Robotic In-Space Assembly with Arm-Augmented Cubesats

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The ability to perform robotic manipulation and assembly actions in space bears great potential for aerospace applications and is a critical milestone in NASA's future technology plans [1], [2]. On-orbit assembly maneuvers, in particular, would facilitate a wide range of important tasks such as rendezvous and docking, satellite servicing, debris removal, or even in-space manufacturing of larger structures. However, the required technology differs substantially from today's autonomous planetary manipulation capabilities exhibited by Mars rovers. Dynamic perception and action generation is needed to deal with changing environmental conditions. We propose an integrated system for conducting in-space assembly in a purely autonomous fashion or via limited human supervision. The system combines mechanical and algorithmic solutions to the challenges encountered in on-orbit assembly. In particular, we leverage an arm-augmented cubesat to allow for low-cost and high-fidelity operations. The specially-designed Remora arm features six degrees of freedom and weighs ≈ 0.75 kg [3]. As a result of the limited weight and the cubesat form-factor, the proposed system can be rapidly built and deployed requiring only a fraction of the costs of a more traditional space robotics framework. The second important component to our system is a Rendezvous and Proximity Operations (RPO) software stack that includes a combination of modern computer vision and robot-control algorithms. In particular, the RPO package is responsible for (1) estimating the state (6D pose in CubeSat reference frame) of manipulated objects, and (2) generating control assembly maneuvers. State estimation is performed via a computationally efficient model-based tracking algorithm, which matches given CAD models of truss components with images taken from cameras positioned on the cubesat. The matching process is realized by solving an iterative re-weighted least squares (IRLS) problem minimizing the residual between projected 3D CAD model edges and image edges [4]. The process also makes use of recent insights from sample-efficient local optimization techniques. In particular, an adaptive learning rate optimization algorithm is used to achieve fast convergence towards accurate 6D pose estimates of manipulated objects. The RPO stack also includes functionality for learning task-specific motion primitives - closed-loop control strategies that encode a diverse set of physical actions. Primitives are designed to execute the corresponding task, even under perturbations of the sensor data, the robot state, or the external environment. They can be learned from a set of demonstrations by a human expert. Due to their reactive nature, motion primitives are computationally more efficient when compared to more traditional motion planning techniques. In our experiments, we trained primitives for (1) grasping, (2) lifting, (3) rotating, and (4) attaching of objects as building-blocks for more complex sequences and plans. Our hardware experiments involved assembling a small truss-structure by lifting and attaching truss components automatically (see teaser figure). All of the computations, including vision, control, and sensing are running on-board on a low-compute device. In our experiments, we have compared execution times of pose estimation on three different low-compute hardware devices namely Raspberry Pi 3B+, Raspberry Pi 4, and NVIDIA Jetson Nano. The Raspberry family of computers achieves frequencies of 1.5Hz to 2Hz while Jetson achieves about 10 Hz in 6D pose estimation. The presented system is presents a fully functioning prototype that demonstrates manipulation and assembly capabilities for an arm-augmented cubesat. It features all necessary components for autonomous and semi-autonomous execution and runs on low-compute hardware platforms.

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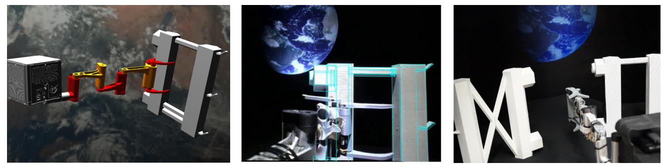

Fig. 1. Left: rendering of simulated robot and environment. Middle and right: physical robot arm manipulating truss elements.

References

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