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Artificial Intelligence for Space Operations (AI)

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Abstract

Artificial Intelligence (AI) is well positioned to aid in imagery space operations, both on the ground and in-flight systems. Imagery is commonly used during space missions for situational awareness, allowing flight operators to monitor and track crew or visiting vehicles during rendezvous and docking. For the International Space Station (ISS) there is a cadre of personnel on the ground who review video and still imagery for sensitive content and to add metadata to the imagery before archiving.

As cameras become ubiquitous and embedded in other technologies, such as automobiles or home security systems, artificial intelligence is becoming key to making that video useful. Home security cameras can now not only alert you to whether something is in motion but can also differentiate whether the movement was from a person or an animal.

These technologies could now be used to streamline space operations, both on the ground and in space. On the ground, AI could be used to reduce the time needed to review video footage by determining which sections of video contain views of astronauts and could even identify the astronaut! In space, AI could be utilized to alert ground controllers to changes or movement based on the application. For example, an external spacecraft camera could provide alerts of micrometeoroid impacts or other changes to the exterior of the spacecraft.
The growing On-orbit Satellite Servicing industry could make use of AI imagery capabilities to identify satellites to assure, autonomously, that a servicing satellite is approaching the correct satellite to be serviced. Similarly, a target spacecraft could transmit video or flag ground controllers when it is approached by another spacecraft.

My paper will explore the potential benefits of AI for both in-space and ground applications supporting imagery, and provide potential engineering solutions for several scenarios, especially for NASA's upcoming Artemis campaign.

In summary, the application of innovative AI technologies in the imagery domain is now a realistic possibility, and will benefit all aspects of space operations, from video capture, signaling ground controllers based on specific triggering events, and in ground processing, cataloging, and archiving. It has the potential to apply to all future missions from the smallest CubeSats to major human spaceflight programs.

Acronyms/Abbreviations

AI	Artificial Intelligence
EVA	Extra Vehicular Activity
NODS	NASA Object Detection System
IO	Imagery Online
ISS	International Space Station

1. Introduction

Philosophy classes still ponder the question asked by Dr. George Berkely, an Anglican Bishop and philosopher in the 1600's-- "If a tree falls in a forest and no one is around to hear it, does it make a sound?" With that in mind, I ask the following—If a still image or motion imagery from a space mission cannot be found during a search, does it exist?

Since the beginning of spaceflight, imagery has been a key form of data collected. Whether for mere curiosity (what does Earth look like from Space?), or for operational reasons (did the solar panel deploy?), or for engineering purposes (what was that object that floated away from the spacecraft?), imagery has been included in space missions. To be useful, though, the image or motion imagery must be accessible and accessed when needed. During the analog era, that typically meant captions and numbers associated with the physical media. With "born digital" imagery, it is possible to add metadata to the image data file. This metadata might include the date and time of capture, mission, camera, exposure data, and similar data fields. Many modern cameras embed some basic metadata into the image file at the moment of capture. The reality, though, is even with today's born-digital enhancements with embedded metadata at the time of capture, reviewing and cataloging still and motion imagery is very labor intensive. Humans review the imagery for sensitive content (privacy concerns, imagery containing proprietary data/subject matter), and to identify imagery containing crew members or imagery that should be reviewed for engineering or scientific reasons. All this review and manual data entry is very time-consuming. Many improvements in Artificial Intelligence (AI), Machine Learning, and processing power now make it possible to identify persons, objects, motion, color, audio with sensitive content, and other details after or while the imagery is captured.

2. Imagery AI in Industry

There are two sectors in the imagery industry that are pushing the state-of-the-art in Artificial Intelligence enhancement of video and imagery—Home security systems and driverless cars. Early home video security systems, like Amazon's Ring system, were very simple. If someone pushed a button (the doorbell) the user could see who was at the door via the doorbell camera. As processing power, data speeds and cloud computing progressed, the systems became more sophisticated. Detecting motion gave way to distinguishing whether the motion or object was a "person". Game cameras can even distinguish what species of animal walked in front of the camera, or whether a deer is a doe or a buck. Meanwhile, the driverless car industry has been teaching its systems to identify all sorts of objects surrounding the automobile very rapidly, at high rates of speed. Distinguishing a stop sign from yield sign, a person from a tree or fire hydrant, a green light from a yellow light, all must be done in milliseconds. That processing has meant the development of systems on a chip with very high-performance CPU's and GPU's working in concert with one-another. Meanwhile, we all participate in generating training data for these machine learning systems when we answer questions on-line to prove we're not a robot. Most of the image identification systems like "Captcha" are asking us to identify stop lights, bridges, crosswalks, and other features useful to an imagery AI tasked with distinguishing these features while your car is driving over 60 miles-per-hour down a highway. All of that data is useful machine learning provided for free across the globe.

