCON controllers for the robot is represented. The following operations are

[‡]Pin activation of BB black in Debian 7.9 available in-
<https://github.com/stvt1991/Control-of-piping-inspection-robot/tree/master/Pin-activation>

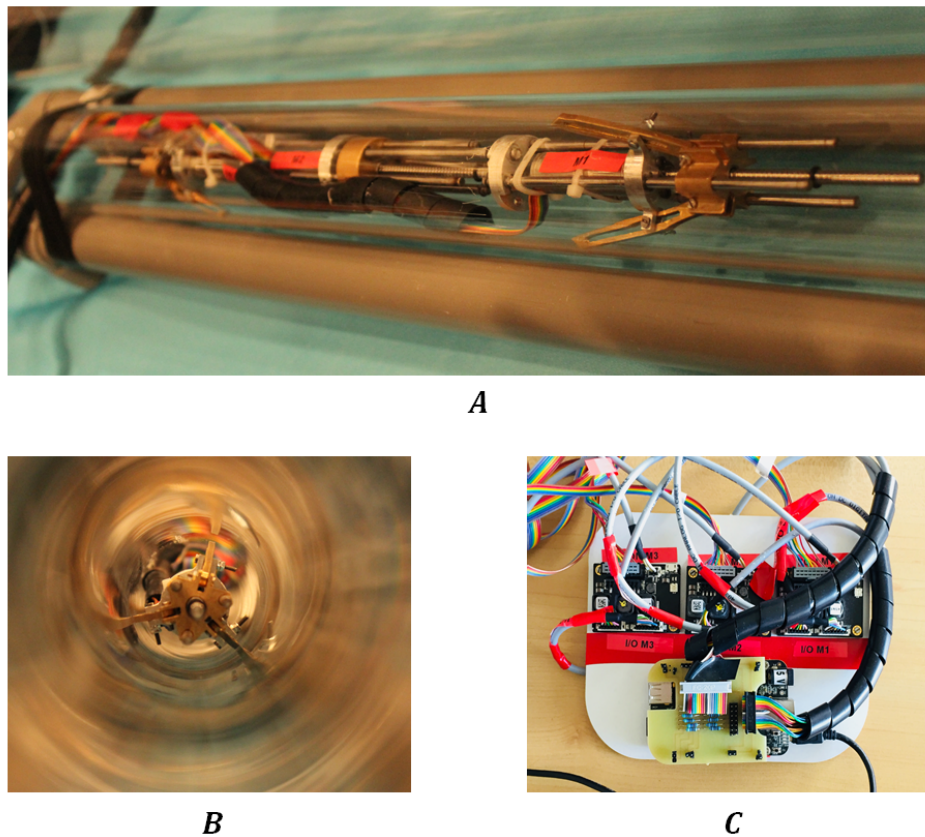


Figure 3: Prototype of the robot developed at LS2N, France^{**}

performed using C program^{††} for the locomotion of the robot which is written as per Algorithm 1:

- Forward motion (twice)
- Reverse motion (twice)

In order to ensure that there is no continuous running of motors after an operation is finished, threshold limits are being set for the clamping/retraction as well as de-clamping/elongation phases. The upper threshold T_U is set at 1.5 V which is 83% of the maximum voltage of ADC and the lower threshold is set at 0.42 V. These values are determined based on experimental trials. Also, these values are ideal when operating inside variable sections as the diameter of any locomotion step is unknown. When the limits are reached, the torque reaches its stall point and the PWM is set to idle phase.

4 Results of experiments for a locomotion cycle

With the interfacing between controllers and BB black being done, the parameters defined below in Table 4 are calibrated for the ESCON controllers before the algorithm is initiated. The experiment is carried out inside a 2.5 m length PVC transparent tube of 74 mm diameter as depicted in Figure 3. The ADC of the BB black generates the output voltage which is extracted and the results can be traced in

^{**}Photography copyrights: Vincent Jacques, Centrale Nantes, France

^{††}Force control algorithm written in C language available in-

<https://github.com/stvt1991/Control-of-piping-inpsection-robot/tree/master/Codes>

Table 4: ESCON controller calibration before initiation of Force-control algorithm

| PWM Duty cycle | ADC voltage (V) | Nominal current (A) | Motor speed (rpm) |
|----------------|-----------------|---------------------|---------------------------|
| 20% | 0 | -0.46 | 10800 (Counter-clockwise) |
| 50% (idle) | 0.9 | 0 | 0 |
| 80% | 1.8 | 0.46 | 10800 (Clockwise) |

MATLAB. The results of output voltage of each motor for two forward and reverse motions is depicted in Figure 4.

