博士論文(要約)

Integration of Electroadhesion and Electrostatic Actuation and its Application for Climbing Robots

(静電吸着と静電アクチュエーションの統合と

その壁面移動ロボットへの応用)

王　宏強

Thesis Summary

Climbing robots have extensive applications, including cleaning and inspection of ships, aircrafts, bridges and high-rising buildings. The previous climbing robots are mainly designed for common conditions, and they cannot be applied to some specific situations. For example, they are not able to climb through the narrow gap between the stator and rotator of a generator in a power plant for inspection. Besides, climbing in a gas turbine is also a big challenge for common climbing robots, considering the small distance between the housing and blades. For these specific applications, the climbing robots should be flexible enough to comply with the complex surfaces of the gaps, and be considerably thin in height to move freely in the confined space. The conventional electromagnetic motors and adhesive devices can hardly satisfy these requirements, and thus other actuation and adhesion methods should be considered.

This dissertation proposes to integrate both electrostatic film actuation and electroadhesion into climbing robots. Because both of these two mechanisms can be implemented by three-phase electrode films, the whole body of a climbing robot can be lightweight, low-height, and flexible. Besides, the robots can even work in a strong magnetic field, since both of the actuation and adhesion are based on electrostatic force.

However, it is not easy to integrate these two mechanisms into climbing robots, and several problems arise. 1) This kind of climbing robots generally encounter the failures of peeling and buckling. When one pulls an electroadhesive film from a substrate, the films is apt to be peeled off. On the other aspect, if one pushes a film, the film will buckle down suddenly once the force exceeds a critical value. Therefore, peeling off and buckling are general challenges for flexible climbing robots, especially the ones proposed in this work. 2) In the integration of the two mechanisms, the effects of the parameters on the output forces are still unclear. Many critical parameters, including the thickness of each layer of the films and the width and gap of the electrodes, should be decided before the fabrication of the robots. Although some literature mentioned the relationship between these parameters and the driving/adhesive force, no one studied the impact of the parameters on the two forces in the integration configuration. A trade-off between the two forces might be necessary for a better performance of the climbing robots. 3) The concept of the integration of the two mechanisms into climbing robots should be verified by prototypes. In the prototypes, the possible configurations, mechanical structures and control strategies need to be investigated.

To solve the problems mentioned above, this dissertation conducted research on five aspects as

follows.

1) This work studies the peeling of electroadhesive film and proposes solutions. Based on Kendall model and the analysis on the electrical energy, this work builds a new model for the peel force of electroadhesion, and experimentally verifies it. This model can calculate the peel force directly from the dimensional parameters, while the conventional model should achieve the factor of adhesive energy density by tests before the calculation. Compared with other adhesive methods such as tapes, this work reveals that peel force of electroadhesion differs in being calculable, controllable, and independent from peel speed. The peel torque of a crawler-type electroadhesive climbing robot is also investigated. It is found that in the peeling process, the peel torque of the robot drops after it arrives to a maximum value. This maximum value can be enhanced by tightening the belt film, proved by experiments. However, the peel torque might drops if the belt film is too tight, considering the unevenness of the substrate surface.
2) This dissertation investigates the principle of buckling of electrode films and suggests approaches to avoid it. Due to the great flexibility of the electrode films, inchworm-type climbing robots made of only these films are apt to buckle on a vertical surface. To solve this problem, this work builds models to analyze the two main buckling modes respectively. Based on these analyses, the critical buckling forces are investigated, and possible solutions are discussed. An applicable solution is selected for an inchworm-type climbing robot on a vertical surface, which is to add an extra balance force on the front foot and to limit the stroke of every step of the movement. Experiments have verified the feasibility of the analyses and solutions.
3) This work investigates the effect of parameters on the driving and adhesive forces by FEM models. It is clarified that, in the integration, electrostatic actuation and electroadhesion do not affect each other on the output forces, although they share the same electrode film. The thicknesses of the layers and the pitch affect both adhesive and driving forces, but they cannot increase these two forces at the same time. To balance these two forces in a climbing robot, this work proposes a coefficient to present the thicknesses, suggests a selection strategy to choose the proper parameters, and verifies the strategy by experiments.
4) To verify the concept and analyses, this work built several prototypes of crawler-type climbing robots. a) The forces on a crawler-type “fully-electrostatic” climbing robot are analyzed. The payload capacity of the robot is decided by the alignment condition of the two electrostatic actuators in the robot. If there is enough extra length on the belt film and a misalignment happens between the two actuators, the payload capacity might decrease to around half of the

ideal condition. b) The torque balance of the robot is also discussed. It is found that the tails' torque should be smaller than the sum of the maximum peel torque and gravity torque and larger than the gravity torque, to prevent the peeling of the head and end sections of the robot. c) Finally, three crawler-type climbing robots are developed, of which two (Crawler Robot I and II) own rigid supporting bodies and one (Crawler Robot III) a flexible body. Crawler Robot II shows that this kind of robots can be lightweight (94 g) and low-height (15 mm). Crawler Robot III demonstrates a deformable climbing robot that can smoothly transition between different planes.

5) This work also designs and fabricates two inchworm-type climbing robots to show the unique characteristics of this kind of climbing robots. A primary prototype (Inchworm Robot I) proves the concept with its lightweight (21.7 g) and ultra-low height (2.4 mm). It can move on a slope of 80°, but will buckle on a vertical surface resulted from buckling. To solve this problem, this work proposes a new controlling strategy and builds another prototype (Inchworm Robot II). It is found that the parameters of the robot should be constrained by two aspects: the elasticity stability and force balance. In the experiments, Inchworm Robot II succeeded in climbing up a vertical surface, and verified the analyses about it.

Overall, to build climbing robots for the inspection of narrow gaps, this work proposes to integrate electrostatic film actuation and electroadhesion into climbing robots. To verify this concept, this work studies the general challenges of peeling and buckling, investigates the effects of parameters on output forces, and fabricates prototypes of different configurations.