3. Imagery AI in Space Operations

Civilian Space Agencies can now exploit these technological developments to incorporate AI into imagery systems, either on-board the spacecraft, in ground operations, or both. These AI systems can dramatically improve efficiencies for reviewing imagery--identifying changes in the condition of spacecraft systems, identifying specific crew members, identifying points on the Earth, or flagging event triggers such as objects in motion. Instead of a human being having to review hours of video looking for a specific person or objects in motion, the AI can quickly point them to the relevant images or video. This process also dramatically reduces the time, cost and errors inherent to manual processing. The AI, however, is only as good as the training it receives. The more data and time put into teaching it, the better it will be. Feedback is also critical. If the AI flags what it thinks is an object in motion, for example, but instead was just a lens flare, then there needs to be a way to teach it the difference. This feedback loop informs the AI and makes it better over time. Without a feedback loop, where the AI's accuracy is confirmed or informed of errors, the AI becomes stale and stagnant. Thus, any AI system used for space use should include a way to continuously improve the system.

There is a way to get a head start in developing an AI system for space operations use—use an existing commercial imagery AI platform. Many such systems now exist, from cloud providers such as IBM (Azure) or AWS. Use of such systems can be a challenge for civilian space agencies, however, due to security implications. Commercial imagery AI providers typically assume the imagery is uploaded to their data servers and then the data is provided back. This model allows the user to take full advantage of the speeds cloud computing provides and allows for efficiencies by scaling the processing power needed for any particular application. Further, by not having to maintain an on-premises data center a space agency can save considerable money in facilities, power, and maintenance. But what if the space agency needs to guarantee the privacy of subjects in the imagery, or ensure the integrity of potentially sensitive imagery containing proprietary data? While most cloud providers insist their systems are secure, there have been numerous examples of data breaches over the years.

One solution to the conundrum of exploiting the power of a commercially developed AI system while maintaining security of imagery data can be solved by incorporating the AI into a closed-loop, on-premises system. The development of self-driving automobiles has dramatically increased the speeds of processing real-time data in a closed loop system. Providers of AI systems have also recognized there are users and applications where an on-premises system is necessary, and now offer solutions where their AI can be licensed for use in on-premises applications. Add the power of Application Programming Interfaces and Machine Learning, and it is now possible to fully exploit the power of AI for ground-based infrastructures.

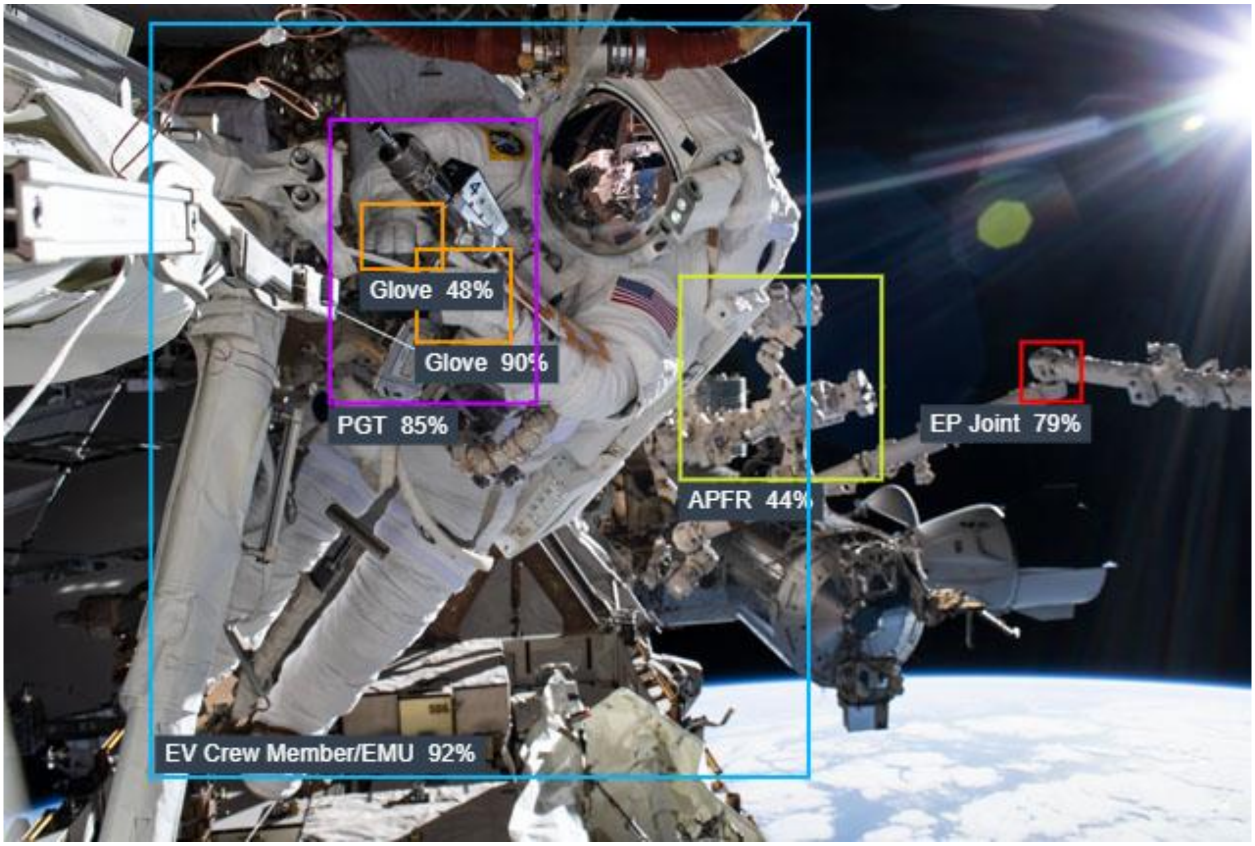
3.1 Imagery AI in NASA's Ground-Based Infrastructures

