別紙４－１（課程博士（英文））

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Department	Student ID Number	Applicant's name	Supervisors
Mechanical Engineering	D111816	Ayato Kanada	Tomoaki Mashimo Zhong Zhang

Abstract (Doctor)

Title of Thesis	Flexible Linear Motors for Mobile Continuum Robots

Approx. 800 words

Organisms that exploit soft structures produce the incredible capabilities for locomotion and manipulation in complex natural environments. While conventional robots with discrete links and rigid actuators are fast, strong, and easy to control, they struggle to operate in such surroundings. Soft robots with a deformable, continuum body and soft actuators can potentially approach this problem due to their elasticity, safety of interaction, and environmental adaptability. However, soft actuators have several problems including a limited stroke, difficulty of control, and slow response time, restricting their deployment. On the other hand, rigid actuators such as electromagnetic and piezoelectric motors widely adopted today solve these drawbacks, but do not have the softness.

A combination of soft and classical technologies may address this challenge. This thesis introduces a concept of flexible linear motors that consists of a rigid motor's stator and a flexible elongated shaft. By moving the flexible shaft linearly via changes of a relative position to the stator, flexible linear motors provide a large stroke, fast response time, and ease of control. This research shows two examples of how flexible linear motors can be realized and investigates how the above advantages contribute to the mobility of continuum soft robots.

One is a flexible ultrasonic motor that consists of a single metal cube stator with a hole and an elastic and long coil spring inserted into the hole. When voltages are applied to piezoelectric elements on the stator, a shaft inserted the hole moves back and forth. To investigate the influence of softness on the ultrasonic motor, we first inserted a slightly flexible coil spring and a solid shaft into the stator. We change both shafts diameter with micron-order accuracy to provide a pre-pressure between the stator and shaft to improve the output of the ultrasonic motor. Experiments show that the coil spring is easier to adjust the pre-pressure and provides a larger output. Next, we use the elastic and long coil spring to bring flexibility for the motor and enables a large stroke. The coil spring also works as a position sensor by regarding itself as a variable resistance. In order to clarify the design methodology, the pre-pressure, motion model, and position sensing of the coil spring are formulated. The resulting sensor-actuator system has good response characteristics, high linearity, and robustness, without reducing flexibility and controllability. We build a continuum robot based on two flexible ultrasonic motors and demonstrate feedback control of planar motion based on the

constant curvature model.

The other is a flexible rack pinion actuator that consists of a pinion gear rotated by DC motor and a flexible metallic tube that works as a rack. Rotating the pinion gear moves the flexible tube linearly by a engage with the helical groove on the tube surface. We build a continuum robot whose section has three flexible rack pinion actuators connected in parallel. The elongation and bending motion of each section can be controlled during operation by varying the speed of each flexible tube. This design not only allows the expansion of the robot to otherwise unreachable work areas but also improves the locomotion velocity by generating a large traveling distance of the flexible tubes. First, we test two types of locomotion on the ground using a continuum robot with the two sections (6 DoF). The results show that earthworm-like locomotion with a large body stretch has good mobility even in a slippery environment. Next, study how soft and large deformations can enhance the climbing capabilities of LEeCH; a natural land leech-inspired continuum robot with the one section (3 DoF) and two suction cups at the ends. The large deformations occurring in LEeCH extend its workspace compared to robots based on constant curvature models, and we show successful locomotion transition from one surface to another at angles between 0° and 180° in experiment.

The findings in this thesis demonstrate that the proposed motors provide capabilities and behaviors that cannot be achieved by either soft actuators or conventional rigid motors alone. Using the concept of the flexible linear motor results in continuum robots with good mobility, and has the potential to erase the boundary between conventional rigid and soft robots.