Abstract of Dissertation

論文の内容の要旨

論文題目　A Probabilistic Motion Estimation and Landmark Mapping Method for 3D Monocular SLAM
（３次元単眼SLAMのための確率的運動推定およびランドマークマッピング手法の研究）

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Small celestial bodies have been the recent focus of attention of major space agencies with JAXA recently completing the Hayabusa mission to the asteroid Itokawa, ESA going ahead with the Rosetta mission, and NASA's NEAR and Deep Impact missions. Developing guidance navigation and control schemes for landing on small celestial bodies such as Near Earth Objects, offers a new range of challenges: safe landing areas with good lighting conditions are rare and narrow; craters and other landmarks used for visual navigation may be sparse or non-existent; the micro-gravity environment makes inertial sensors unable to detect accelerations with respect to the celestial body, limiting their use to self-referenced spacecraft motion estimates which are prone to large drift errors over time; the spacecraft's baseline-to-depth ratio makes an onboard stereo-camera system ineffective during most of the landing phase; and teleoperation becomes very difficult when delays of 15 minutes are to be expected at about 1 AU from Earth.

Pinpoint landing is paramount for such missions, allowing increasing scientific return by collecting data closer to targeted sites, and reducing the risks of damaging the spacecraft when landing close to hazardous terrain.

Addressing the need for robust pinpoint landing capabilities, this research proposes a novel method for the motion model and landmark database of an online monocular navigation scheme based on the Simultaneous Localization and Mapping (SLAM) approach; the latter providing the attitude and position (or pose) estimates during the Approach, Descent and Landing (ADL) phase, while simultaneously mapping the topography of the celestial body.

The proposed method relies on combining data from a camera and one or more range sensors (e.g. LIDAR) in order to maintain several hypotheses – or particles – of the most likely spacecraft pose and landmark position at any given time. This method uses a double staged Monte-Carlo simulation to represent:

Stage 1: A sample population of relative spacecraft poses approximating the distribution of all the possible spacecraft motions between pairs of camera images taken at successive time steps.

Stage 2: A sample population of possible scaling factors mapping the relative spacecraft poses and the relative landmarks 3D position to a unique and scaled real-world coordinate system attached to the celestial body. The population of scaling factors provides an approximate distribution of all scaled motion estimates and landmarks 3D position on the surface of the celestial body.

Each particle is associated with its own scaled landmark population which is stored in a database called an occupancy map. The role of the occupancy map is to track the position and visual signature of previously observed landmarks, and to spatially represent the probability of finding other landmarks in their neighborhood. Such probability is referred to as the obstacle probability since it also represents the probability of finding obstacles within the vicinity of a landmark. The occupancy map's basic principle is based on the octree algorithm which represents the space enclosing the target celestial body by a rectangular cuboid of known dimensions. This initial volume is discretized by recursively subdividing each cuboid into 8 sub-cuboids of equal volume, and by continuing this process until all cuboids have a near-homogeneous state with respect to their obstacle probability, or have reached the preset minimum dimensions.
Each occupancy map is cross-referenced with a Red-Black Tree database which sorts all observed landmarks by their visual signature. This mechanism enables landmark retrieval to be performed in logarithmic time $O(\log N)$ during the landmark re-identification process, regardless of the size of the occupancy map.

The novelty of the method proposed herein is based on three aspects: (i) a novel monocular probabilistic approach for scaling landmarks position and spacecraft motion with respect to real-world dimensions; (ii) a novel occupancy map cross-referenced with a visual landmark database which allows dynamic memory usage optimization, as well as a fast and robust visual signature-based landmark re-identification process; (iii) a novel fast computing statistical algorithm to estimate the motion hypotheses' likelihood, which in turn defines each hypothesis' probability of being selected for the next iteration of the SLAM algorithm. The new algorithm scores the likelihood of a hypothesis by multiplying the likelihood of each observed landmark for that particular hypothesis. The novelty lies in the use of the P-value – i.e. confidence interval – as a fast and statistically meaningful way of computing the likelihood of re-observed landmarks, and the direct use of the obstacle probability values provided by the occupancy maps as an initial estimate for the likelihood of newly observed landmarks.

This novel method is meant to achieve a higher localization accuracy compared to conventional landing control techniques, and to provide an added robustness compared to past monocular SLAM approaches. It may be valuable for future Hayabusa follow-up missions, as well as NASA's future Near Earth Objects missions in agreement with their new space exploration roadmap. On a broader scope, this work may also be useful for precise and robust pose estimation in real-world 3D environments dealing with various kinds of autonomous mobile robots.