NASA's Johnson Space Center utilizes a custom application for managing human spaceflight imagery called "Imagery On-line" (IO). Users granted access to IO can quickly search and obtain imagery from years of human spaceflight missions. The usefulness of the system is entirely dependent on the meta-data attached to the imagery. Imagery from missions years ago often depended on human beings entering data about the imagery. Humans can make mistakes--they might get in a hurry, make errors like misspellings, or miss something that may, at the time, have not seemed important. That older data can now be augmented by the power of AI. A simple example might be identifying astronauts. There may have been scenes with multiple crew members in the frame. The human entering the metadata might have only referenced the crew members most prominent in the image, not referencing crew members in the background. Teaching the AI to recognize crew members by entering multiple images of each crew member could add many more references to the data base by going back through the collection and identifying frames or scenes where a crew member might have been present. Once confirmed by a human, that data can be added to the metadata attached to that image or video. Facial recognition could also enhance emergency operations where ground controllers are trying to confirm the location of all the crew during an emergency egress.

A public web site, the "Gateway to Astronaut Photography of Earth", https://eol.jsc.nasa.gov , utilized multiple machine learning models to improve the accuracy of searches of its extensive database. Images that feature notable geographical parts of the Earth have been used to teach the AI to help users find multiple images that include sites like lakes and rivers, peninsulas, and similar Earth features.

Perhaps a more critical application for AI and Machine Learning is teaching the system to identify specific objects of a spacecraft. Spacecraft that operates in space over long-periods of time are subject to decay, damage by space debris, and general wear-and-tear. The International Space Station is now in its third decade of operation. The Gateway, part of the Artemis Program, will be in orbit around the Moon for at least 15 years. Documenting the exterior of these spacecraft over time is a valuable tool in assessing decay or damage over time.

Computer scientists at the Johnson Space Center have recently developed a system called the NASA Object Detection System (NODS). Using machine learning, imagery analysts can quickly find images of specific objects spanning years of imagery collection. This provides an ability to compare the condition of an object or component of the space station from one increment to the next, one year to the next. Objects of interest include key parts of the robotic arm, solar panels, straps, radiator panels, gloves, Extra Vehicular Activity (EVA) suits, and similar objects. Users can select the object they are interested in, a date range (or select a specific EVA), and confidence filter percentage. Selecting a lower confidence filter might provide a much larger list of results, thus more imagery to cull through. Via machine learning and AI, the value of existing and new imagery is increased many times over. The more the system is used, and feedback is provided, the more accurate the system becomes.



Example of NASA Object Detection System identification of specific object in a still frame from International Space Station video during an Extravehicular Activity (Spacewalk). Courtesy NASA/JSC

Teaching the system what these objects are, however, takes time. Known images of the objects of interest must be identified. Finding images with different focal lengths, lighting conditions, and angles dramatically increases the accuracy of the detection. The investment in time up front, though, pays dividends later. If a ground operator notices something on a live video stream, a detached section of a solar array, for example, using NODS could allow identification of the likely timing of the problem more efficiently and with considerably more accuracy than what was available prior to the use of AI and machine learning.

