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Smart-Spider: Autonomous Self-driven In-line Robot for Versatile Pipeline Inspection ⋆

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Abstract: This paper presents the design and development of a conceptual prototype of an autonomous self-driven inline inspection robot, called Smart-Spider. The primary objective is to use this type of robot for offshore oil and gas pipeline inspection, especially for those pipelines where the conventional intelligent pigging systems could not or be difficult to be deployed. The Smart-Spider, which is real-time controlled by its own on-board MCU core and power supplied by a hugged-up battery, is expected to execute pipeline inspection in an autonomous manner. A flexible mechanism structure is applied to realize the spider's flexibility to adapt to different diameters of pipelines as well as to handle some irregular situations, such as to pass through an obstacled areas or to maneuver at a corner or junction. This adaption is automatically controlled by the MCU controller based on pressure sensors' feedback. The equipped devices, such as the selected motors and battery package, as well as the human-and-machine interface are also discussed in detail. Some preliminary laboratory testing results illustrated the feasibility and cost-effective of this design and development in a very promising manner.

Keywords: Pipeline inspection, inline robot, autonomous control, flexible legs, HMI interface.

1. INTRODUCTION

Pipelines, used for offshore gas, oil and water transportation, tend to be corroded after some time. Many pipelines are located in some harsh marine environment, such as on or under the seabed, or even deep underground, and the geometries and configurations of the pipeline systems can be very complicated. The condition inspection and integrity check of these pipelines can be very challenging, and even impossible by deploying the conventional inspection tools, such as the intelligent pig systems, even though often the economic cost can also be tremendous, see Christian (2016) and Iszmir (2012).

Many existing commercial inline robots need to be equipped with tethers/cables for data transmission and power supply. Thereby, the inspection geometries is quite limited by these tethers/cables. See Young (2012). A crawler-type pipeline inspection robot is designed to inspect 80-100 mm diameter indoor pipelines in that paper. The four-bar mechanisms is introduced to assure that the flexible diameter of the robot can expand to firmly grip the pipeline inner surface. However, this robot still needs cables for transmitting the commands and the inspection data between the remote workstation and the robot.

An autonomous mobile robot for pipeline exploration, called FAMPER, is described in Jong (2010). Four independent suspensions are applied to link each caterpillar track and the central body, which structure makes the caterpillar track parts can contract in a small scale to adapt to bended pipelines. Because of the independent speed control of the four caterpillars, it has efficient steering capability to go through the pipelines with different branches. However, this robot can only be used for pipelines with a fixed diameter, that is 150 mm.

MRINSPECT V, a fixed diameter inline robot for 8-inch inner diameter pipelines is developed and presented in Se (2008). This inline robot can realize part of autonomous navigation, and the power for the electronic system and the motors is supported by the on board batteries. Besides that, a differential driving structure is adopted on the mechanism design, which makes the motion of the proposed robot adapt to different pipeline shapes. Moreover, the application of clutches is also highlight, which is able to select the suitable driving method based on different conditions for saving energy. The mobility and the efficiency performance of the robot are validated through experiments. However, although some wheels are installed on the two battery packages, there are no actuators on them. Thus, the motion of the two battery carriages cannot be controlled directly by the controller, but only depend on the push and pull from the other two actuator carriages. Furthermore, the proposed robot lacks the flexibility of adapting to different pipeline diameters.

An innovative Pipeline Inspection Gauge (PIG) for industrial pipelines with small diameters is designed and developed in Firas (2015), the functions of which are to clean and inspect pipelines. The diameter of the proposed

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PIG can adjusted to adapt pipelines with 6” to 14” inner diameters, by adapting its shirts. Ultra Sonic sensors and Arduino software are applied to inspect the diameter of the pipeline. Several arms are configured on the proposed robot to maintain the moving speed and the position as expected. The feasibility of the inline motion is validated using the Solidworks motion simulation tools. However, this robot model is only at the simulation stage, therefore, no physical model or experiments has been reported.