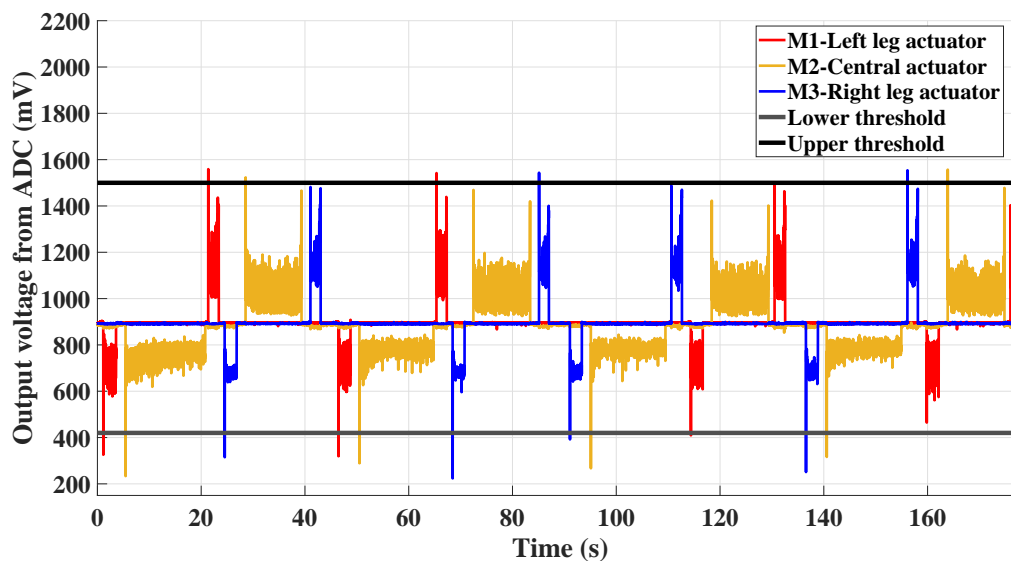


Figure 4: Output voltages of motors measured from ADC during experiments

The total time taken for the completion of the entire algorithm is 179 seconds. At 89.5 seconds, two sets of forward motions are completed and the reverse motion is initiated. At the end of experiments, the robot returns to its initial position to an over-constrained posture. The de-clamping operation on both legs could be performed to take out the robot. In Figure 4, the red and blue lines indicate the left and right leg actuators. The orange lines highlight the central motor. The threshold voltages are indicated by black and gray lines. It could be observed from the results that higher noises are generated in the output voltage of ADC. There are several factors which could contribute to these noises. When one set of leg mechanisms are clamped and the other end is free, a bending phenomenon was observed which could lead to potential numerical errors in the measure. In order to overcome this issue, a numerical filter is applied. Using MATLAB, the frequency of the noise is measured. With the help of Savitzky-Golay filtering technique in MATLAB [12], the measured frequency is matched with the desired frequency of BB black (2 kHz) for reducing the noise.

Using the smoothed output voltages, the current induced on the actuators can be estimated by the equation:

$$I = \frac{V_t I_c}{V_{idle}} - I_c \quad (1)$$

In Eqn. (1), V_t is the ADC output voltage at a given time t of the locomotion cycle. I_c is the nominal current of motor which is taken from Table 1. V_{idle} is the ADC voltage at 50% duty cycle which is

taken as 0.9 from Table 4. However, the current value obtained from Eqn. (1) does not provide the actual current as there exists power losses in the DC motor that is generated due to the resistance of the windings. The actual current measured from the motor is given by:

$$I_a = I - I_n \quad (2)$$

Here, I_n is the no-load current of motor and this value is subtracted from the result of Eqn. (1) to obtain the actual current induced in the motor. The results of actual current induced on each motor during the locomotion cycle is represented in Figure 5.

