論 文 の 内 容 の 要 旨

論文題目　Study on Robotic Intelligence for Vision-based Planetary Surface Navigation
（惑星探査ローバの画像航法誘導における知能化に関する研究）

氏　　名　大津 恭平

Robotic probes on remote planetary surfaces have been the recent focus of major space agencies and private companies. These robotic intelligence has established landmark studies in planetary science, as well as demonstrating the state-of-the-art technologies of extraterrestrial surface mobility. To accommodate the requirements of challenging future missions, mobile robots should acquire advanced mobility that enables longer distance traversal in complex terrain with lesser human intervention. Since every stride brings a robot into a place where no one has ever been, the robotic pioneer must handle difficult and usually unpredictable challenges raised by unknown environments. This the- sis focuses on the onboard decision-making systems to accomplish fully autonomous navigation in substantial distance on challenging planetary surfaces, while maintaining the safety of precious robots with intelligent perception, planning, and localization capabilities.

An important requirement for future exploration robots is accurate traversability assessment in natural terrain. Unordered planetary terrain puts high-level complexity on the perception problem, requiring a capability to sense not only the geometric topology but also the non-geometric properties of extraterrestrial terrain surfaces. A current limitation on autonomous perception is the inability to detect non-geometric terrain hazards, such as sandy ripples which reduces the wheel traction, and pointy pebbles which may damage the wheels. This thesis proposes two learning-based perception methods which extract non-geometric terrain properties using multimodal sensors. A key common idea is to employ a self-learning scheme which enables a robotic system to learn physical experience of distant terrain from exteroceptive and proprioceptive sensing. In the first method, semantic terrain types are estimated using a vision-based machine learning classifier which is trained in collaboration with mechanical measurements. In the second method, energy consumption in the mobility system is accurately predicted with a model-based estimator that learns complex wheel-terrain interactions. The proposed techniques could interpret measured data as qualitative and quantitative forms. The validity of the proposed methods are shown through real-world experiments with test-bed robots in Mars-analogous fields.

After perceiving the environment, the robot is required to determine the next motion while considering various hazardous factors arose from the environment and system's kinematic constraints. Future missions will require autonomous exploration in challenging complex sites where the surface is covered with an abundance of obstacles to avoid. Such environments pose difficulty in a simple conservative planning strategy which tries to generate a detour path around the obstacles. This thesis proposes a robust and efficient algorithm for motion planning in obstacle-abundant terrain, which navigates the robot onto the destination while avoiding obstacles with straddling motions. The developed method has two components: kinematics-based state estimator and receding horizon trajectory planner. These components are organically coupled to provide an optimal path which is safe and robust to various uncertainty with less computational expense. The proposed planner is analyzed with synthetic terrain simulating Martian rock distributions and showed a high success rate up to 15% rock abundance.

Finally, a robust and efficient localization method is developed to accurately guide the robot to the target coordinate. Recently, visual odometry has gathered substantial attention as a robust localization method in natural terrain, whereas its computational cost is challenging for limited onboard computers. One of the computationally expensive operations is the robust estimation of pose parameters with a sampling-based outlier rejection scheme. The sampling efficiency can be drastically improved by reducing the minimal number of data points for relative pose estimation, which is theoretically three for a stereo camera system. This thesis presents a novel formulation which reduced the minimal number to two, by employing a common reference direction derived from a distant point measurement. A field test in volcanic terrain shows that the proposed method can successfully estimate robot trajectories with increased computational efficiency.