Video and Telemetry Anomaly Detection and Prioritization for Autonomous Deep-Space Robotics

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I. Introduction and Motivation

Robotic systems operating in deep space will require high levels of autonomy for operation, maintenance, repair, and navigating unexpected situations. These systems will face several unique challenges including communication delays, intermittent communication dropouts, high levels of electromagnetic radiation interference, restrictive communication bandwidth limits, and limited crewed-time.

Our goal is to build a proof of concept on-board system that is capable of detecting anomalies in video and telemetric data generated by a robot operating in deep space, and prioritize this data for transmission to ground-stations.

A direct application benefiting from this system would be the Canadarm3 robotic system, also referred to as Deep Space eXploration Robotic (DSXR), which will be Canada's contribution to the Lunar Gateway as part of NASA's Artemis Program. The Lunar Gateway will be a space-station that will orbit the Moon, built to serve as an outpost to enable sustainable human exploration of the Moon and beyond. [1]

Canadarm3, a highly-dexterous and autonomous robotic system, will be used for the Gateway's construction, maintenance, inspection, capture of visiting spacecraft, module relocation, and support of astronauts during spacewalks. Thus, Canadarm3 will serve a role similar to that of Canadarm2, also known as the Mobile Servicing System (MSS), on the International Space Station (ISS) [1].

With Earth-based ground-stations expected to have only an estimated 8-hour communication window per week with the Gateway, a smart agent would be required on-board to both detect and assess anomalies using telemetric and video data. The short communication window also imposes constraints on the total bandwidth of data that can be transmitted to Earth, shifting the tasks of data-processing, categorizing, and decision-making to on-board systems. These are the challenges our system aims to resolve.

II. Approach and Methodology

Leveraging lessons learned from the International Space Station and other deep space projects (such as Mars rovers) is a central tenet of the systems engineering approach which will be employed in the design of all Lunar Gateway engineering activities, as agreed upon by the international partners of the Artemis Program, including the Canadian Space Agency (CSA). For this project, we will be employing a similar systems engineering approach. Thus, although the project will be designed for use on the Lunar Gateway, we will use data gathered from similar space systems as surrogate for Lunar Gateway data. In particular, the design team will leverage its vast experience with Canadarm2 data and other sources of publicly available space telemetry data (ex. Mars Space Loboratory Rover telemetric data).

III. Project Plan and Milestones

This project will be developed using an Agile Project Management approach, with the team working in parallel "sprints" on different aspects of the project.

This project is being undertaken, in part, to fulfill the requirements of the CP8318 Machine Learning course at Ryerson University. However, owing to the fact that the scope of this project is defined by real-world applications, and not simply driven by "demonstration of capability", only a subset of the entire project will be completed before the end of the course. Thus, the project has been broken down into the Work Packages (WP) for execution, presented in Table I. Tasks in WP1 to WP5 will be completed as part of CP8318.

It should be noted that, as all projects in the proposal stage, it is possible, and expected, that the project team will deviate from this initial plan, when required.

IV. Project Execution and Experimentation

In order to complete the tasks identified in the Project Plan, the project team will employ a strategy of combining existing resources with new tools, as required. In particular, this strategy will be used for data engineering, Machine Learning model development, and model evaluation.

A. *Data Engineering*

Video and image data used in the project will be obtained from the resources identified in Table II.

Telemetry data used in the project will be obtained from the resources identified in Table III.

TABLE I: Work Breakdown Structure and Milestones

WBS	Task Description
WP1	**Data Gathering and Engineering**
1.1	Acquiring required permissions via NDAs for access to NASA and CSA flight data and videos
1.2	Gathering flight video and telemetric data
1.3	Generating synthetic video and telemetric data
WP2	**Video Anomaly Detection and Prioritization**
2.1	Anomalous Object Detection in Images
2.2	Anomalous Object Prioritization Classification in Images
2.3	Anomalous Object Detection in Video
2.4	Anomalous Object Classification and Prioritization in Video
WP3	**Telemetric Anomaly Detection and Prioritization**
3.1	Telemetric Anomaly Detection
3.2	Telemetric Anomaly Classification
3.3	Telemetric Data Prioritization
WP4	**Failure Analysis, Testing, and Refinement**
WP5	**Project Report and Presentation**
WP6	**System Integration**
6.1	Data Integrating
6.2	Data Transmission
WP7	**Testing**
WP8	**Deployment**

TABLE II: Video Data Resources

Data Resource	Description	Note
ISS On-board Flight Images and Videos	Actual videos and images captured from on-board cameras on the MSS and elsewhere on the ISS (Fig 1).	Requires NASA/CSA Clearance.
Simulated High-Fidelity ISS Images and Videos	Synthetic images and videos generated using MDA's MOS3D proprietary tool developed for MSS support and simulation. Uses the Ogre3d game engine.	Requires MDA Clearance
Simulated Mid-Fidelity ISS Images and Videos	Synthetic images and videos generated using the publicly available spacecraft modeling and orbital mechanics simulation tool Astrogator STK (Fig 2).	

Fig. 1: On-Orbit ISS and MSS Image (courtesy CSA)

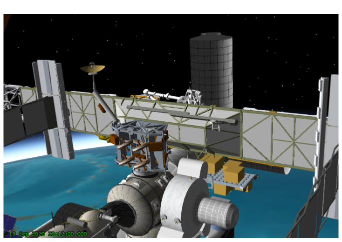

Fig. 2: Synthetic ISS Image Generated in STK

TABLE III: Telemetry Data Resources

Data Resource	Note
Real Historical ISS and MSS Flight Telemetry	Requires NASA/CSA Clearance.
Simulated Mid-Fidelity ISS/MSS telemetry generated using MDA's proprietary tool SAIF	Requires MDA Clearance
Mars Space Laboratory (MSL) Rover Environmental Monitoring Station Telemetry (REMS) open dataset. It contains real meteorological "measurements of air and ground temperatures, wind speed and direction, pressure, humidity and ultraviolet radiation" obtained by the Mars Rover [2]	

B. *Machine Learning Model Development*

The development team plans on experimenting with several techniques for both video and telemetry modeling. Some preliminary techniques identified are:

- Convolutional Neural Networks for Image/Video Segmentation and Anomalous Object Detection
- Recurrent Neural Networks for time or sequence dependent modeling, such as object tracking
- Support Vector Machines for data classification
- XGBoost or other tree-based techniques for prioritization
- Pre-trained ANN models, as applicable, for transfer learning

These techniques will be explored using existing libraries and frameworks, including, but not limited to:

- Keras + TensorFlow
- PyTorch
- SciKit-Learn
- Standard Python data manipulation and visualization libraries such as Numpy, Pandas, Matplotlib, etc.

C. *Model Evaluation*

Models will be evaluated against real and synthetic data, as applicable. Evaluation metrics will be finalized based on the data available and model techniques employed, but can be broadly categorized into the following categories:

- Precision of anomaly detection: True anomalies detected with respect to total anomalies detected.
- Accuracy of object classification: Total accurate classifications as a ratio of total test samples.
- Weighted score of prioritization ranking.

References

[1] About Canadarm3. Canada.ca. https://www.asc-csa.gc.ca/eng/canadarm3/about.asp. Published July 7, 2020. Accessed October 1, 2020.

[2] Rover Environmental Monitoring Station Telemetry. Kaggle. https://www.kaggle.com/peijenlin/msl-m-rems-2-edr-v1.0. Accessed October 1, 2020.