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Screw Transformation Mechanism of Screw-Propelled Robot for Efficient Void Detection in Grease Pipe

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Abstract

In general, detection robots using ultrasonic sensors are equipped with sensors to protrude outward or to contact objects. However, in the case of a screw-propelled robot that detects the inside of a reactor tendon duct, if the ultrasonic sensor protrudes to the outside, resistance due to grease is generated, and thus the propulsion efficiency is reduced. To increase the propulsion efficiency, the screw must be sharp, and the sharper the screw, the more difficult it is to apply a high-performance ultrasonic sensor, and the detection efficiency decreases. This paper proposes a screw shape-changing mechanism that can improve both propulsion efficiency and detection efficiency. This mechanism includes an overlapped helical ring (OHR) structure and a magnetic clutch system (MCS), and thus the shape of a screw may be changed to a compact size. As a result, the Screw-propelled robot with this mechanism can reduce the overall length by about 150 mm and change the shape of the screw faster and more accurately than a robot with a linear actuator.

Keywords

Screw-propelled
Overlapped-screw
Magnetic clutch
Grease robot

1. Introduction

In general, mobile robots use various sensors to identify the environment, and in particular, light detection and ranging (LiDAR), radar, and ultrasonic sensors are used to detect objects [1]. Among them, ultrasonic sensors are widely used in non-destructive testing (NDT) because they are resistant to noise generated by various media, although they lack range and resolution compared to other sensors [2]. Ultrasonic sensors can measure the distance to the object being detected, which is calculated by measuring the time it takes for a pulse sent from a transmitter to bounce off the boundaries of the medium and arrive at the receiver [3]. Therefore, robots using ultrasonic sensors must either project the sensor outwards or position the sensor in contact with the object to be inspected to efficiently measure the distance to the defect [4,5].

Among the inspection robots that use ultrasonic sensors is a small-diameter screw-driven robot [6], which was developed to inspect internal defects in the post-tensioning of nuclear reactors. The reactor post-tensioning consists of a 100 m long tendon channel with strands to increase the strength of the structure and grease to fill the remaining space to prevent corrosion of the strands, as shown in **Figure 1** [7]. However, there have been cases of grease leakage in nuclear reactors at home and abroad, and when voids occur due to grease leakage, the strand exposed to the air can be corroded, and in severe cases, the strand can even break. To prevent this, the proposed robot, which is inserted into the tendon duct to inspect the inside directly, uses an ultrasonic sensor to detect voids in the grease in the tendon duct, unlike general robots that detect objects in the air.

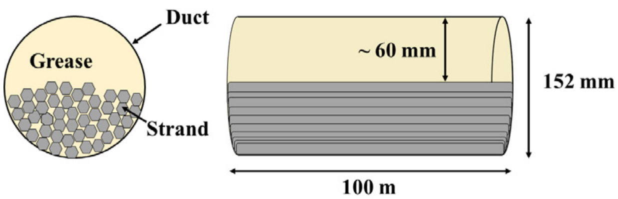

Figure 1. Tendon duct in an atomic pile

Since it is difficult to see the inside of the tendon canal with the naked eye, a high-resolution ultrasonic sensor is required to improve the reliability of detection. Therefore, considering the acoustic impedance of grease and its semi-solid state, a high-frequency sensor should be used to increase the resolution, and a large-diameter sensor should be used to stably receive signals disturbed by grease [8].

In addition, the robot uses the rotation of the screw to move in the low-liquid grease and to avoid noise caused by the rotation of the screw, the ultrasonic sensor is mounted at the front of the robot to detect grease voids inside the duct. In the event of a grease void, the ultrasonic sensor calculates the distance from the robot to the void to determine if a void exists, as shown in **Figure 2**.

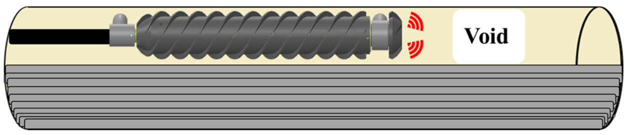

Figure 2. Void detection of screw-propelled robot

However, in this set-up, where the ultrasonic sensor is positioned at the front of the robot, as the robot advances, the friction from the grease impacts the overall surface of the ultrasonic sensor, thereby hampering its efficacy in propelling the robot forward (see **Figure 3**). As the cross-sectional area of the ultrasonic sensor increases, the efficiency of propulsion decreases. Beyond a specific size, the resistance of the grease surpasses the propulsive force of the robot, leading to immobilization.