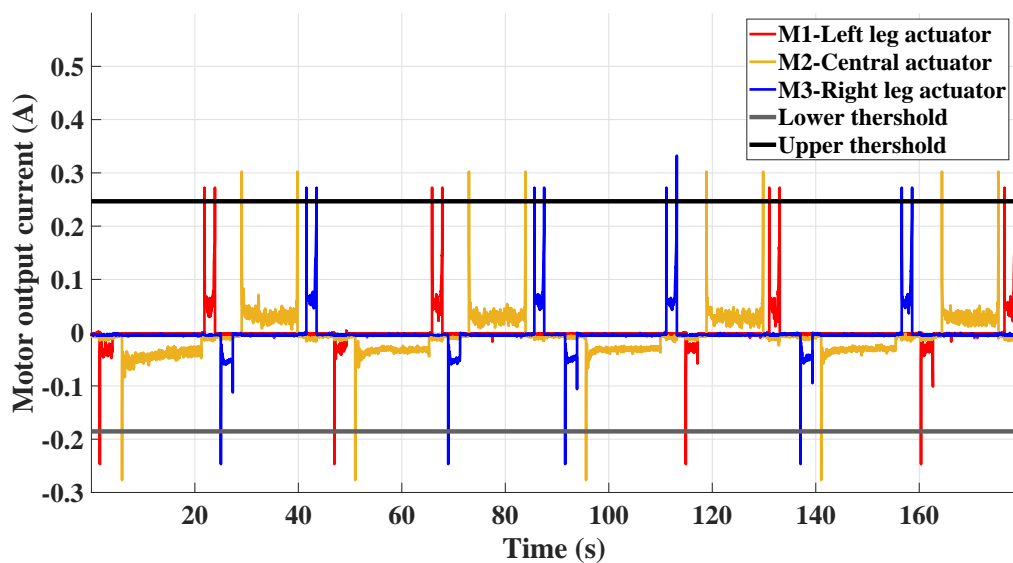


Figure 5: Actual currents induced on motors during the experiments

It could be observed in Figure 5 that smoother results are obtained with the application of filter. Also, higher starting voltages and currents are observed for each motor when a duty cycle is applied. This is because the motor rotates at a constant velocity and the time taken to attain this velocity when a duty cycle is applied is very short. This can be however rectified by following a motion profile such as "bang-bang", where the velocity is gradually increased until it reaches a constant value [13]. The de-clamping operation of motors $M1$ and $M3$ is not done completely in order to achieve larger displacements as the output velocity of the spindle drive is very low of around 0.43 mm/s [14]. However, the central actuator always extends/retracts to a maximum and this could be observed in Figures 4 and 5.

With the help of the output currents, the torques induced on the motors followed by the forces can be calculated by the below equations.

$$\tau = I_a K_T G \eta_m \eta_s \quad (3)$$

$$F = \frac{2\pi\tau}{p} \quad (4)$$

The parameters in Eqns. (3)-(4) such as the torque constant (K_T), gear ratio (G) and efficiencies (η_m and η_s) can be taken from Tables 1- 2. In Eqn. (4), p represents the pitch of the screw in the spindle

drive. The output forces and torques can then be studied for comparison with the results of simulation estimated in [14].

5 Conclusions and future works

The control of a bio-inspired piping inspection robot was studied in this article. Using a BB black micro-computer, the robot was tested inside a transparent PVC pipe of 74 mm diameter for a period of 179 seconds. It was possible to study the voltage induced on the motors during the cycle using the ADC of BB black. By applying numerical filters, the results were smoothed in order to derive the actual currents induced on the motors after power losses. The currents generated can then be used for estimating torques and forces induced on the motors during the locomotion cycle. The force control algorithm allowed us to carry out the experiments "blind" without going through a complex procedure. By experimental trails, the threshold limits were derived wherein the forces necessary to clamp the robot with pipelines walls can be attained. Higher threshold limits cannot be set as they not only damage the motors but also can possibly deform the leg mechanisms after the contact is established.

The force control algorithm allowed us to test the robot inside a pipe of 74 mm diameter. However, with varying pipeline diameters, it cannot be assured that the same threshold limits can hold good. This is one of the major limitations of this algorithm. In order to overcome this issue, in the future, the existing BB black will be replaced by a BB blue micro-computer. With the BB blue, the eQEP can be incorporated to the robot and it will be possible to detect the displacement of legs for an unknown pipeline diameter. The algorithm will be extended with the eQEP that will have a relation between leg displacement and the threshold limits. Another advantage of the BB blue is that it requires comparatively lesser cables for connection between the ESCON controllers over the existing BB black.

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Appendix

Algorithm 1 Forward sequence force algorithm

```

1: Initialization
   Hyper – static posture
2: while ADC of M1 <  $T_U$  do           ▷  $T_U$ - Upper threshold: Operation of motor till stall torque
3:   Front leg modules clamping: M1 rotation at constant speed
4: end while
5: while ADC of M2 <  $T_U$  do
6:   Central module retraction: M2 rotation at constant speed
7: end while
8: while ADC of M3 <  $T_U$  do
9:   Rear leg modules clamping: M3 rotation at constant speed
10: end while
    Advancement of robot                               ▷ Two forward motions ensured by a for loop
11: for  $i = 1 - 2$  do
12:   while ADC of M1 >  $T_L$  do           ▷  $T_L$ - Lower threshold: Operation of motor till stall torque
13:     Front leg modules de-clamping: M1 rotation at constant speed
14:   end while
15:   while ADC of M2 >  $T_L$  or ( $t < 2s$ ) do       ▷ Estimation of stroke as a function of speed
16:     Central module elongation: M2 rotation at constant speed
17:   end while
18:   while ADC of M1 <  $T_U$  do
19:     Front leg modules clamping: M1 rotation at constant speed
20:   end while
21:   while ADC of M3 >  $T_L$  do
22:     Rear leg modules de-clamping: M3 rotation at constant speed
23:   end while
24:   while ADC of M2 <  $T_U$  do
25:     Central module retraction: M2 rotation at constant speed
26:   end while
27:   while ADC of M3 <  $T_U$  do
28:     Rear leg modules clamping: M3 rotation at constant speed
29:   end while
30: end for
31: return ADC values

```