Without concerning to use any tethers or cables, a conceptual prototype inline robot, called Smart-Spider, is designed and developed in this work. A flexible mechanical structure is designed in order to handle versatile pipe diameters, and the control cores and electronic system as well as a Graphical User Interface (GUI) are also designed accordingly.

In this paper, the flexible mechanism structure is described in detail in Section 2. Section 3 describes the automatic control mechanism implemented in the MCU to real-time adjust the legs to different conditions based on the pressure variation on the wheels. The implementation of the proposed pipeline inspection robot platform, including the controller, some devices’ specifications and the preliminary experimental results, are described in Section 4 and the conclusion are followed in Section 5.

2. ARCHITECTURE OF THE SMART-SPIDER

2.1 Whole Smart-Spider System

The Smart-Spider system, as shown in Fig. 1, is composed of the robot device and the workstation. The Smar-Spider can move inline for performing some tasks automatically, without any tethers or cables connecting to the workstation. Regarding to the spider itself, the mechanism structure consists two parts: the main body and the flexible mechanism. The electronic system manages motion control, leg automatic adaption, data collection and storage etc. On the remote workstation side, the graphical user interface (GUI) are used for mainly two purposes: (1)sending start and end commands at the beginning and the end of one automatic inspection experiment; (2)monitoring the (pseudo-) real-time information in the experimental stage, via wireless communication between the robot and workstation.

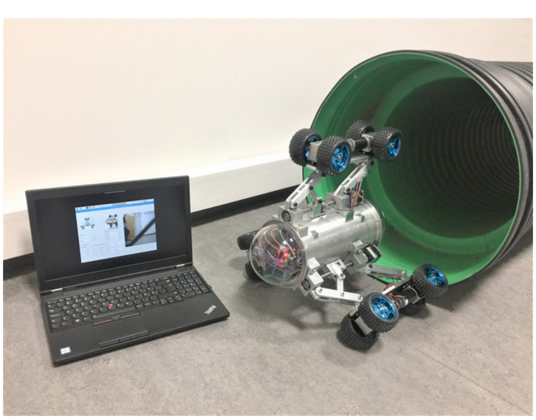

Fig. 1. The whole system of the inline inspection robot - the Smart-Spider

The main mechanism structure is represented in Fig. 2, which is composed of two parts: the tube body and the three flexible clutch mechanisms. Both of these two parts are processed by aluminium alloy. Inside the tube body is the rack for the electronic system and the three flexible clutch sets. The electronic system, consisting of a battery and two layers of electronic PCBs and components, is fixed on the tube inside. On the exterior surface of the tube body, the three sets of flexible clutch mechanisms are integrated with 120 degrees interval angle, which can make the Smart-Spider suit well for pipelines with round cross section. Besides, two transparent acrylic domes are assembled at the front and the rear sides of the tube body respectively.

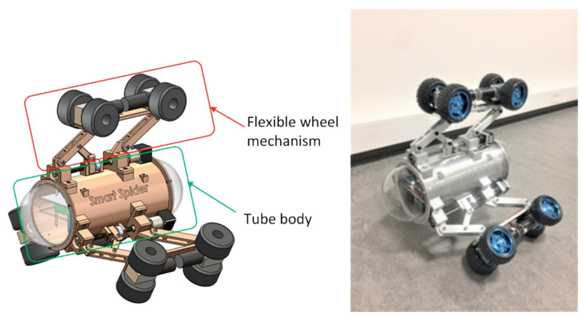

Fig. 2. The mechanism structure of the Smart-Spider

The length of the Smart-Spider is 426 mm and the exterior diameter is 300 mm. Based on the flexible mechanism, the exterior diameter of the Smart-Spider can adjust from 450 mm to 575mm, which means the variation of the flexible mechanisms can reach 78%. The diameter transmission range of the Smart-Spider is represented in Fig. 3. Therefore, the Smart-Spider can be applied for the inspection tasks in the pipelines with the diameter in this range.

