Image-Based Visual Servoing for Autonomous Robotic Manipulation In-Space

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1 Introduction

Space robotics has enabled humans to expand their space exploration capabilities. Robotic arms are crucial for scientific data collection, handling samples on other planets, and vital servicing operations in orbit like refueling, maintenance, assembly, and debris removal. Existing space manipulation systems often rely on teleoperation, posing challenges due to communication delays and the need for skilled operators [1]. A key element in enabling autonomous robotic manipulation is the development of visuomotor skills, which allow robots to recognize and track objects, as well as to navigate through complex and dynamic environments, when executing manipulation tasks. A robot can acquire visuomotor skills by using Visual Servoing (VS) strategies to control its motion based on visual observations [2]. This work compares four image-based VS (IBVS) techniques for autonomous space robotic manipulation, evaluating different depth estimation methods, sensor modalities, features, and control laws in a complex roto-translational scenario. Additionally, we assess In-Space Servicing, Assembly, and Manufacturing (ISAM) capabilities through an assembly scenario.

2 Methodology and Experiments

A 7-DoF Kinova Gen2 robot with a depth camera mounted on its end-effector, aiming to reach a pose over an April-Tag marker (Fig. 1), is used for the assessment. The visual features to control are the four corners of the marker.

Four VS methods were tested: 1) classical IBVS with homography [2] for depth estimation; 2) classical IBVS using camera depth sensor; 3) 2.5D VS combining 2D and 3D features to decouple rotation and translation; and 4) partitioned IBVS decoupling Z-axis motions using only image features.

3 Results

2.5D VS method exhibited key characteristics for space robotic manipulation, such as rapid convergence, low error, controlled camera and feature trajectories, and efficient iteration times. Therefore, it was selected for the assembly task of a hexagonal module commonly used in space structures.

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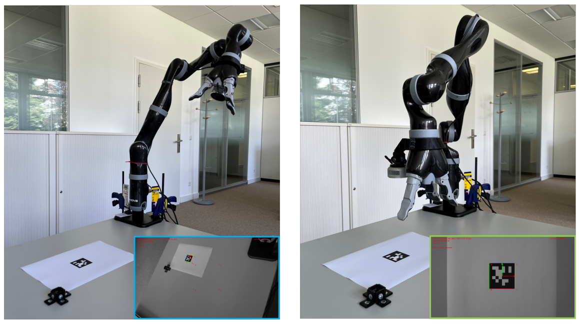

Figure 1: Initial and desired poses and visual features

Fig. 2 shows features and camera trajectories when reaching for one of the beams from the hexagonal module. Feature points remained within the camera's field of view. The right plot shows that 2.5D VS strategy sequentially corrects translational and rotational errors in the plot. These minimal feature and camera motions make this approach well-suited for in-orbit operations, like autonomous assembly tasks.

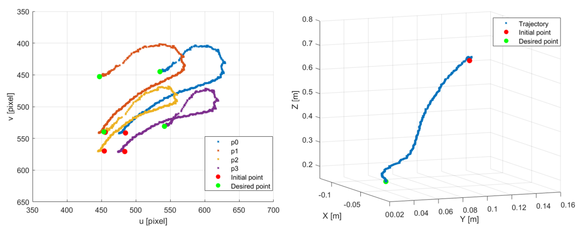

Figure 2: 2.5D VS: Assembly task visual features (left) and camera trajectories (right)

4 Ongoing Research

Future work includes exploring hybrid VS strategies, testing them in space-relevant scenarios, and identifying potential challenges for space missions.

References

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