There are generally two approaches to “teaching” an imagery AI system—Supervised or Unsupervised. The supervised approach begins with a human identifying objects in a training data set. Next, the model trains using that set of images and then a separate set of images is used to validate the model. The unsupervised approach begins with the AI simply identifying objects with distinct features, typically using edge detection, and then identifies similar objects with additional image data sets. It labels these objects with generic names (object 1, 2, 3, etc.) which is then labeled properly later by humans.

What about applications where it is impractical to utilize an AI for object detection or event detection using ground assets? Imagery requires a lot of data and thus a lot of bandwidth. The ISS has the luxury of a communications system that has been enhanced over the years to allow up to 600 Megabits per second (Mbps) downlink. As we extend our reach beyond low Earth orbit, such speeds are not practical. Increasing bandwidth requires powerful transmitters and large antennas. Spacecraft such as NASA’s Orion, and the planned Gateway, cannot come anywhere near to having the hundreds of Mbps data rates enjoyed by the ISS. In such cases, moving the power of the AI to the spacecraft’s imagery system is going to be required.

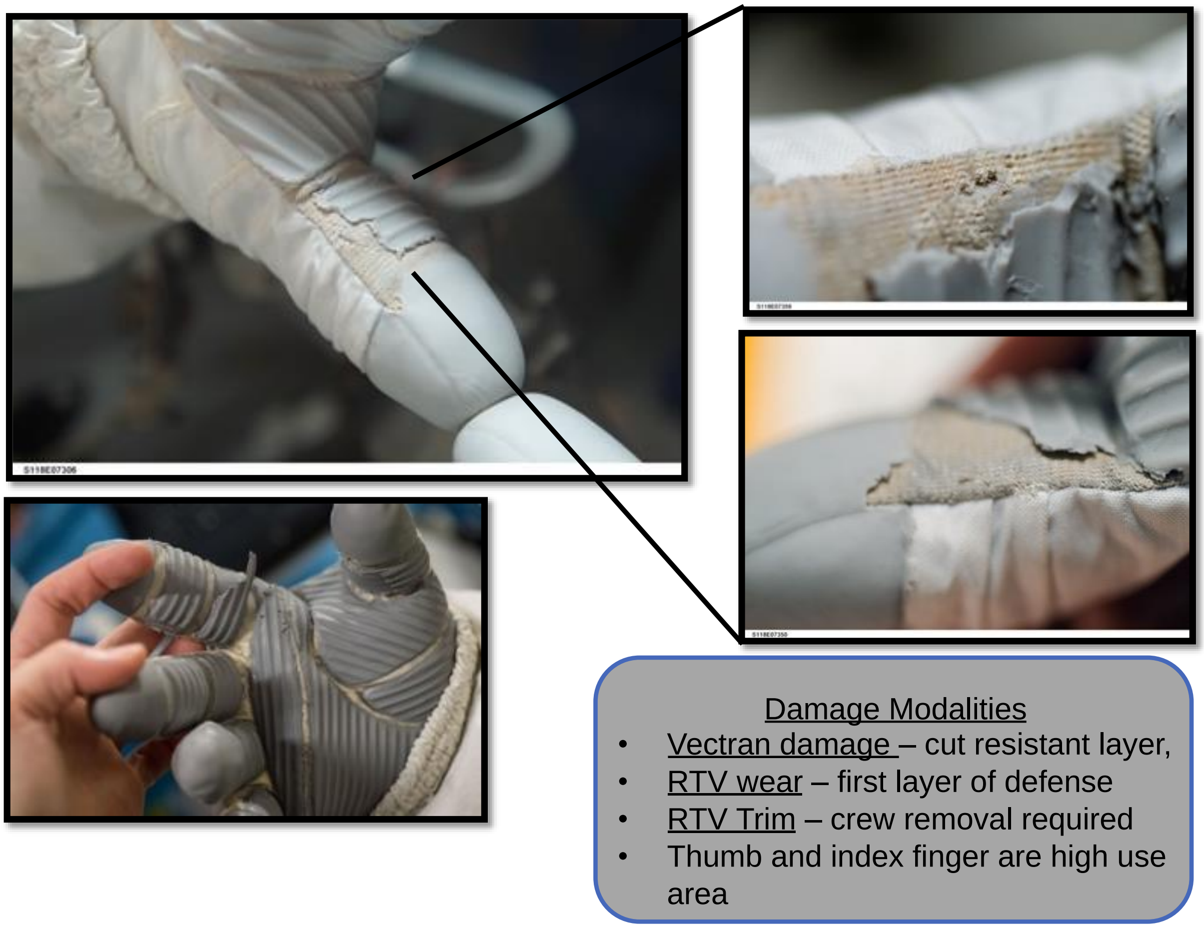
3.2 Imagery AI for Gateway

The Gateway will be uncrewed for over 10 months a year. During that time, systems will be powered down to the minimum required for the health of spacecraft. Sensors on-board will provide health-and-status data to ground controllers. But those sensors often have a trigger before they activated. An example might be the pressure inside the cabin, or heat in the case of potential fires. Without crew on-board, the likely solution to putting out a fire might include de-pressurization, exposing the cabin to the vacuum of space. Depressurization would have dramatic impacts to the spacecraft. It would be important to determine whether such a step, or any emergency mitigation, is truly necessary before execution. Imagery, especially real-time video, could provide a second data set to confirm the condition of the spacecraft. But downlinking real-time video during minimal operations will likely be impractical. The data rates required for streaming video of any quality will likely require multiple Mbps. If the on-board imagery system could utilize the power of an AI, it could then play a key role as a secondary or primary data provider for the monitoring of the spacecraft's condition. The imagery system, used during crewed ops for real-time monitoring of key events such as rendezvous and docking, or for public awareness and outreach, now becomes akin to a security video system.

A Gateway exterior camera system could be trained to recognize the key structures and placement of the exterior of the modules, solar panels, and other key elements of the architecture. Any deviation of that structure could trigger ground controllers to either begin a live stream from that camera for review or download previously recorded video on-board. Likewise, any movement detected by the camera system could trigger a review. An interior camera system could also be trained to recognize the normal placement of structures and flag either movement within the cabin or any deviation of the edges of a structure. If there were to be a meteor strike or a pressure change it is likely to alter the basic structure and would thus trigger controllers to review the imagery. Unlike other sensors that require some deviation beyond the norm to trigger the sensor, imagery can detect near-misses, such as a structure that floats by and misses the vehicle. Imagery can also detect deterioration that happens slowly over time, such as delamination of solar panels.