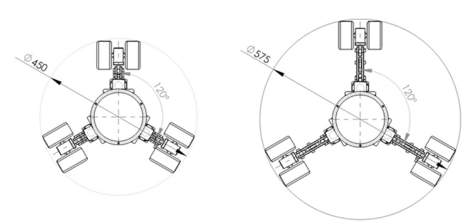

Fig. 3. The diameter transmission range of the Smart-Spider can be from 450 mm to 575 mm

2.2 Flexible mechanism

Three sets of flexible wheel mechanisms are integrated in the Smart-Spider, and all their structures are completely same. Each of these flexible wheel mechanisms consists of three units: the driving mechanism, the linkage clutch mechanism and the wheel units, shown as in Fig. 4 and Fig. 5, respectively. In order to be more compact and more flexible, a screw rod is applied to replace the traditional spring axe, which was used in Young (2010) and Young (2012), and an improved 4-bar structure is designed for the linkage clutch mechanism, compared with the design in Fa (2015). Every wheel unit is composed of two sets of wheels and every wheel set consists two wheels. Each wheel set is driven by a DC motor, which is equipped with a worm gear box, as shown in Fig. 5.

The driving mechanism is responsible for actuating the 4-bar linkage clutch mechanisms to extend or contract, followed the wheel units to adjust to different pipeline diameters. The screw rod is driven by a stepper motor to revolve clockwise or anticlockwise. Therefore, the U-shape slider and the connector slider crossing on the screw rod can move forward and backward respectively. Then, the angle in the 4-bar linkage clutch transforms according to the position of the sliders, which determines the exterior diameter of the Smart-Spider.

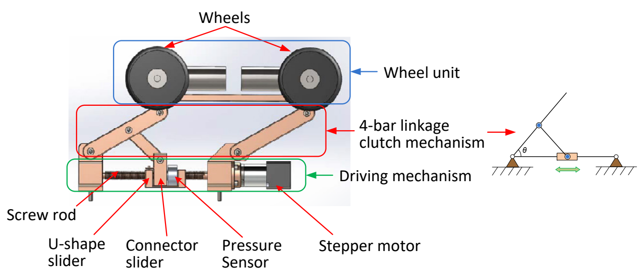

Fig. 4. The horizontal view of the flexible mechanism of the Smart-Spider

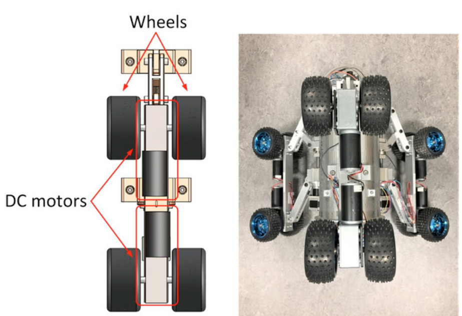

Fig. 5. The top view of the flexible mechanism of the Smart-Spider

The force relationship between the force on the wheels and the pressure on the sliders is shown as in Fig. 6. Through this relationship and the pressures measured by the pressure sensors, the pressures and the friction forces between the wheels and the pipeline inner surface can be calculated. The friction forces are caused by the pressures, and suitable friction forces ensure the Smart-Spider moving smoothly. Therefore, these pressures and friction forces are critical to the dynamics of the robot.

The length of the bar PE is l. The length of ME and the slider bar SE can be considered to be the same, which is represented as l'. The torque on point P relative to point E, which is T_P, and the torque on point M relative to Point E, which is T_M, are equal, described in equation (1).

$$T_P = T_F \tag{1}$$

The torque on point P relative to point E can be calculated as:

$$\begin{aligned} T_P &= F_P \cdot \cos\theta \cdot l + F_f \cdot \sin\theta \cdot l \\ &= F_P \cdot l \cdot (\cos\theta + \mu \cdot \sin\theta) \end{aligned} \tag{2}$$

where F_P is the pressure on the P point, F_f is the friction between the wheels and the pipeline inner surface and μ is the friction coefficient.

