早稲田大学大学院 先進理工学研究科

博士論文審査報告書

論　文　題　目

The Motion Generation of Stable Vertical Ladder Climbing Capable of Recognizing Rungs for a Four-limbed Robot

四肢ロボットの安定かつ桟の認識が可能な垂直はしご昇降の運動生成

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Aiming at the realization of stable vertical ladder climbing of a four-limbed robot, in this thesis the applicant proposes planning, generation and feedback systems of ladder climbing and their total integration. The background of this thesis explains that human beings have been suffered from natural as well as man-made disasters. With the rapid development of robot technique, disaster response robots are drawing increasing attention and expected to be a superior option in comparison with human as the solution of performing rescue tasks in disaster sites. As a common and popular tool for locomotion in the vertical direction, vertical ladders have been utilized by human for a long history. So far, it is rather difficult for the mainstream of disaster response robots existing to deal with the ladders that may be equipped in disaster sites, especially for indoor facilities. Taking this insufficiency of concern and solution to the requirement of ladder climbing of robots into consideration, this thesis mainly discusses the issue about how to generate and guarantee stability in ladder climbing motion of a four-limbed robot.

In the introduction part, referees found that there was no sufficient study on disaster response robots as the comparison with the robots in this thesis, thus the classification of main types of rescue robots and discussion of them were added in this thesis.

In the motion generation system, the applicant proposes end-effector trajectory planning with separated path and time profile, so that they two can be planned individually, as the applicant points out that the position constraints in ladder climbing are more strict than conventional multi-legged walking in: (i) While in multi-legged walking the robot can contact the ground, which is a surface, but in ladder climbing the robot can only contact the ladder on lines, which are rungs of the ladder and (ii) During the ladder climbing, the path of end-effector must be appropriately planned to avoid unexpected collision between the end-effector and rungs, such as the case that end-effector collides with the rung from the bottom, which is essentially equivalent to an obstacle avoidance problem. With these 2 features, path planning in ladder climbing of end-effector must be individual and should not be changed by the change of time profile. However, referees pointed out that whole-body motion planning and generation is not discussed, and according to this comment the applicant added the contents of “body trajectory planning” so that the combination of (i) End-effector motion, (ii) Body motion and (iii) Ladder climbing gaits that shows the pattern of order that limbs of the robot moves forms complete whole-body motion in ladder climbing.

As for the sensor feedback systems, there are 2 types proposed and described detailly in this thesis, which are force sensor feedback and proximity sensor feedback system, improving the stability of ladder climbing greatly. The contents of these 2 systems were divided and discussed individually at first. However, referees pointed out that the contents of 2 systems should be integrated, and the integration experiments should also be done with results and discussion to prove that these 2 systems are compatible and both contributive to the ladder climbing in this thesis. Besides, at first the feedback of proximity sensor system is only used for error compensation between the robot and ladder, and referees suggested that proximity sensor feedback system could also be utilized in recognition of ladder, so that the originality and contribution of this thesis can be improved further. According to all these comments, experiments of total integration of motion generation and 2 sensor feedback system were made as well as the experiment of rung recognition with the results given and discussed in the thesis, verifying that they are truly effective and compatible in ladder climbing.

Additionally, at the result of application of proximity sensor feedback, the whole continuous motion process of (i) Approaching motion of the robot on the ground to the target ladder to climb with “crawling” motion; (ii) Attaching motion of the robot from the ground to the ladder autonomously without the assistance of human and (iii) Ladder climbing was given in this thesis as a chapter. However, the referees pointed out that this part was not directly related to the main topic of this thesis, the realization of stable ladder climbing, thus should not be included in the main text of this thesis. As the response to this comment, this part was simplified and moved into the appendix of this thesis.

The achievements of this research mainly include the technique of realizing successful and stable ladder climbing of human-sized four-limbed robots, with sensor feedback to avoid unstable states during ladder climbing and preliminary environment recognition capability as the solution to variety of specification (or even unknown specification) of ladders in reality, which has not claimed to be accomplished by former related studies before. It is expected to improve the capability and compatibility of ladder climbing of human-sized robots and can be extended to the reinforcement of autonomy of ladder climbing robots. Consequently, we hereby admit that this thesis is worth enough to present as a doctoral dissertation.

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