Enabling Technologies for Deep Space Imaging

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From the beginning of the Space Age, imagery, particularly motion imagery, has been a part of crewed and un-crewed missions. As technologies have evolved the imagery gets better, more compelling, and more useful for operations and monitoring of systems, crew, and spacecraft. As we look forward now to crewed missions beyond low-Earth orbit, such as the Lunar Orbiting Platform-Gateway being considered as a pre-cursor to future crewed Mars missions, there are both opportunities and challenges in implementing a multi-faceted imaging system that advances mission capabilities and technology. This paper will present a vision for an imaging system that is relevant for operations of the ISS and future crewed missions in deep space, with a detailed look at some of the key innovative technologies required to enable such a system. Specific enabling technologies included are: Innovative camera systems capable of providing a 360° field-of-view without moving parts; Ultra-high Definition (or higher) resolution; High Efficiency Video Coding compression; Compatibility with Delay Tolerant Network protocols; and Intelligent systems capable of monitoring the field-of-view for un-crewed missions. Opportunities where Standardization can enable interoperability are also identified.

I. Introduction

The recent Hollywood film, *The Martian*, told the story of an abandoned astronaut's attempt to survive and his ultimate rescue and return to Earth. The Producers of the film contacted this author asking questions about imagery capabilities for such a mission, asking specific questions about how video would be transmitted, what would happen if the communications links were limited or prone to outages, and how video would be used by both the crew and operators on the ground.

Imaging from space, especially motion imaging from deep space, presents several challenges when considering an end-to-end system. The system starts with the camera. Considerations for the camera include field-of-view, pointing (or pan-tilt), spatial and temporal resolutions (pixel dimensions and frame rate), internal or external use, and whether the camera will have internal recording and/or live output capability.

Since raw, uncompressed digital video requires considerable bandwidth, compression will have been utilized in order to further distribute the video. For example, the live output of a High Definition camera is typically 1.5 Gigabits per second (Gbps). Ultra-High Definition (UHD) cameras can output up to 12 Gbps depending on frame rate. Therefore, significant compression will have to be applied to transmit live video and to reduce the size of data storage for recorded video. Where that compression is applied also must be considered. Figure 1 illustrates the components for a system to produce live and recorded video from a spacecraft.

