Enabling Intelligent Robotic Manipulation in Space

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***Abstract*— Robotic manipulation in space is crucial for minimizing human risks and promoting sustainable space exploration and commercialization. Future orbital and planetary missions will require autonomous robotic manipulation capabilities for object capture, sample collection, in-space assembly, and inspection, among others. This paper presents the research activities of the Space Robotics Research Group (SpaceR-SnT) at the University of Luxembourg, which focus on enhancing robotic manipulation through improved perception (vision and touch); exploring learning-based approaches to navigate the challenges of the dynamic and unpredictable space environment; and advancing ground testing by developing simulation environments and specialized testing facilities.**

I. Motivation

The rapidly growing commercial space sector is driving a paradigm shift, where autonomous robotic systems stand to revolutionize significant portions of the industry. In particular, Robotic Manipulation Systems (RMS) will be essential for enabling scalable ISAM (in-orbit servicing, assembly, and manufacturing) missions that either infeasible or too costly for astronauts. Most of the existing manipulation systems in space rely on teleoperation by astronauts or ground controllers, which presents challenges due to communication delays and the need for highly skilled operators. However, the accelerating in-space industrialization with commercial ISAM capabilities demands RMS capable of operating autonomously in diverse and dynamic environments without human intervention. The future of space robotics will emphasize greater autonomy, adaptability, and seamless human collaboration. Key challenges include harsh space conditions and computational constraints.

II. Robotic Manipulation at SpaceR

Founded in 2020, the SpaceR research group is dedicated to advancing the autonomy of planetary and orbital robotics, with robotic manipulation as a key driver of progress in the field. the group is developing cutting-edge approaches in Perception and Control of Robotic Manipulation Systems. Identified research gaps include the lack of data for AI development, the absence of benchmarking strategies, and challenges in sim-to-real transfer of algorithms. SpaceR is addressing these gaps through its research efforts.

As shown in Fig. 1, SpaceR explores cutting-edge advancements in robotic manipulation by integrating object centering grasp generation and 3D reconstruction for unknown objects [1], [2] and hybrid visual servoing strategies to precisely maneuver in space using visual data [3]. By leveraging vision-based reinforcement learning we enable robots to acquire manipulation skills through continuous interaction with the environment [4]. Our research goes beyond theoretical models, incorporating on-ground testing [5] and paralellized simulations [6] to validate real-world applicability. Additionally, we focus on developing compliant end effectors [7] equipped with tactile sensing, allowing robots to handle objects with human-like dexterity. Through these interdisciplinary efforts, we aim to push the boundaries of intelligent robotic manipulation systems in space.

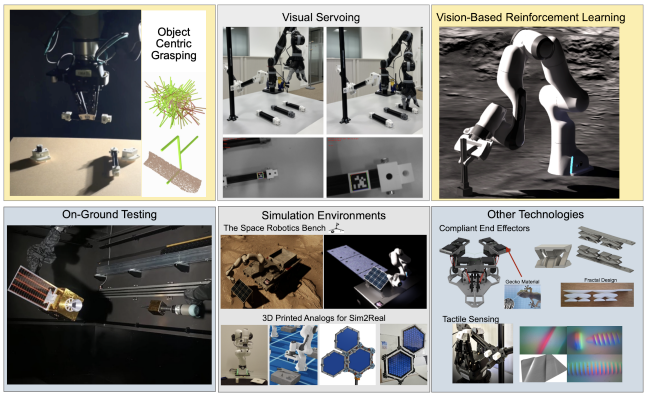

Fig. 1. Research Activities at SpaceR

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