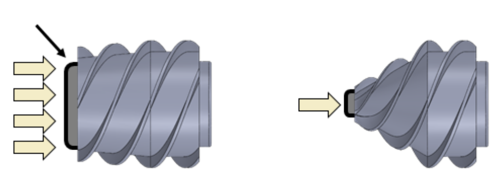

Figure 3. Shapes for ultrasonic sensor's size

To increase propulsion efficiency, it is necessary to sharpen the robot's leading edge. However, since the robot's screw diameter must be smaller than 60 mm, it becomes more challenging to apply an ultrasonic sensor of adequate size and performance the sharper the leading edge is. Thus, when the screw head is sharpened to improve propulsion efficiency, the efficiency of void detection decreases due to the inability to install a sufficiently performing ultrasonic sensor.

To address this issue, the paper introduces a mechanism capable of optimizing propulsion and inspection efficiency. The said mechanism entails modifying the shape of the screw-propelled robot head based on the prevailing situation. A combination of an overlapped helical ring and a magnetic clutch is employed to implement this screw structure change mechanism. This approach enables the mechanism's application without requiring significant changes to the robot's size.

2. Mechanism modeling

2.1. The concept of the mechanism

The screw structure change mechanism for efficient propulsion and inspection of the robot is divided into two modes, propulsion and inspection modes, and changes modes depending on the situation. As illustrated in **Figure 4**, during the propulsion mode, an ultrasonic sensor is embedded within the robot while the leading edge maintains a sharp shape to reduce grease resistance and improve the robot's efficiency of propulsion. In contrast, the probe mode involves cutting the screws on the head to accommodate the ultrasonic sensor, which protrudes from the robot's head to detect grease voids.

To enable the ultrasonic sensor to protrude from the robot, linear motion is necessary, which is typically generated using a linear actuator. However, this requires more space than the distance the ultrasonic sensor needs to move (see **Figure 5**). Therefore, the application of a linear actuator augments the robot's overall length, by including the motor-driver for operation.

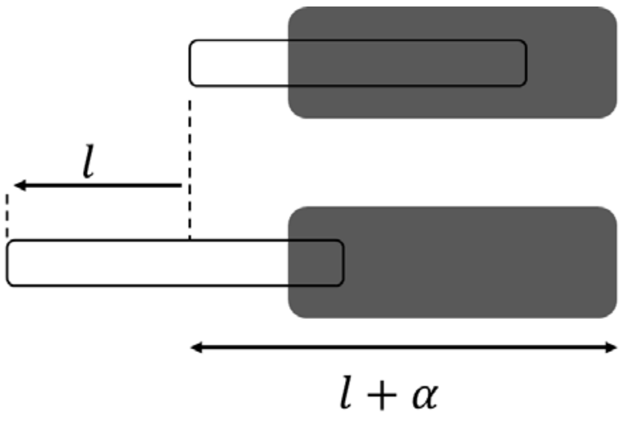

Figure 5. Schematic diagram of a linear actuator's motion

This paper presents a modification mechanism of the screw structure, integrating an overlapped helical ring configuration that allows rapid and efficient movement of the ultrasonic sensor while limiting changes in the robot's overall length. Additionally, the integration of a magnetic clutch enables power supply from the robot's propulsion motor, without the need for an added rotary motor to maneuver it.

2.2. Overlapped helical ring mechanism

The overlapped helical ring (OHR) mechanism is based on the principle of a screw, which converts rotational motion into linear motion. It comprises multiple rings with overlapped helical grooves. As illustrated in **Figure 6**, when one helical ring rotates due to the motor, other helical rings are gradually deployed and the extent of linear motion can be modified based on the number of rings and the helix pitch. The abbreviations of technical terms will be explained during their first use.