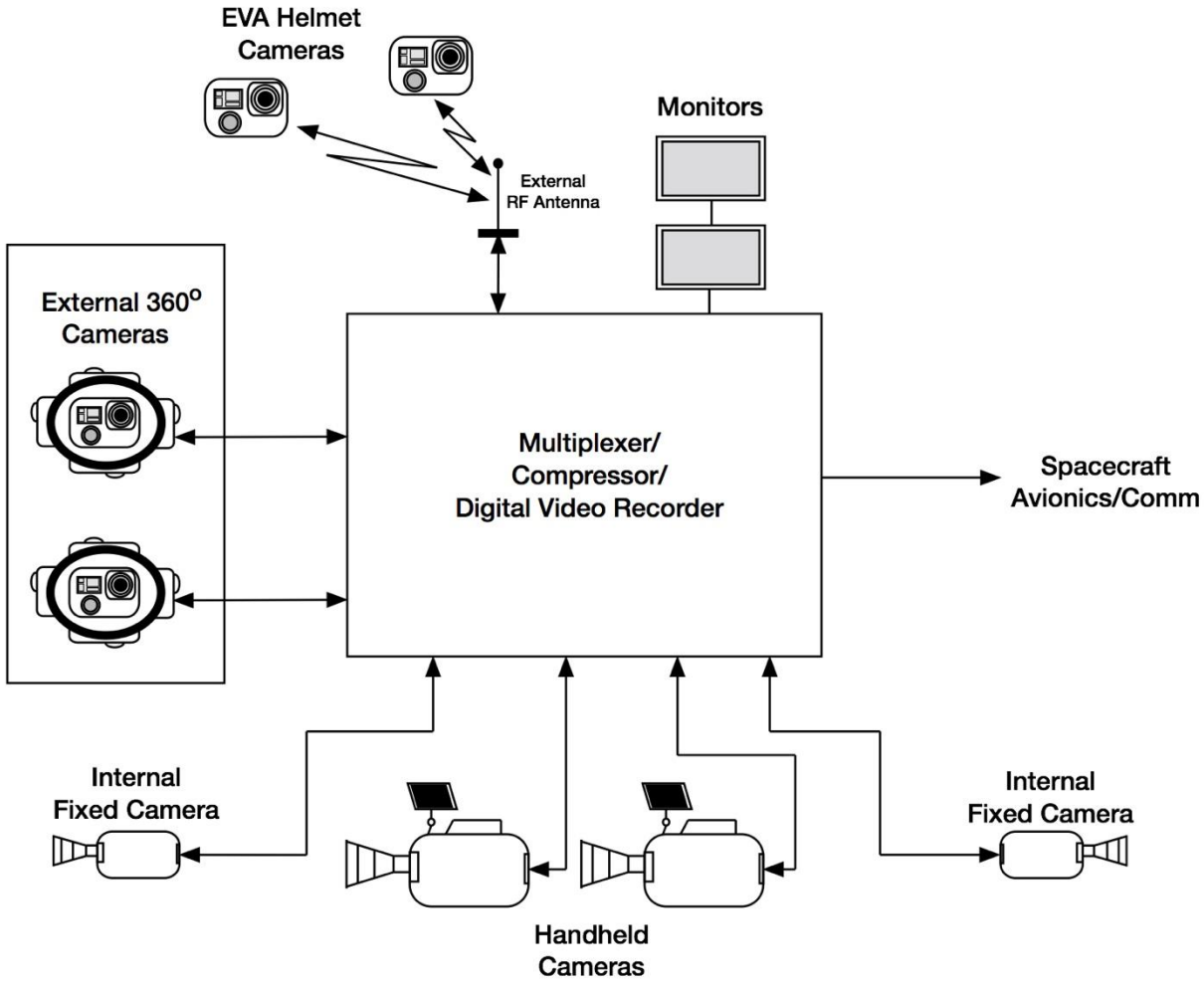

Fig. 1 Simplified System Diagram of Spacecraft video system

Here on Earth we have the luxury of internet protocols that manage the transfer of high bitrate video streams from server to device. Any disruptions in the network typically go unnoticed. If there is a disruption we may have to tolerate some skipped video (if viewing a live stream) or some buffering, or if there is high demand for the video the server may get overwhelmed and not allow new viewers. What happens, however, if the internet link has a one-way delay over several minutes? How would live video from Mars or a Mars-bound spacecraft work? Compressed video streams or video file transfer must take these link disruptions and delay into consideration.

Missions such as the Lunar Orbiting Platform-Gateway or missions to Mars envision periods of time when the spacecraft are uncrewed. During these phases of the mission there may still be a need for motion imaging. Imaging systems that can detect movement, changes in spacecraft integrity, or even sounds may prove useful for operators on the ground or crewed spacecraft bound for the outpost. For example, if a sensor in the uncrewed spacecraft indicates a fire, visual confirmation of the spacecraft's condition may be critical before operators go to the extreme measure of venting the spacecraft.

Viewers of the film *The Martian* may recall how important motion imaging was for both the abandoned crew member and ground controllers. With crewed CisLunar and Mars missions now more likely to happen in the coming two decades, it is prudent therefore to begin developing the enabling technologies and system interfaces to turn fantasy into reality.

II. Cameras

The earliest crewed spaceflights in the 1960's included film cameras, and later video cameras, to document the experience. The imagery captured the imagination of the World, but were also very useful for operations, engineers, and scientists. Over the decades the cameras became more sophisticated and provided better and more useful imagery. In the late 1990's NASA began flying High Definition Television (HDTV) cameras that recorded spectacular footage on video tape. Later in the 2000's HDTV cameras that recorded on small memory cards were flown on the International Space Station. As encoders were developed that were small in size, live HDTV from the ISS became routine. In 2017 a live UHD downlink was demonstrated at the National Association of Broadcasters. Looking ahead to CisLunar outposts and Mars missions it is logical to presume that continued advancement in capability and resolution will be the norm.

There are two use cases for cameras in spaceflight—internal and external. Internal cameras can be both fixed and crew operated. Often on the ISS, the same make/model of camera can be used for both use applications. There are several types of camera mounts and devices that allow the camera to be pointed or aimed for maximum coverage. Smaller hand-held cameras can be carried by the crew, placed in hard-to-reach areas and provide unique views of life on a spacecraft. These internal cameras are also very useful for ground operations to aid the crew with issues they may be having with equipment or systems, provide some hint as to the well-being of the crewmember, and are useful data for science and experiment documentation.

