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論　文　題　目	SCALABLE EEL-LIKE ROBOT USING SERIES OF SOFT ACTUATORS: DESIGN BASIS, EVALUATION, AND APPLICATIONS
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論文の内容の要旨

In this thesis, we developed an eel-inspired soft robot for both aquatic and terrestrial locomotion and showcased theoretically and experimentally how the structure and control parameters many benefit efficient swimming. In terms of theoretical approach, a hydrodynamic model that considers the effect of whole-body movement of the eel-like body's locomotion was constructed. The model was built based on the continuum approach, in which the reactive force at any point along the mid-line is determined. The model was then utilized to predict the propulsion of the eel robot at different working regimes. Also, the model brings in an approach for estimating the drag force coefficient of anguilliform movements, even when it is difficult to set up an experiment and conduct measurement due to the complex motion of the object. Regarding the practical aspect, a control regime was proposed for mimicking the anguilliform swimming of the eel soft robot built by a series of soft actuators. Here, pulse signals with the shifting phase are supplied into actuators. For the efficient generation of sine-waveform, four pairs of the actuators that were divided into three segments were chosen to construct the robot body, therein, the head segment was built from two pairs because it plays a role as a wave source, while the others work as propagation parts. Smooth propagation waves generation is considered the key to realizing swimming efficiency. Besides, three novel swimming strategies (C shape mode, passive body level 1 - one-fourth passive body, and passive body level 2 - a half passive body) that cannot be done by natural animals and traditional rigid robots were introduced. Surprisingly, differing from the natural eel and rigid elongated body robot, the soft eel robot with a passive tail and performing C shape can even swim with higher efficiency than the fully active one. This result is important for the development of the robot for long journey tasks for energy-saving purposes, also, enlarges the working conditions of the robot.

By scaling down the soft eel robot, we present the preliminary design and evaluation of a self-propelled soft colonoscopy robot employing a series of soft actuators, equipped with a control strategy for creating forwarding movement. The design permits the robot to move efficiently, thanks to creating transient bending segments between crest and trough segments, resulting in smooth propagating waves along the robot's body. Control parameters, including frequency, shifting phase (that characterizes the creation of propagation waves from head to tail,) and pressure of supplied air strongly affect the locomotion gait. The obtained results in this paper would be applied to the creation of an autonomous soft colonoscopy robot in the future.

Keywords: eel inspired robot, pneumatic actuator, anguilliform, body partially damage, colonoscopy robot

論文審査の結果の要旨

Animals have evolved their body shapes, locomotion gait, or interaction method with the surroundings to ultimately adapt to the living environment. Among them, underwater creatures mostly have soft, flexible body that benefit the agile swimming or maneuver ability. Research in robotics have mimicked such movement in bio-inspired robotic system, mostly utilized rigid articulated joints for realization of flapping or wave-generating motion. However, the stiffness of such design limits agility and adaptivity of the robot compared with natural creatures. On the other hand, dynamic behavior of soft-bodied robot in relation to surrounding ambient environment (underwater) has not been clarified with specific showcases. The research content in this thesis an eel-inspired soft robot for both aquatic and terrestrial locomotion has been designed with theoretical and experimental demonstrations for clarification of how the structure and control parameters many benefit efficient swimming of an elongated soft-bodied robot. In details:

1) In terms of theoretical approach, a simplified thrust force model that considers the effect of whole-body movement of the eel-like body's locomotion was constructed. The model was built based on the continuum approach, in which the reactive force at any point along the mid-line is determined. The model was utilized to predict the propulsion of the eel robot at different working regimes. Also, the model brings in an approach for estimating the drag force coefficient of anguilliform movements

2) A control regime was proposed for mimicking the anguilliform swimming of the eel soft robot built by a *series of soft actuators*. Smooth propagation waves generation is considered the key to realizing swimming efficiency. Three novel swimming strategies (*C-shape* mode, passive body level 1 and 2) that cannot be done by natural animals and traditional rigid robots were introduced higher efficiency

3) By scaling down, a design and evaluation of a self-propelled soft colonoscopy robot employing a series of soft actuators was demonstrated. The obtained results would be applied to the creation of an autonomous soft colonoscopy robot in the future.

Overall, the thesis succeeds in proposal of a scalable design of an elongated robot with various control strategies for realization of efficient locomotion in water or in narrow space. Also, obtained results contribute to fulfilling knowledge of soft morphology in interaction with surrounding environment. The research content in this research paves a way to wide application in robotics, from environment inspection to medical devices. The student could prepare papers, thesis, and present the content in English without any problem. Therefore, this thesis is sufficient to be rewarded as doctoral thesis