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東京大学
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Image Enhancement and 3D Reconstruction for Underwater Environments

（水中環境の画像補正と 3 次元復元）

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Rescue robots have shown high effectiveness for disaster rescue and investigation. The unknown environment is a challenge for robots and human operators when implementing investigation. 3D reconstruction of the unknown environment can be one of the strategies to reduce the unknown factors and providing useful information about the surroundings. Structure from Motion (SfM), as one of the 3D reconstruction techniques, can estimate the 3D structures using a moving single camera. SfM in air environments has achieved intensive investigations. However, most of the studies focus on the clear scenes, for extreme underwater environments, the standard SfM pipeline may be invalid because water affects image formation by two different aspects compared with the air environment.

First, light absorption and scattering cause the image losing the contrast in general and foggy. Moreover, if extra noises (e.g., floating particles, water bubbles) exist, the image is degraded by these unwanted signals. The deteriorated images may lead the conventional SfM invalid because of lacking sufficient feature matching. Next, the camera equipped on a robot is typically confined in a waterproof housing. Thus, the light is refracted twice in this situation. The first happens at the interface between water and camera housing medium, and the second happens at the interface between the camera housing medium and air. The refraction causes the perspective camera model generally used in conventional SfM pipeline is invalid. On the whole, to achieve accurate 3D reconstruction of the structures, image degradation and refraction problems should be solved.

In this thesis, a systematic SfM approach is proposed for the extreme underwater environment application. The approach mainly includes two part: image enhancement and refractive structure from motion.

In Chapter 2, the underwater light propagation process will be described firstly to give basic knowledge about the phenomena in underwater environments. Then, the underwater image formulation is presented to describe the underwater light model, and the camera models used in underwater environments are summarized. Next, related work on underwater image enhancement is presented. Finally, related work on underwater 3D reconstruction is described for state-of-the-art studies.

In Chapter 3, the challenges, assumptions, and objective are stated to give an overview of this research.

In Chapter 4, the image enhancement method based on the proposed underwater light model will be described. Compared with the conventional underwater light model, the proposed model is improved by considering two new factors: underwater noise and non-uniform ambient light. Generally, these two factors exist in practical use because of substances in the water and artificial light on the robot. Thus, the proposed enhancement method can achieve denoising and dehazing in non-uniform ambient light environment. Experiments on real images show the effectiveness of the proposed method on color correction, dehazing. The proposed method can achieve better results compared with the state-of-the-art studies.

In Chapter 5, the refractive structure from motion procedure will be presented. First, the camera system with arbitrary parametric camera housing is modeled based on ray tracing and Snell's law. Then, a novel calibration method is proposed for camera housing parameters. Next, the refractive camera pose estimation method and 3D points reconstruction method are depicted for recovering the structure. Finally, a new bundle adjustment approach, as the final step of SfM for refining the camera poses and reconstruction, is proposed for the refractive camera system. Simulation and real image experiments were carried out to confirm the effectiveness of the proposed approach.

In Chapter 6, experiments in extreme underwater environments, Primary Containment Vessel of Unit3 at Fukushima Daiichi Nuclear Power Station, was implemented. The proposed method can reconstruct the 3D structures from the video sequences of the investigation. It shows that the proposed SfM pipeline can apply to challenging environments.

Finally, Chapter 7 gives the conclusions.