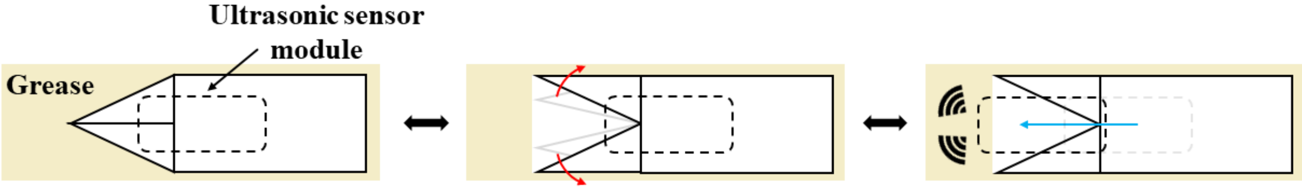

Figure 4. Schematic diagram of screw transform mechanism

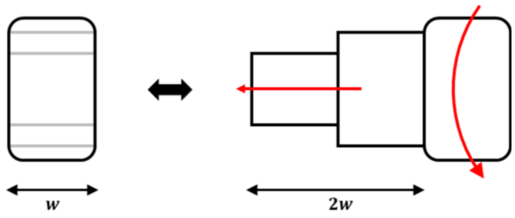

Figure 6. Schematic diagram of the overlapped helical ring (OHR) mechanism

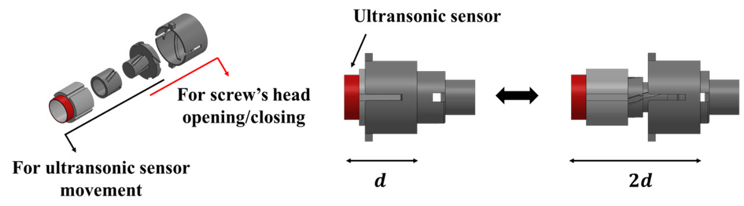

Figure 7. Modeling of the overlapped helical ring (OHR) for a screw-propelled robot

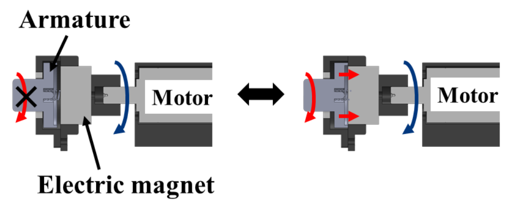

Figure 8. Schematic diagram of magnetic clutch system (MCS)

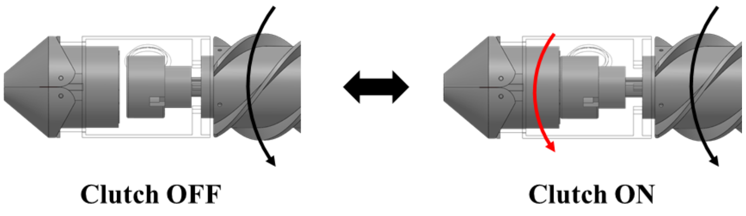

Figure 9. Modeling of the magnetic clutch system (MCS) for a screw-propelled robot

In this paper, we developed an OHR model to produce a linear displacement of 40 mm within a 20 mm area, as demonstrated in **Figure 7**. Both the screw-opening/closing mechanism and the ultrasonic sensor-moving mechanism operate simultaneously, enabling alterations to the screw structure.

2.3. Magnetic clutch system

Although clutches are commonly employed for regulating power transmission in automobiles, such bulky clutch systems are not suitable for small robots with a diameter of 60 mm or less. Therefore, in order to apply to small-diameter robots, a small electromagnet motor with an on/off clutch operation type and an armature for power transmission is configured as presented in **Figure 8**.

When the armature makes contact with the electromagnet through the application of a signal, the OHR mechanism is activated, transmitting power from the robot's propelling motor. However, during propelling mode, when the robot is in motion, the signal to the electromagnet is disconnected, causing the armature to drop and preventing the transfer of power from the propelling motor to the OHR. The magnetic clutch system (MCS) utilized a relay module as an energizing switch for activating and deactivating the electromagnet motor. This allowed for continuous structure changes while the robot was in motion.

A model of the MCS was developed and subsequently miniaturized to suit the size of the screw-propelled robot, as illustrated in **Figure 9**. In the propulsion mode of the robot, the clutch is disengaged to allow movement without affecting the OHR structure. When switching to inspection mode, a signal activates the clutch to transfer power to the OHR. The activated OHR alters the screw structure, enabling the robot to identify grease voids.