The torque on point S relating to point E is:

$$T_F = F_1 \cdot l' \tag{3}$$

Therefore, F_1 can figure out. Then through dividing F_1, the force on the slider bar F_2 is:

$$F_2 = F_1 \cdot \cos(\alpha - 90°) \tag{4}$$

Because $\alpha = 180° - 2\theta$, F_2 can be represented as:

$$F_2 = F_1 \cdot \cos(180° - 2\theta - 90°) = F_1 \cdot \sin(2\theta) \tag{5}$$

The pressure on the slider F_S, which is collected by the pressure sensor, can be got by dividing F_2:

$$F_S = F_2 \cdot \cos\theta \tag{6}$$

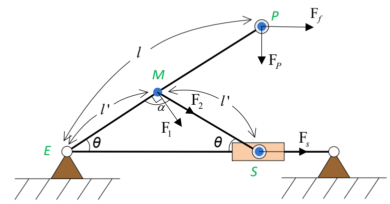

Fig. 6. The force analysis of the linkage clutch mechanism

3. IMPLEMENTATION

3.1 Flexible mechanism motion control strategy

The motion of the flexible mechanisms are controlled by the MCU based on the pressure data between the wheels and the pipeline inner surface, which are related to the pressures between the connector slider and the U-shape slider. In normal straight pipeline without diameter transformation, the pressures are within the threshold ranges. For some special pipelines, such as oil pipelines, the friction between the wheels and the pipeline inner surface, which is decided by the pressure between them, must be big enough to guarantee the Smart-Spider's normal rolling movement. However, when the inner diameter of the pipeline changes, the pressures on the wheels will change, and the pressures between the sliders will transform accordingly. The flexible mechanisms will contract when the pressures exceed the threshold ranges when the pipeline inner diameter changes into smaller, for example, there is an obstacle or a corner. On the contrary, the flexible mechanisms will extend when the pressures reduce lower than the threshold ranges.

The pressure threshold range for different flexible mechanisms on different positions can be different, that is, the pressure threshold for the two bottom flexible mechanisms are much higher than the top one if the robot moves mainly in the horizontal way. In some situations, the attitude of the Smart-Spider changes during moving along the pipeline, and if the variation of the attitude is big enough, a rolling motion can happen. Therefore, the positions of the previous top and bottom flexible mechanisms may exchange. In the MCU, the pressure threshold ranges for each flexible mechanisms need to adjust according to specific attitude orientations, where the attitude is collected by

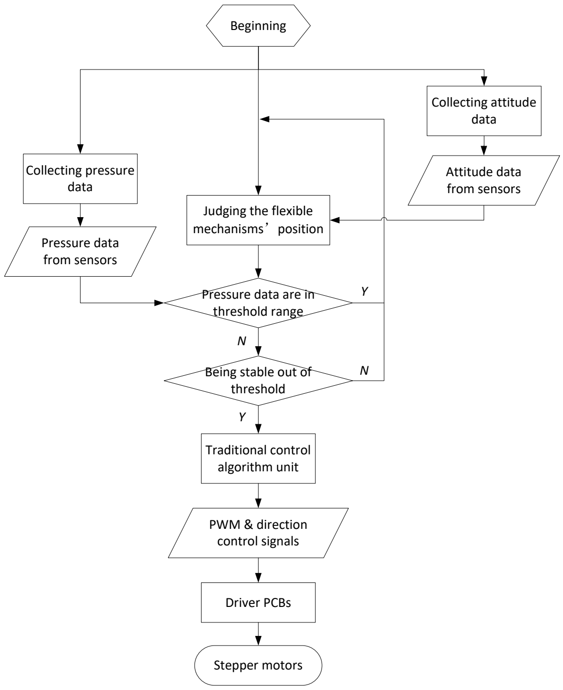

Fig. 7. The flow chart of the flexible mechanism motion control based on pressure data

the attitude sensor and the threshold ranges are set by ad hoc experimental experience at this moment.

