Autonomous Limbed Climbing Robots for Challenging Terrain Exploration

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論文内容要約

In recent years, robotic surface mobility has been utilized in various missions. Teleoperated robotic missions are effective, especially in a dangerous environment for humans. Robotic mission example includes volcano monitoring, disaster response, infrastructure inspection, and planetary/lunar exploration. Field robots for these missions are required to move around in the complex environment where they are deployed and perform tasks on behalf of humans. Surveying the recent successful deployment demonstrations of the mobile robots, it is apparent that legged robots have shown promising traversability and versatility in the current research field of mobile robotics. However, among the numerous fields to which robot technology is applied, the steep and irregular terrain represented as an outcrop, cliff wall, cave ceiling, and Lunar and Martian lava tubes is still unreachable for the conventional mobile robots even though there exist highly scientific resources in such places.

For exploring this challenging terrain, the legged robot equipped with the spine type gripper that enables it to support its body on the steeper rocky terrain is regarded as an effective solution. Since such a limbed climbing robot is capable of locomoting on the wall and even ceiling-like terrain, this novel type of robot is to be the innovative strategy to expand the traversable areas by a mobile robot. However, the current limbed climbing robots' motion depends highly on the gripper's strong adhesion, and it is limited to some demonstration of the manual control by a human operator or few cases of the implementation of the semi-autonomous climbing motion in the controlled environment. Thus, there is still a significant technological gap to execute the autonomous climbing locomotion. For the advanced exploration mission, tackling the challenge to realize the autonomous limbed robot's climbing action is essential.

To this end, this research, therefore, addresses mainly the three issues: 1) development of the perceptive technique to extract the graspable target for the spined gripper in the constructed terrain map, 2) establishment of the stable climbing motion planning method based on the theory of Tumble Stability, and 3) multi-aspect evaluation for the different topologies of the legged system for the practical design of the limbed climbing robotic platform. In this dissertation, Chapter 1 details the research purpose, approach, and literature reviews on climbing robotics research.

Perceptive locomotion is a crucial part of autonomous robotic climbing. The robot should generate the terrain map of the surrounding environment and select the appropriate footholds to execute the stable ground-gripping locomotion. For this issue, first, the terrain mapping algorithm is produced by combining multiple frames of the three-dimensional (3D) point cloud image taken by the robot's front depth sensor. Since the backside of the convex shape is hidden from the front view, such occlusion parts are interpolated by the linear compensation method. Subsequently, a grasping target detection algorithm is applied to the constructed terrain map to maximize the reliability of the spine type gripper's holding performance. This technique extracts the convex shapes as a suitable topography to be grasped by the spined gripper by evaluating the matching ratio between the local terrain shape and the ideal graspable convex shape designed based on the geometrical configuration of the gripper. This perception algorithm development is described in Chapter 2 of this dissertation.

Building the climbing motion planner is a core part of this dissertation. To plan the stable motion for a limbed robot, the conventional stability theory depends on the geometrical relationship between the support polygon and the horizontal projection of the robot Center Of Mass (COM) or Zero Moment Point (ZMP). However, this classical theory to evaluate the two-dimensional (2D) condition between the support polygon and the projected point cannot be utilized for wall- or ceiling-climbing application because COM projection or ZMP cannot be found in such cases. Therefore, it is essential to plan the stable robotic motion without depending on the classical stability criterion. This study employs the newly proposed stability criterion for Gravito-Inertial Acceleration (GIA) of the robot, which is the resultant acceleration by the inertial and the gravitational effect. The extracted stable region for the GIA in the acceleration space shapes the polyhedron-like domain without the base attached around the support polygon. By assessing the three-dimensional relationship between the polyhedron and the GIA vector instead of the support polygon and ZMP, it is possible to evaluate the robot stability spatially, which is no longer dependent on the conventional 2D stability assessment. Thus, this stability assessment method is applicable to the wall- and ceiling-climbing cases. Also, the stability margin, named GIA Margin (GIAM), is defined as the minimum distance from the GIA vector to the plane of the polyhedron. Using this quantitative stability margin makes it possible to actively control the limbed robot's stability while the climbing motion.

The proposed climbing motion planner is established consisting of 1) the optimal selection of the swing limb and its foothold, and 2) the optimization of the robot base position and orientation to maximize the GIAM and the kinematic reachability of each limb. The proposed planner's capability to produce stable climbing motion even on the wall and ceiling is demonstrated in the developed simulator assuming the quasistatic climbing by the developed four-limbed climbing robot testbed for this research. In this dissertation, Chapter 3 presents this planning method.

Subsequently, the perception system and the motion planner are integrated as a single system to realize the autonomous limbed climbing locomotion. The integrated simulation showed successful autonomous wall-climbing in the virtual environment assuming the vertical irregular terrain. After which, the actual robot is operated in the indoor experiment testbench. In this experiment, every time the planning of one step is completed in the simulation platform, the actual robot receives a set of commands to execute based on the planned motion: 1) next swinging limb code, 2) next foothold, and 3) next base pose. Then the real robot performs the planned motion with respect to its own base coordinates frame. To keep an accurate base pose relative to the test field in the real as well as in the simulated scenario, the base pose compensation action is additionally implemented every time before the planned climbing motion for the hardware experiment is executed. By comparing the Visual Odometry (VO) of the base measured by the front depth sensor and the ideal base pose updated in the simulation, the robot can execute the base pose compensation motion before the climbing step. With this operation sequence, the robot could autonomously climb on 45 degrees inclined rugged slope under Mars gravity. In summary, the integrated simulation and experimental validation confirmed the successful proof-of-concept of the autonomous limbed climbing robot. These results are exhibited in Chapter 4 in this dissertation.

Furthermore, towards the practical design of the limbed climbing robot, a topological analysis is performed. This analysis evaluates the climbing capability of the quadrupedal robots' two different standard leg configurations (insect and mammal) in terms of stability, versatility, and energy efficiency. As for the evaluation metrics, GIAM, manipulability measure, and torque consumptions are measured while the different topological robots climb on the steep slope. The result of an iterative simulation shows that both topologies are capable of climbing by adjusting the base to increase stability. However, the insect topology is relatively superior to the mammalian configuration because the insect robot can adjust the base position according to the terrain inclination to increase the stability without sacrificing the limb's manipulability. This topological design consideration is described in Chapter 5 of this dissertation.

In conclusion, this research achieved the following outcomes to realize the autonomous limbed climbing robot: 1) perceptive technique to detect the graspable footholds in the irregular terrain map, 2) motion planning method to build the stable climbing locomotion based on the stability theory for GIA of the robot, and 3) limb topology analysis result to lead to the robot's stable climbing posture and the efficient limb design. Those contributions would be beneficial to expand the robotic exploration coverage to the challenging terrain and the control theory of legged robots to more advanced locomotive applications. Those contributions statements and the future direction of this research are summarized in Chapter 6.

In addition, all the essential developments are summarized in this dissertation. A) HubRobo: the novel 3 kg class quadrupedal robot testbed is developed. B) Indoor experiment testbench is also developed. It can reproduce steep slopes, uneven terrain, and different gravity in which the robot will be deployed. C) ClimbLab: legged robot climbing simulator that is already open-sourced are developed. In addition, D) a versatile one limb kinematic model was presented, and an analytical solution of inverse kinematics for the limb model was derived. This inverse kinematics solver can be used for the robot limb trajectory tracking control. These developments are detailed in the appendices in this dissertation for facilitating future comprehensive research on legged climbing robotics.