Towards Multi-Modal Sensing for Space Robotic Manipulation: Exploring the GelSight Vision-Based Tactile Sensor

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***Abstract*— Robotic manipulation in space is crucial to reducing human risks and advancing space industrialization. Future In-Space Servicing, Assembly, and Manufacturing (ISAM) missions require autonomous robotic manipulation capabilities. Tactile sensing technology enhances robotic perception by creating meaningful representations of the environment, improving dexterity and precision, and enabling complex behaviors for on-orbit and planetary tasks such as object capture, sample collection and analysis, assembly, and inspection. This paper explores the use of tactile sensing technologies to support robotic manipulation taks in ISAM activities looking to address the challenges of the dynamic and uncertain space environment.**

I. Tactile Sensing for Space

Robot perception is a key element to enabling autonomous operations, by providing environmental awareness to robots to interact and adapt to the environment. Traditionally, vision is used in isolation. However, multiple sensing modalities will allow the learning and the design of more robust environment representations (by complementing sensory information) enabling the design of complex robot behaviours. Currently, perception for space robots remains challenging in both orbit and planetary use cases due to the on-board resource contraints and unstructured environment, heavily relying on pre-defined fiducial markers to enable partial cooperation with the target objects [1].

Touch sensing is essential for contact-rich tasks, providing critical information of the shape, surface, texture, stiffness, of the objects, and more. Tactile sensing technologies have significantly shifts from touch detection to sophisticated systems capable of recreating and improving the sense of natural human touch enabling more intelligent robot interactions [2]. Integrated into the hands or fingertips of robots, this technology have proved useful in terrestrial applications, for object property estimations (shape, texture, and hardness classification) [3], slip detection, deformable object manipulation, among others.

In the space domain, tactile sensors need to function precisely for extended durations (often years) without the chance for recalibration. They must operate in a near vacuum, endure radiation, withstand direct sunlight (heat) and complete darkness (cold), and handle temperature fluctuations ranging from approximately +120 to -160 °C. Thus, the use of tactile sensing in space has been studied from various perspectives, including the investigation of the technical requirements needed for tactile sensors to withstand harsh and challenging space conditions [4], and developing an on-ground experimental setup allowing further studies into the application of tactile sensing in space [5]. In [6], a specially designed two-fingered gripper has been showcased for tasks inspired by the Astrobee free-flying robots on the International Space Station (ISS), including gripping corners, identifying misaligned grasps, and enhancing load distribution across contact areas during pinch grasps.

In 2020, NASA in *2020-NASA Technology Taxonomy Report* [7] stated the need of space-qualifiable tactile sensors for orbital debris characterization, sensing, and perception pipeline of autonomous robots. Therefore, aligned with NASA's roadmap, this paper explores potential use cases of a low-cost widely used visual tactile sensor. Our research focuses on exploring the capabilities of this sensing modality to enhance robot perception and increase the level of autonomy in space operations.

II. Proof of Concept

A. System Overview

GelSight tactile sensors will be placed at the finger tips of the robot end effector. GelSight technology (Visual tactile) provides high resolution measures of a contacted surface [8]. Machine Learning models are trained to extract meaningful information for the manipulation task during contact, such as shape, contact regions surface hardness, force, among others. Fig. 1 shows the workflow. Some AI-oriented features such as 3D representation, depth analysis, touch detection, slip detection are already available with the open-source PyTouch package [9].

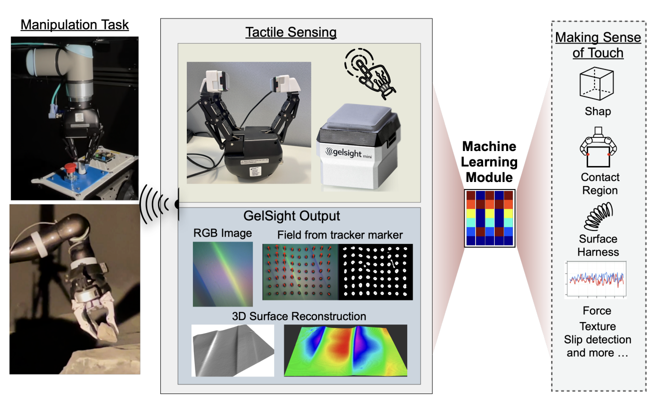

Fig. 1. System Setup. Machine Learning Models will extract meaningful information, such as depth, touch and slip detection.