The motion strategy of the flexible mechanisms in the MCU is shown in Fig. 7, and this is for one control-cycle period. At first, the positions of the three flexible mechanisms are estimated based on the proposed robot's attitude measurement, and the threshold ranges for each one can be decided, where the attitude data are collected by the attitude sensor. Based on the definite threshold ranges, the pressure data for each flexible mechanism are compared with the range. For calculation efficiency, these ranges are directly defined for the pressure between the sliders, which omits calculating the pressure on the wheels. If one or more pressures exceed higher or lower than the threshold ranges, the MCU will not drive the motors to transform the Smart-Spider's diameter immediately, but will store the pressure situations until several sampling periods later. If all these pressures are beyond the threshold ranges, the MCU will control the stepper motors by sending PWM signals to the driver boards after the PI controller. All the three flexible mechanisms contracting or extending at the same time can ensure the equilateral triangle mechanical structure of the three flexible mechanisms, which is a stable structure for the Smart-Spider to fit motion requirements, see Se (2008).

3.2 Task processing

The tasks of the electronic system can be divided into two categories: real-time tasks and non-realtime tasks, shown as in Fig. 8. The real-time tasks are implemented by a MCU PCB, which is equipped with STM32F407 control core. And the non-realtime tasks are implemented by a Raspberry Pi, installed with Debian operational system. Data and commands are transmitted between the MCU and the Raspberry Pi through UART.

In the real-time control system, the collection and the analysis of all the sensor data, and the motion control of all the stepper motors and DC motors are handled by the MCU. The pressure data from the three pressure sensors and the attitude information from the attitude sensor are collected by the MCU. Moreover, the flexible mechanisms' motions based on the pressure and each DC motor's speed is judged in the control strategy in the MCU. Then, the PWM signals for controlling the stepper motors and the DC motors are generated by the MCU to the driver boards. Meanwhile, the real time sensor data are transmitted to the Raspberry Pi for displaying on the GUI.

Regarding to the non-realtime control system, the workstation communicates with the Raspberry Pi through Wifi in experimental environment. The GUI system is designed to monitor the image collected by the on-board camera, and display the (pseudo-) real-time data of the Smart-Spider. Besides, users can configure the inline robot's motion mode (Auto or Manual) and the motors' motion situations through the GUI, which are transmitted to the MCU. Meanwhile, all the real-time data are written into a SD card for storage and post analysis.

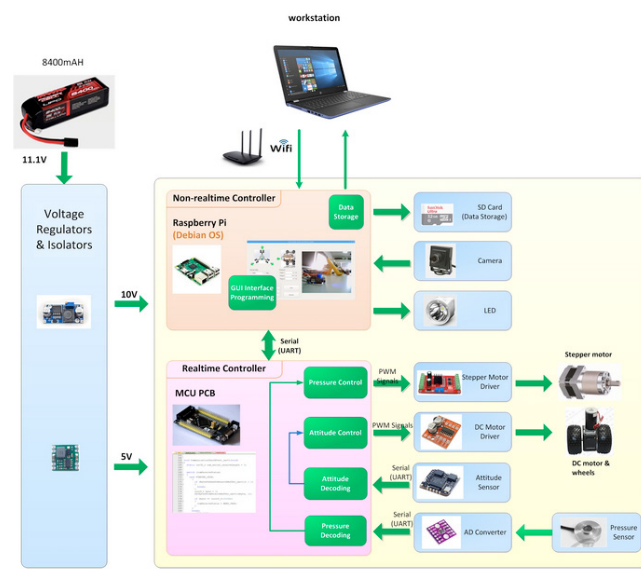

Fig. 8. The structure of the electronic system

3.3 Actuators and Battery

DC Motor DC motors with a worm gear box are used to output a given torque on the purpose of driving the wheels to move in a given direction at a specific speed. Every two DC motors are fixed on the top of one flexible mechanism, so there are six DC motors in total in the Smart-Spider. Each DC motor is equipped with a worm gear box to increase the output torque, so each DC motor with a gear box can actuate two wheels. The speed and the direction of the DC motors are controlled by the MCU controller, based on the requirement of the motion. The specifications of the DC motor with a worm gear box are listed in Table. 1.