3.3 Imagery AI onboard the International Space Station

NASA recently explored the use of an AI onboard the ISS in a collaboration with Microsoft, using their Azure AI, and Hewlett Packard. The gloves worn by spacewalking astronauts are subject to tearing and deterioration. NASA routinely tasked crew members to take photos of the gloves before and after spacewalks and would send those images to the ground for analysis by trained specialists. In this collaboration, a computer vision application was created utilizing actual images of gloves, and models of the gloves in pristine condition. The application was loaded on board the ISS's Hewlett Packard's Spaceborne Computer 2. This allowed local, onboard analysis of the glove's condition. Conceptually, using an on-board AI, areas of wear, cracks and other anomalies could easily be detected and allow the crew to conduct further investigations and analysis before utilizing the gloves, without utilizing any ground computing or data services.



Examples of machine learning to identify damage to an Extravehicular Activity Suit Glove. Courtesy NASA/JSC

The on-board imagery AI test was conducted in December 2021. The Space Borne Computer 2 was able to complete analysis of 61 images in 28 seconds. Ground-based analysis had taken 45 seconds using an Intel i5 laptop. The analysis results onboard matched the predictions of the ground-based analysis. The test exposed some work-flow challenges that will be modified for future tests, but overall showed a great deal of promise.

4. Conclusion

As human space exploration looks toward crewed missions to Mars, imaging systems will by necessity be designed with embedded AI systems. The limited bandwidth and light time required to send imagery to Earth, wait for analysis and processing and then get the required data back to Mars would likely take too long to be practical. Analysis of imagery will need to be done on Mars. Architects for future spacecraft should plan on including embedded AI in their imagery architecture. Prior to launch the systems should already have been “taught” what hardware looks like using as-built baseline imagery, as well as whatever imagery exists of the terrain where the spacecraft intends to land or be placed. It is far better to consider the use of AI systems during the design phase than to try to add it later to an already designed or built system.

In summary, thanks to the technological developments driven by the self-driving automobile industry, security industry and processing power improvements of computer and graphics processors, machine learning and artificial intelligence is now practical for spaceflight imaging applications. NASA has already begun exploiting these capabilities to enhance metadata of current and recent imagery from the ISS. Using machine learning, tests have been conducted to utilize AI to flag imagery of EVA suit gloves condition prior to and after EVAs on-board the spacecraft. As missions move further and further away from practical real-time data communications with the Earth, embedding AI into imaging systems on the spacecraft will not only be possible, but necessary. Spacecraft designers should factor into their design the processing and data storage necessary to enable AI applications in their imaging system design.

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