External cameras present several more challenges. The cameras must be protected from the harsh temperature extremes and vacuum of space. Lenses must be coated to reduce the effects of radiation. The camera's sensors and electronics will also be subjected to radiation that can cause either image defects such as "dead" pixels, or latch-ups that cause the camera to cease functioning properly. Designers of external spacecraft cameras must also consider the desired field-of-view of the external camera. If the camera is to be used for surveillance and situational awareness of the entirety of the external area and vicinity of the spacecraft, then either multiple cameras must be used or the camera must be fitted with a device to physically move the camera, typically a pan-tilt mechanical structure. Pan-tilt mechanisms that can operate in the extreme environment of space are difficult to build. The seals that house the mechanisms and lubricants required to move on two axes must be able to survive extremes in temperature as well as the ravages of radiation over time. There is a third option however: utilize a camera system with a 360° field-of-regard.

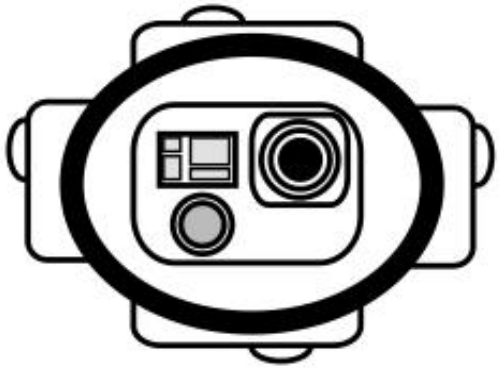

Fig. 2 Camera configuration for 360° field-of-view

The convergence of the gaming industry and nascent video industry interest in virtual reality has brought forth a variety of cameras or camera rigs that stitch together video from multiple cameras to provide a virtual pan-tilt functionality with no moving parts. Commercial cameras such as Nokia's OZO and Insta360's Pro provide a peek at the future of cameras that provide a near 360° field-of-regard that allow viewers to choose their own field-of-view. The cameras are actually multiple cameras configured with just the right distance and lens combinations to allow seamless stitching together of video from at least three of the cameras to provide full coverage viewing (Figure 2). The challenge with these systems is having the graphics processing power to do the stitching in real-time. Fortunately, the gaming industry is pushing the state-of-the-art in graphics processors that it is possible to have a processing system attached to these cameras that is low profile and power. With some of these commercial cameras it is possible for multiple viewers to have simultaneous views with a different field-of-view. That means a crew member could use the same camera as the ground operators but actually see a different field-of-view. Today operators have to take turns with external ISS cameras as each field-of-view requires physically maneuvering the camera to change its view.

What if more detail or variability in field-of-view is needed? A zoom lens is usually the answer in such cases. The commercial virtual reality cameras have fixed lenses. For external cameras zoom lenses are a challenge because the seals and lubricants required to move the multiple optics in the lens must be able to survive the extreme temperature variations in space. Another option is over-sampling the video. For example, if the live viewing is in 1280 x 720 progressive HDTV format, but the camera itself has a 4K, 6K or 8K sensor, then it would be possible to digitally zoom into the field-of-regard of the sensor with no reduction in image quality. If the virtual reality 360° camera mentioned above was utilizing 8K cameras, for example, it would be possible to have a 6x zoom capability still with no moving parts (by windowing a 1280 x 720 image from a sensor with 8192 x 4320 pixels).

Another practical function of over-sampling, or using a higher-resolution camera system, is the ability to use a wider-angle lens to cover a wide field-of-view with no loss of detail. For example, an 8K video camera inside the cabin of the Gateway could use a wide-angle lens and provide a wide field-of-view, yet zooming in on details in the video would still yield good quality when compared to a conventional HDTV camera outfitted with a wide angle lens. This may prove useful for on-board crew and ground operators using the imagery for inspection or conducting analysis of details such as settings on switches or data on a screen within the field-of-view.

There are several technical challenges with implementing a 360° field-of-view cameras as described here, including: processing the real-time stitching of all the live feeds from the cameras, managing the IP command and control traffic between either the cabin or ground controllers and the camera system, routing uncompressed video from the cameras to the graphics processor that performs the stitching, and compressing the "stitched" video for viewing either on-board or on the ground. These challenges are worth resolving, however, given the benefits already referenced, especially the dramatic reduction in mass vs. a physical pan-tilt mechanism, and the ability to provide multiple field-of-view feeds simultaneously.