3. Experiment Results

A model of the screw structure change mechanism was developed using OHR structure and MCS. The screw is made relatively sharp in the propulsion mode to enhance the propulsion efficiency, while in the inspection mode, the ultrasonic sensor is moved to the robot's front to minimize the impact of screw rotation while maintaining contact with the grease. Refer to **Figure 10** for a depiction.

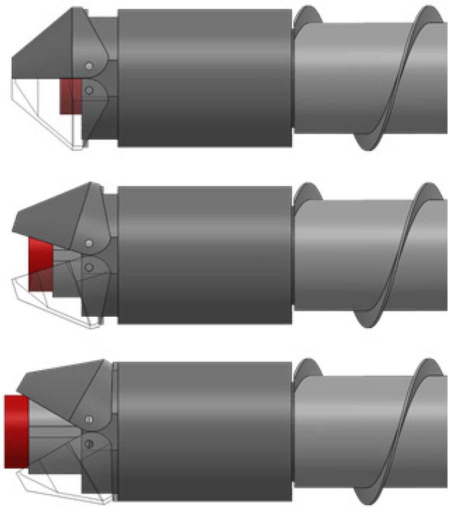

Figure 10. The sequence of the screw transform mechanism

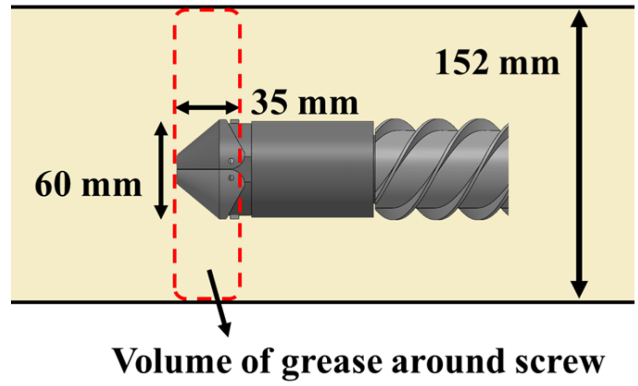

Figure 11. Volume of grease

Table 1. Various volume values

Volume of grease in the duct (V_d)	Volume of the screw (V_s)	Volume of grease around the screw ($V_d - V_s$)
635.10 cm^3	32.98 cm^3	602.12 cm^2

Based on the previous modeling, a 3D printer produced a prototype of the screw structure modification mechanism that can be implemented in the screw-propelled robot. The minimum force required to cut the screw was assumed to be the weight of the grease surrounding the modified screw, which is illustrated in **Figure 11**. Therefore, the amount of grease encompassing a screw with an outer diameter of 60 mm was determined by calculating the volume of grease present inside a duct with an inner diameter of 152 mm and subtracting the volume of the screw (see **Table 1**).

By utilizing the density of RP 600 grease, which was used in the field (0.9 g/cm) [9], the weight of the grease surrounding the screw was evaluated as 5.3 N. Thus, a minimum force of 5.3 N was necessary to sever the screw. As the amount of grease in the duct is lower than that assumed in **Table 1**, due to the insertion of a lecture wire in the actual field, a screw can be incised with a force greater than 5.3 N in the actual field.

By measuring the force required to cut the screw with the OHR in the air using a load cell, it was determined that the screw is cut with a maximum force of approximately 25 N, as depicted in **Figure 12**. Therefore, it is hypothesized that by adequately expelling the surrounding grease, the screw can be cut within a second.

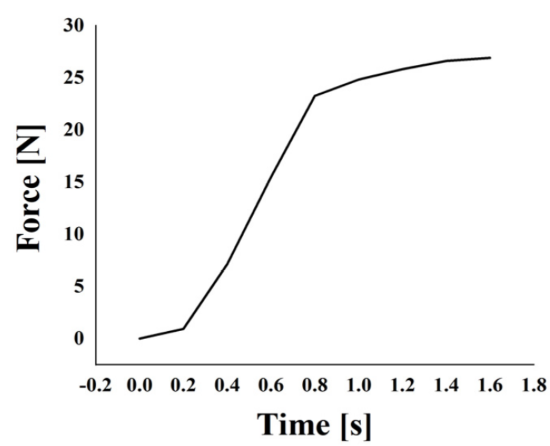

Figure 12. Result of the screw opening force

Furthermore, a testbed was constructed to examine the operation of the prototype MCS and confirm its ability to transmit power (see **Figure 13**).