Stepper Motor The function of the stepper motor kits in the Smart-Spider is to actuate the screw rod, so that the flexible mechanisms can stretch or contract. Three stepper

Table 1. Specifications of the DC Motors

Specification	Value
Nominal Voltage	12.0 V
Nominal Speed	28 rpm
Max. Speed	72 rpm
Rated Current	0.6 A
Max. Current	2.3 A
Rated Torque	12.0 Kg.cm
Max. Torque	57.0 Kg.cm
Reduction ratio	1:108

motors are used, and each stepper motor kit is equipped at the end of a screw rod, which follows the motion of the motors by a coupling connection. To get strong enough torque for driving the flexible mechanisms, a gear box is applied in the stepper motor kit. The reduction ratior of the gear box is 1/52, and the static torque can reach 12.0 Kg.cm. The specification details of the stepper motor with a gear box are listed in Table. 2.

Table 2. Specifications of the Stepper Motors

Specification	Value
Step Angle	1.8 degree
Nominal Voltage	10.0 V
Rated Current	1.0 A
Static Torque	12.0 Kg.cm
Reduction ratio	1:52

Battery The Li battery is the main source of the whole electronic system, the details of the specifications of which is listed in Table. 3. The capacity can reach as high as 8400 mAh, although the size is small enough to fixed inside the body tube. Due to the rated current of the DC motors is 0.6 A, and the rated current of the stepper motors is 1.0 A, the battery can support the Smart-Spider moving inside the pipeline for around 2 hours.

Table 3. Specifications of the Battery

Specification	Value
Type	LiPo
Output	11.1 V
Cells	3S
Capacity	8400 mAh
Size	155×44×45mm

4. EXPERIMENTS

In this experiment, the automatic motion of the Smart-Spider and the feasibility of the flexible mechanisms are verified in the laboratory pipeline, the material of which is PVC and the inner diameter is 500 mm. The proposed inline robot moves forward automatically completely after a simple launching.

Firstly, the Smart-Spider moves in a pipeline with smooth inner surface, that is, there is no obstacle inside of the pipeline. Before the experiments, the initial attitude of the Smart-Spider is that the two bottom flexible mechanisms are nearly at the horizontal flat, that is, the top flexible mechanism is perpendicular to the horizontal flat. So the initial pitch(around -4deg) and the roll(around 1deg) of the inline robot is very small, shown as in Fig. 9. And the initial pressure forces on the flexible mechanisms are approximately 118 N, 88 N and 10 N respectively, shown in Fig. 10. From the diagrams we can see that the Smart-Spider can move smoothly along the inner pipeline, although a small rolling happens, the attitude of the robot keeps stable.

The four steps of the pipeline robot overcoming an obstacle in the pipeline are shown as in Fig. 13, and the pressure data and the attitude information during the process are shown as in Fig. 11 and Fig. 12. From 0 s to around 20 s, the Smart-Spider keeps moving forward smoothly, although some small frequent fluctuations are generated because of the dumps of the pipeline. At around 20 s, the robot begins overcoming the obstacle. When the pressures increase and exceed higher than the threshold, and hold higher for 10 sampling periods, the three flexible mechanisms start contracting at the same time, driven by the MCU until the pressures fall back to the threshold bands again. From around 42 s, the robot begins leaving the obstacle, so the pressures on the flexible mechanisms decrease suddenly. Therefore, the flexible mechanisms start stretching to adjust to the pipeline diameter. During this process, the variations of the attitude of the Smart-Spider is small, that are less than 1.5 deg for roll and around 5 deg for pitch respectively. Therefore, the rolling of the Smart-Spider can be ignored during this process, so the threshold range for each flexible mechanism does not need to be adjusted during the entire experiment.

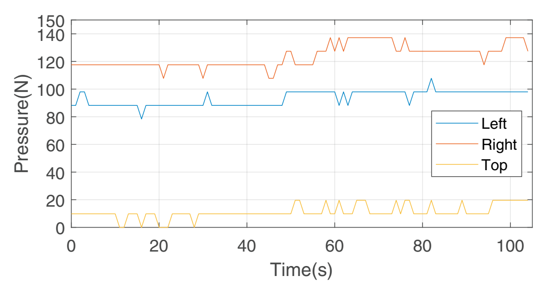

Fig. 9. The pressure on the three flexible mechanisms of moving in smooth situation