No discussion about cameras in space is complete without acknowledgement of the damage to sensors caused by ionizing radiation. Since the first HDTV cameras were flown in the late 1990's, it has been obvious that HDTV camera sensors were highly susceptible to ionizing radiation, especially Charged Coupled Devices (CCD). Damage to the sensors result in video with colored or white pixels. Later flights on the Shuttle and ISS that utilized cameras with Complementary Metal-oxide-semiconductors (CMOS) fared slightly better. Numerous cameras have been flown on the ISS over the years from different manufacturers and with slightly different sensor configurations. Results have varied with little discernable consistency between camera sensors that fare better than others. Pixel pitch, or distance between pixels, seems to play a role in whether a camera's sensors will show damage. Beyond that, it seems the best strategy is to design camera systems that can be easily replaced instead of trying to design a camera sensor that can withstand the ravages of ionizing radiation.

III. Compression

As previously stated, raw uncompressed output of HDTV cameras is ~1.5 Gbps. Depending on frame rate, the output of an Ultra-High Definition camera can be up to 12 Gbps. An 8K camera's raw uncompressed output would be even higher than that (it would vary depending on frame rate). Therefore, a considerable amount of compression will need to be applied to make the video from these cameras practical for distribution and viewing, especially between spacecraft and the ground and from spacecraft to spacecraft (or an EVA suit or rover, for that matter). The first ever HDTV downlink from the ISS utilized MPEG-2 compression @ ~30 Megabits per second (Mbps). In the early 2010's, MPEG-4 (specifically MPEG-4 Part 10, also referred to as h.264) compression became widely used in the television and video industry. Today, using MPEG-4, multiple streams of very high-quality HDTV are downlinked from the ISS, with each stream compressed to 8 Mbps. The next generation of high-quality compression algorithm, dubbed High Efficiency Video Coding (HEVC) or h.265 enables orders of magnitude improvements in quality per bit compressed. For example, the same video stream compressed to 8 Mbps with MPEG-4 could be compressed to 2-3 Mbps using HEVC with no loss in quality. HEVC was also designed to scale up to higher resolution video. MPEG-4 could not compress video beyond 4K or Ultra High Definition.

In April, 2017 the first ever live Ultra High Definition downlink from a spacecraft was conducted during a session at the National Association of Broadcasters in Las Vegas, Nevada. A Red Epic Dragon camera that was already on board the International Space Station was used as the source of UHD video. The camera was equipped with a device to provide live UHD output @ 30 frames-per-second by splitting the video into four HD-SDI (SMPTE 292, Bit-Serial Digital Interface) outputs. Those four HD-SDI outputs were routed to a h.265 encoder provided by AWS Elemental. That encoder combined the four HD-SDI feeds into a single UHD signal and applied significant compression, going from 6 Gbps input to 18 Mbps. The demonstration was a success. The video was presented live on large screens in very high quality.

The use of h.265 encoding is a dramatic gain in efficiency. The bandwidth required for high-quality full motion video can be reduced by a factor of 2 or 3 times what is required using current MPEG-4 encoding. The algorithm also provides for much higher resolution video. Commercial encoder & decoder manufacturers are providing more hardware and software offerings. Apple Inc. included h.265 encoding and decoding in its latest iPhone, for example. Converting from an MPEG-4 based system to h.265 does require new encoders, and more importantly, new decoders. In most cases the hardware processing required for h.265 decoding exceeds what was used in MPEG-4 decoders deployed in recent years.

Compression of High Definition video on the ISS has thus far utilized MPEG-2 Transport Streams (MPEG-2 Part 1, Systems ITU-T Rec H.222.0) packetized as UDP/IP for routing to the avionics data transport systems on-board. MPEG-2 Transport Streams are routinely utilized for transporting real-time video over IP networks. Most commercially available encoders create a MPEG-2 Transport Stream as default output. Audio is synchronized with video and is not in danger of getting out of synchronization when utilizing transport streams. For low Earth orbit applications, modern encoders utilizing MPEG-2 Transport Streams make sense, but as we begin to get mover further from Earth consideration will need to be given for transport that works well with disruptive networks, or applications where live or "real-time" transport is not practical (for example, transit to or from Mars or on the surface of Mars). Compatibility with bundle protocols and other Delay Tolerant Networking standards should be assumed in any future deep space bound spacecraft. The Consultative Committee for Space Data Systems has both a Delay Tolerant Networking and Motion Imaging & Applications working group investigating methods for transport of data streams over bundle protocols.