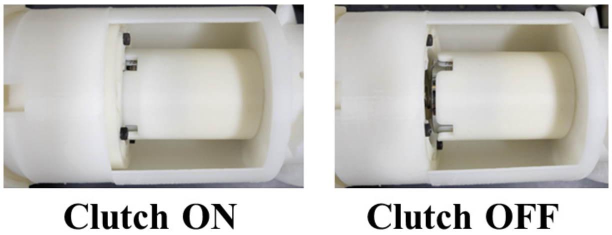

Figure 13. Change of MCS state

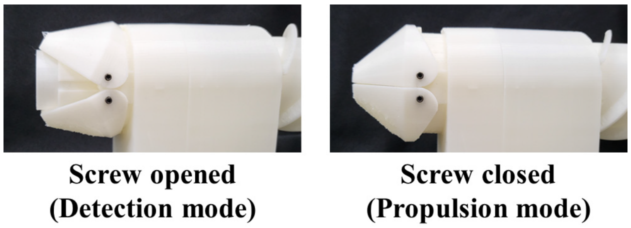

Figure 14. Applying the mechanism to the robot

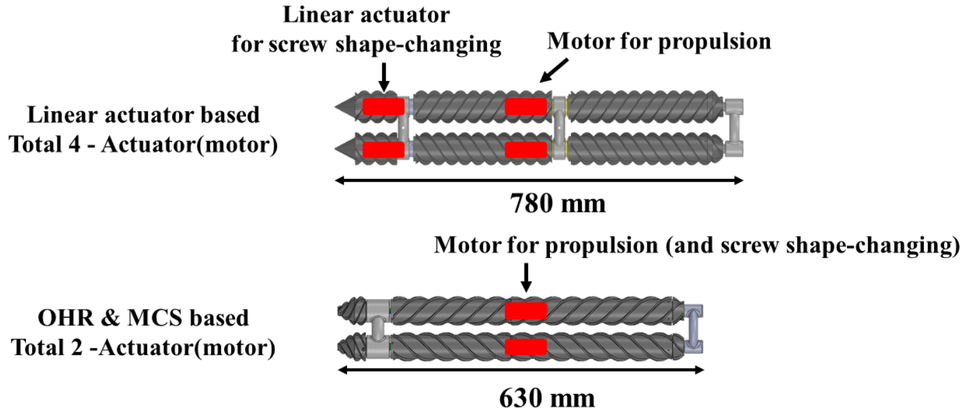

Figure 15. Comparison of robot's size between linear actuator-based robot and OHR & MCS-based robot

The screw structure change mechanism prototype, which integrates OHR and MCS, was installed on the robot's testbed for driving experiments. Through airborne experiments illustrated in **Figure 14**, the screw structure was adjusted according to the situation.

As a consequence, the mechanism alteration utilizing OHR and MCS synchronizes the power system, allowing effortless management of the mechanism whilst the robot is in motion. This reduces the robot's total length by roughly 150 mm when compared to a robot employing a linear actuator (**Figure 15**).

4. Conclusion

This paper proposes the use of the OHR structure and screw structure change mechanism with MCS to enhance the propulsion efficiency of the robot by embedding the ultrasonic sensor and maintaining a sharp leading edge. Additionally, this approach can improve inspection efficiency by cutting the screw and relocating the ultrasonic sensor to the foremost position during inspections. Experiments have demonstrated that the screw-propelled robot using this mechanism is capable of altering its shape to suit the situation. It is anticipated that this will address the issue of diminished propulsion/inspection efficiency resulting from structural concerns associated with the robot during inspection missions. However, to implement it in the field, research is necessary to overcome the manufacturing limitations of 3D printing and the material's durability. Furthermore, an experiment will be required to develop a structural design that prevents the clutch from slipping during robot operation in grease pipes.

Disclosure statement

The authors declare no conflict of interest.

Acknowledgment

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