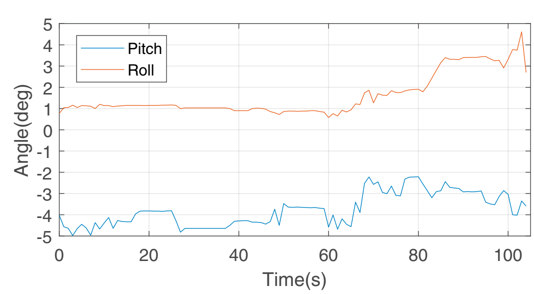

Fig. 10. The attitude of moving in smooth situation

The user interface of the Smart-Spider system is shown in Fig. 14. Not only the real-time image from the camera, the graphical motion situations and some sensor data can be monitored on this interface, but also some motion commands can be handled by the buttons.

From the experiment results, the motion feasibility and the flexible mechanisms' automatic control are validated, and the expected functions of the Smart-Spider are realized satisfactorily.

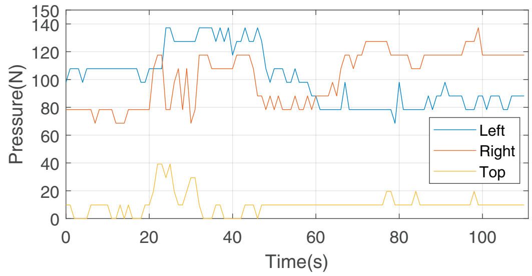

Fig. 11. The pressure on the three flexible mechanisms of overcoming an obstacle

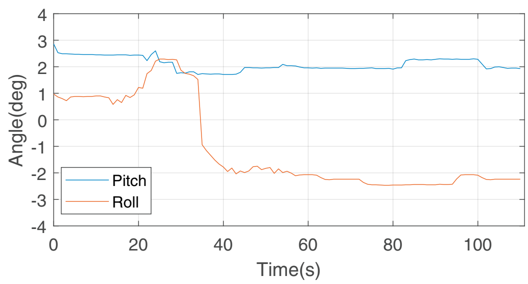

Fig. 12. The attitude of overcoming an obstacle

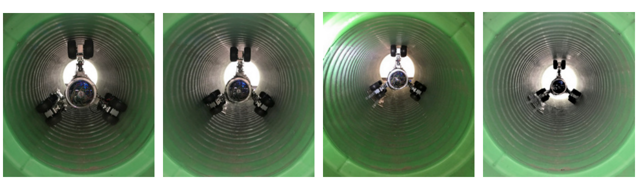

Fig. 13. The three-stage motions of the Smart-Spider during the experiment (a)moving smooth stage (b)preparing-to-overcome stage (c)on-obstacle stage (d)obstacle-overcome stage

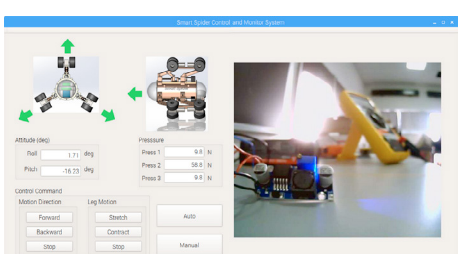

Fig. 14. The user interface of the Smart-Spider

5. CONCLUSION

In this paper, an automatic inline inspection robot prototype, called Smart-Spider, is designed and developed. It can move along the pipeline to implement some tasks and handle some specific conditions, such as an obstacle, completely automatically, which dues to the application of the MCU controller and the flexible mechanisms. Besides, without the limitation of any tethers or cables, the proposed robot's motion can be more flexible and more distant, which are important features for the inspection of some complex industrial pipelines. Lastly, the stability of the robot's motion and the feasibility of the automatic control of the flexible mechanisms are verified in the laboratory pipeline, and the experimental results are presented and analyzed.

For the future Smart-Spider generations, many improvements will be applied:

(1) On-board algorithms for automatic path recognition and planning for complex or unknown pipeline environments;
(2) Integration with inspection tools for specific applications;
(3) Strategies for self-monitoring and self-rescue in case of getting stuck inside the pipelines;
(4) Smart power management design from information collection and energy efficiency aspects.

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