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B. Assembly Use Case

Two Gelsight sensors was integrated in the fingertips of a 3-Finger ROBOTIQ Gripper (see Fig. 2). The sensor information can be used to enhance the information the gripper uses to perform its tasks. This tactile sensor offers by default an important range of data outputs, namely a raw RGB image for surface inspection, 3D reconstruction capabilities and a point cloud array representation is also available. These outputs become important to analyse the materials and surface. Thus, for an assembly use-case this technology can be used for:

- Precision and Control: by providing precise feedback on the force and pressure exerted during assembly tasks. This is essential for handling delicate components and ensuring they are properly aligned and connected without causing damage.
- Enhanced Manipulation Skills: by allowing robots understand the fingers-object location, facilitating intricate assembly tasks such as screwing, fastening, and fitting components together with high precision.

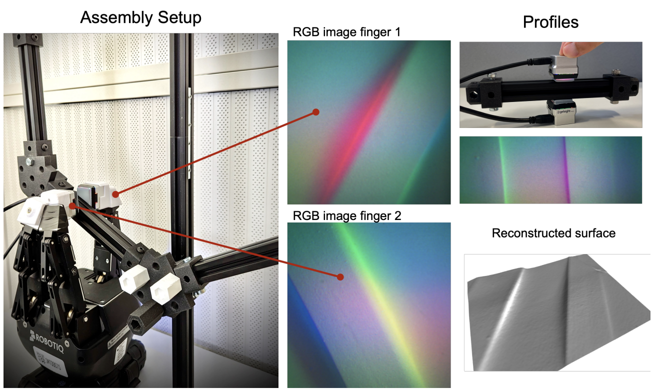

Fig. 2. Assembly use case

C. Inspection Use Case

Following the terrestrial assembly applications such as in the aerospace industry; where Boeing has been using GelSight sensors for aerospace manufacturing and MRO (Maintenance, Repairs, Operations) processes. This technology takes advantage of the optical properties of its elastomeric gel, which conforms to any surface in contact with the sensor, hence providing better results compared to traditional surface inspection [10].

With this in mind, we use the sensor to inspect the surface of a 1U CubeSat shown in Fig. 3. The crack is almost unnoticeable to the naked eye (for example total darkness during eclipse), however, the image provided by the sensor clearly shows it. Therefore cracks and other integrity concerns can be examined with precision (see in Fig. 3, the images produced by a screw). Moreover, tactile sensing can determine the surface topology including the type and properties of the inspected material. Hence, for the inspection use-case this technology can contribute to:

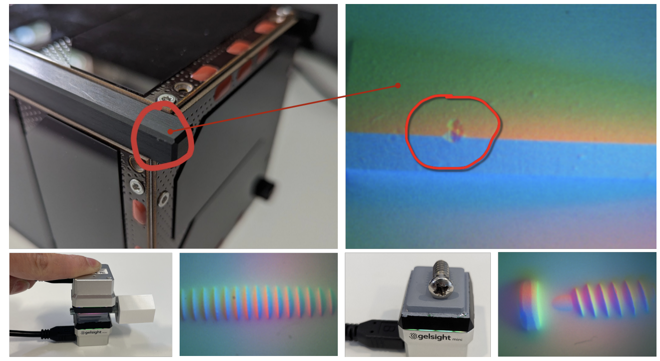

Fig. 3. Inspection use case

- Performance monitoring and maintenance: by detecting damaged components including the significance of the defective parts' role in the overall system.
- Safety: Allowing the system to halt, warning the operators, or adjust operations to prevent accidents.

III. Conclusions

This paper explored the GelSight visual tactile sensing technology and its potential applications for ISAM activities. Tactile sensors will be required for the successful assembly of future in-orbit structures. To get beyond state-of-the-art, future work will focus on training new ML models to enhance tactile-based features for object grasping, and the integration of visual-tactile information for manipulation.

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