別紙４－１（課程博士（英文））

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Department of Mechanical Engineering	Student ID Number	D 209106	
Applicant's name	Mohamed Mostafa Abdelaziem Khalil		

Supervisors	Prof. Kotaro Takayama

Abstract (Doctor)

Title of Thesis	Design and Control of a Micro Ultrasonic Motor-Based Insect-Scale Robot for Inspection Purposes

Approx. 800 words

The inspection and monitoring of industrial sites, machines, and infrastructure are important issues for their sustainability and further maintenance. A major problem that always exists in civil structures and industrial sites is that they are rarely uniform in shape and are not typically designed with considerations for easy inspection access. The same problem is associated with machines, where inspection of complicated machines like turbine engines requires the disassembly of a lot of components which can be costly and time-consuming.

A common element that exists in all industrial sites, civil structures, and machines is the countless number of tubes and pipelines to transport all kinds of fluidic materials. We consider these tubes and pipelines as direct routes to the core of an inspection site or a complicated machine. We currently take advantage of these pipes and tubes to explore inaccessible structures and the core of complicated machines by the borescopes. Although it provides crucial information, it is extrinsically manually actuated by an operator which makes it hard to point it to a specific spot. It is time to think then of the next generation of borescope as a miniature robot intrinsically actuated and capable of navigating inside narrow tubes and pipelines efficiently. This research addresses different challenges of scaling down robots, that require the significant integration of component technologies such as actuators, fabrication techniques, and sensing machines.

The first challenge is the driving mechanism, downsizing an actuator to a micro size comes with a lot of problems. For example, electromagnetic actuators that dominate at the macro-scale diminish their power at the micro-scale due to their scaling law. Instead, piezoelectric ultrasonic motors perform at such a scale as the most prominent microactuator because of their high-power density and good machinability. However, despite their great scalability, they have obvious nonlinear and time-varying characteristics that deteriorate their performance in prolonged operations. We investigated that problem by studying the effectiveness of the motor's internal parameter changes, such as a temperature rise and the resonant frequency variation. For that, a mathematical model was derived from scratch, followed by several experiments to verify the hypothesis experimentally. The experiments also prove that such deviation affected the motor performance by enlarging its steady-state error with time. To solve this dilemma, we introduced a model-free, real-time-adaptive extremum seeking controller (ESC) that can coop with the non-linear characteristics of the motor. To build the control structure, we constructed the smallest rotary actuator-sensor system in the world that consists of a micro-ultrasonic motor, a tiny TMR sensor, and a tiny magnet. The resulting system was assembled into a size with a height of 3.2 mm, a width of 3.2 mm, and a length of 5 mm. Several experiments that involve constant and variable speed commands show that the controller succeeded to drive the motor at the desired angular velocity with a minimum steady-state error by continuously tracking and localizing the optimum driving frequency.

The second challenge is the design itself of the robot. An inspection robot is expected to reach inaccessible areas by navigation in confined places including inside narrow tubes and pipelines in harsh working environments. To fulfill these requirements, we have taken design principles adapted from the caterpillar. The caterpillar's prowess is due to a combination of design features that work together to permit rapid and smooth locomotion. This functionality is achieved by the proposed robot by a light rigid structure made of 2 links connected by an active pivot joint that allows the climbing robot to extend and flex. The pivot joint enables the robot to navigate inside a wide range of pipelines from 12 to 25 mm by changing its height. The joint also allows the robot to exert a force against the upper walls for holding the robot inside the pipes, which can be treated as an integrated holding force mechanism. Two locomotion modes to propel inside pipelines are presented, and a proposed motion strategy to navigate complex pipe configurations, including vertical and bent pipes, is presented and validated by a series of experiments.

To extend the working domain of the inspection robot, we study the possibility of merging the robot with an adhesion mechanism to perform more challenging tasks such as replacing manual inspection at heights. For that, numerous adhesion methods were investigated until we come up with an approach of using low-cost dry adhesive materials to address climbing challenges, including surface-to-surface transitions, and vertical and inverted locomotion with high payload capacity. This idea was inspired by the climbing action of caterpillars on vertical surfaces as stationary legs provide anchoring force to hold their weight. In addition, different dry adhesive materials were analyzed and the selection criteria for the appropriate adhesive material to cover the full range of motion were also demonstrated. Final experiments prove the viability of the insect-scale robot to navigate complex structures (vertically and invertedly) while performing different cases of surface-to-surface transitions. A payload-mass ratio of 120% was also achieved while climbing on a vertical surface.

The findings of this thesis prove the functionality of the insect-scale robot for various maintenance tasks, and it also demonstrates the potential of low-cost dry adhesive materials in the field of miniature climbing robots. Using the concept of mimicking the locomotion pattern of biological creatures results in an unprecedented mobility performance for an insect-scale robot.