On the ISS, end-to-end latency for compressed HDTV averages just less than one second. That is the time from image capture, compression, routing through on-board ISS avionics and communications systems, routing through the Tracking Data & Relay Satellites, reception on the ground, routing to decoders, and finally display. Missions in CisLunar space would likely have slightly longer latencies if the communications systems use radio frequencies. Once missions leave CisLunar space, transmission delays will get progressively longer. At some point "real-time" communications between the ground and the spacecraft will cease to be practical. Typically, a latency beyond 5 seconds between two parties becomes problematic. Both parties must be disciplined to state the end of their communication to avoid talking over one another. As the one-way communications time increases, monitoring of video from the spacecraft can be accomplished in multiple ways. It can be viewed and recorded as it is received, or it can be stored and viewed later. Likewise, video from the spacecraft could still be streamed in real-time or could be recorded and forwarded as a file. Use of delay tolerant networking for the transmission would assure that any gaps in transmission are filled, but on the ground, operators would have to decide whether to monitor the transmission as received (with gaps if any occur) or whether the entire transmission is received and reconstructed before viewing.

IV. Intelligent Systems

The Lunar Orbiting Platform—Gateway currently being considered by NASA and international partners envisions long periods where the spacecraft will be uncrewed. Likewise, crewed missions to Mars presume placing spacecraft in orbit and on the surface before the crew embark on the mission. During these periods of uncrewed activity, sensors will be monitoring the spacecraft's health and status. Imaging systems with built-in intelligence could prove to be valuable additions to the suite of sensors monitoring the spacecraft or, in the case of Mars surface vehicles, the area around the vehicles.

Embedding intelligence into the video system could provide valuable data to either confirm other sensors or alert controllers and crew that something has changed. Examples include whether heat is detected, something is in motion, or the shape of a known object has changed. Surveillance systems in common use today are often set up to monitor and record for a period of time and then the oldest recorded video is dumped and replaced. Using triggers, the camera system could flag video, record and store the relevant section, and send notice to controllers to download and review later. Such a system could be invaluable in the case of collisions or debris strikes. One mechanism for managing fires on-board a spacecraft during uncrewed operations would be to vent the spacecraft. Before taking such an extreme step, video confirmation that there is indeed a fire onboard could prevent unnecessary damage to the craft.

Even during crewed phases, built-in intelligence in the video system could aid during routine operations and emergency procedures. If there was an emergency where the crew had to evacuate, having facial recognition or using color to track each crew member (each crew member could be outfitted with specific color patches) could help

controllers quickly determine the location of each crew member. Similar intelligence would prove valuable to monitor EVA activities, especially if there is an emergency.

Adding metadata into the video including x/y/z axis of field-of-view, camera location, and timing will also aid crew and controllers. This data should be viewable either as an overlay on the video, or separately.

If the camera system is at a fixed and known location, such as the exterior of the spacecraft, having the ability to baseline the location of fixed edges of the spacecraft could be used to trigger recording and notification of controllers during uncrewed phases if the edges or shape changes. This would allow more immediate detection of delamination, damage from debris strikes, or other anomalies with the integrity of the spacecraft structure.

In all cases, imaging systems for spaceflight should be characterized prior to flight. Characterization of the lenses and sensors will allow controllers and analysts to confirm whether something detected in the imagery is genuine or an artifact of the imaging system, and to allow photogrammetric methods to be used to more scientifically determine the size, shape and orientation of objects.

V. Conclusion

The first decades of human spaceflight missions included either custom developed video hardware systems or highly modified commercial-off-the-shelf hardware. The last decade has seen a dramatic shift to utilizing mostly commercial-off-the-shelf camera systems. Imagery, especially motion imagery, is valuable data for engineers and scientists, but is also valuable because it engages the public in ways scientific papers and verbal presentations can never match. As humans venture beyond low Earth orbit, the area around Moon, and on to Mars, we here on Earth will no doubt watch in wonder and amazement. We will watch only if we solve some of the challenges referenced in this paper, that is. Hopefully some of these challenges will be resolved in time.