博士論文（要約）

Capture scheme for rotating space debris based on probabilistic contact mode estimation

（確率的接触モード推定に基づく回転するスペースデブリの捕獲スキーム）

by

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The problem of space debris poses an urgent issue relative to sustaining space development activities. A collision of large space debris objects produces thousands of small debris fragments, and could become the show-stopper of space development once a chain reaction of collisions has started (called the *Kessler syndrome*). The final goal of this research is the removal of large space debris objects.

In order to achieve this goal, large space debris objects must be captured reliably. The space debris capture problem is classified as a *non-cooperative capture problem*, where the target does not have a target marker and docking port, and is not under control. The non-cooperative capture problem involves generic space robotics challenges, including time delays in teleoperation, qualification tests and limited computation resources, as well as non-cooperative-capture-specific challenges. In particular, the space debris is expected to be rotating a few degrees per second. Since the space debris does not have a target marker, relative position/pose measurements must be conducted in an unrehearsed problem setting. Consequently, camera sensor data is expected to be unreliable before and during capture involving collisions.

The purpose of this thesis is to provide an autonomous rotating space debris capture methodology using probabilistic contact state estimation. In particular, this thesis aims to develop the following:
(1) a computationally optimized mode estimation method;
(2) a force-torque sensor-based contact mode estimation method; and
(3) a rotating space debris capture by impedance control with evolved contact mode estimation

For this, probabilistic Bayesian filter representation, more specifically, its good, well-theorized approximation particle filter are used. The Bayesian filter and particle filter are reviewed as the mode estimation method used as a basis throughout the paper.

First, *the State Segmented Particle Filter (SSPF),* where both a continuous state vector and fault states are segmented accordingly to allow flexible reasoning for mode and motion estimation, was proposed. For each segmented space, an attempt is made to construct a corresponding posterior distribution independently, resulting in a reduction of the number of particles. The experimental simulation demonstrates fault diagnosis among billions of fault modes. The state-segmentation approach reduced 98% of particles compared with the ordinal particle filtering approach. This part of the thesis depicts the essence of particle filter implementation, where it is necessary to narrow down the search space to the extremes that must be searched. As seen in the proposed SSPS, it was revealed that an aggressive spatial reduction method is essential, such as dividing and localizing dynamics equations. More importantly, it also has the effect of improving mode estimation accuracy. For the contact mode estimation discussed, this knowledge is utilized to further develop discussion.

Then *Collision-model-based Contact Mode Estimation* (CCME), enabling a force-torque sensor-based contact mode estimation to determine when to close the robotic hand for capture, was proposed. The *chaser*, a spacecraft to capture *the target*, space debris, is equipped with the camera sensor and force-torque sensor, and both are used for this purpose. However, the camera sensor expected to become unstable just before capture due to the difficulties mentioned previously. The sensor information must be segmented to conduct contact mode estimation. The collision information, the most reliable and essential information obtained from the force-torque sensor, is used for triggering the major evaluation and resampling process of the particle filter. As a prediction model of collision phenomenon, Brach's model has been utilized because it uses intuitive collision properties for sampling that indicate affinity with the particle filter approach, and is computationally light-weighted compared to more elastodynamics approaches. The advantage of the proposed method is experimentally demonstrated by achieving the highest success rate using the computationally estimation time of average of 3.9 milliseconds and worst of 6.1 milliseconds with the given setup, where the requirement of estimation time is within 200 milliseconds after collisions. The method is also verified computation resource (or number of particles) depends on the size of motion estimation error in the pre-capture phase.

While in the previous part, CCME is evaluated with the chaser fixed, is then finally implemented for the capture of a rotating target with the chaser robot arm also under control, which entails the use of impedance control. A novel robust capture strategy (capture steps) is proposed. Contact mode estimation under impedance control, the key technology for camera sensor independent capture, is presented. Impedance control causes a longer collision duration, which makes more difficult to distinguish the neighboring modes. For this, computationally-light-weighted slide-triggered filter algorithm is presented, where different collision profiles, sliding contact modes are defined and combined for prediction and detection. The novel method is implemented in the air bearing robotic system, and demonstrated its superiority with the highest success rate (100%) with slide-triggered filters compared to the method without it only yields 87.9% of success rate. Computation resource is demonstrated to be limited; computation time of 4.2 milliseconds in average and 8.3 milliseconds at worst that fits to the requirement above.

To sum up, this research established a novel grasping methodology for the robust non-cooperative capture of rotating space debris by providing the capability to conduct contact mode estimation using a force-torque sensor that is independent of the camera sensor, in order to obtain ready-to-close information of the robotic hand to establish object closure.