The Standardization of In-space and Surface Docking Systems

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Abstract

The International Docking System Standard (IDSS) was developed and establish to aid on-orbit crew rescue and joint operations between different spacecraft. For the International Space Station (ISS), the IDSS has successfully enabled global interoperability for commercial crew and it is now being extended to the Artemis campaign. Similarly, as more companies, agencies, and nations announce their intentions to explore and occupy Low Earth Orbit (LEO) and Cis-Lunar space, including the Lunar surface, it is a natural supposition that new, vehicle interface standards will be required to support the build-up of infrastructure for campaign-based exploration or permanent occupation by national and multi-national agencies, industries, and companies.

A surface version of the IDSS, a.k.a. IDSS-Surface (IDSS-S), is under consideration at the NASA Johnson Space Center (JSC) by the docking discipline leads responsible for the leadership of technical development and negotiation of the original IDSS over a decade ago. The IDSS-S, like its predecessor, will ultimately detail the physical geometric mating interface and design load requirements to ensure physical interoperability and to support a broad set of design reference missions which, if accommodated, increases the probability of successful Lunar surface docking between different modules enabling the accessibility and inclusivity required for multi-national, sustainable Lunar exploration.

Introduction

For many years, NASA and JSC have been critically involved in activities leading to the development and establishment of standards. One such standard, the International Docking System Standard (IDSS), was born out of joint collaborative docking mechanisms development work which began under the JSC X-38 Program. Despite the X-38 Programs cancellation, the efforts of the two principal collaborating partners, NASA and ESA, caught the attention of Senior NASA Manager Bill Gerstenmaier who set forth in motion the action for JSC Engineering, along with the existing ISS International Partners, develop the framework for creating and establishing the first in-space docking system standard. This paper does not delve too much into the background of the development of the IDSS. However, the experience of developing, implementing, and managing the IDSS as a standard provides valuable insight and lessons learned which would be applicable to the creation of a Surface IDSS, or IDSS-S, as future Lunar surface element providers pursue the development of modules, systems, and infrastructure that require the mating and assembly necessary to enable a permanent, sustainable Lunar capability. The in-space docking standard IDSS can be viewed as a success; demonstrated by the fact that several commercial vehicles are now able to dock to the ISS, and that new commercial LEO platforms, as well as, the Lunar Gateway, are all using the IDSS to drive their critical interface specifications and enable their interoperability and compatibility.

While there will always be naysayers, including those within the spacefaring community of practice, who have expressed doubts about the inevitability of successfully achieving a crew rescue mission, events over recent years have highlighted the real potential for the most basic form of spacecraft interoperability by, as a minimum, ensuring first vehicles are equipped with the basic fit and form necessary to enable a crew rescue function. While we have never yet performed an in-space crew rescue mission, it is only a matter of time as more entities, nations, agencies, and commercial partners, develop and fly more vehicles supporting more missions, there will eventually come a time that a rescue, or even worse case a recovery

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mission, could be attempted to aid the distressed. To accentuate this point it wasn't that long ago during the inaugural unmanned demo flight of the Boeing Starliner crew transport vehicle, the unmanned craft failed to make orbit and according to published accounts very nearly reached the point where it could not reenter either. Had this vehicle been crewed and outfitted with a fully compliant IDSS interface, it is conceivable that a second vehicle, similarly outfitted could have been launched to rendezvous and provide whatever assistance could have been delivered. Harkening back to the ill-fated Columbia mission, it could be possible that at some point in the not too distant future that had a prepositioned rescue vehicle could provide agencies more options when dealing with critical situations. The primary lesson here is that with the proper planning and implementation, in the future it will be more possible that aid can delivered in time to impact mission outcomes, or to simply aid in recovery. This lesson has not been lost on the submariners community as there are also interface and operations standards in place to aid in rescue and recovery globally even for aiding those who are traditionally not our ally. A simple internet search on the acronym ISMERLO will lead you to information highlighting an highly analogous, world-wide, ocean-based emergency rescue capability and community of practice.

Beyond basic crew rescue interoperability, there is a larger level of interoperability which entails both pre-planned as well as impromptu mission planning yielding permanent, semi-permanent, or temporary element-to-element docking with prescribed resource transfer connectivity for the sharing of things like fluids, power, and data. As activities for exploration, colonization, and occupation of the Lunar surface by an ever-growing list of participants increases, it seems practical to begin the dialog concerning the continued development of standard interfaces and operations enabling both nominal and off nominal capabilities.

History and Evolution of the IDSS

As mentioned earlier the IDSS evolved out of the interaction between NASA and ESA while pursuing the development of docking mechanism for the X-38 Vehicle. However, the real roots of international docking go further back to the 1970's during the Apollo Soyuz Test Program (ASTP), where the United States (US) and Russia demonstrated that it was possible with the right interface design and requirements for two independent developers to design, test, and execute in-space docking of two vehicles from different sources (Figure 1). A key point worth highlighting is that prior to the ASTP, in-space docking mechanisms were of designs which relied on prescriptive male and female geometry (e.g., probe/cone), meaning that mating pairs of vehicles always had to have the right combination of geometry to achieve docking. In as much as ASTP was geopolitical historical event between the two cold war powers, it also showcased that a more universal geometric interface arrangement demonstrating equality was possible by the selection of a 3-petal androgynous interface. The benefit of an androgynous docking interface layout is it bypasses the physical limitation of always having to have the correct pair of docking interface geometry.

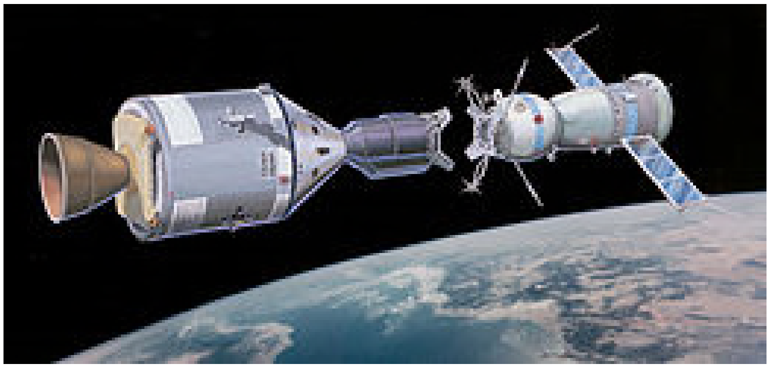

Figure 1. A 1973 artist's conception of the docking of the two spacecraft using 3-petal androgynous interface (source http://spaceflight.nasa.gov/gallery/images/apollo-soyuz/apollo-soyuz/html/s73-02395.html)

Fast forwarding through the 1980's, 1990's and into the 2000's, both the U.S. and Russia had retained the androgynous geometric interface layout in docking systems developed or in development. For the Russians, who had gotten farther along in their development than the U.S., they had already certified their androgynous docking system - Androgynous Peripheral Assembly System (APAS). So when the call to action came to develop the first international docking standard, the basic groundwork for true docking interoperability had already been set in motion decades earlier. The real challenge at that point was to establish a basic detailed design specification and the critical dimensions necessary to base the standard interface definition on. While recent NASA efforts in the development of new docking system used modern technology, it was ultimately decided that the IDSS be based on the NASA ISS-Shuttle docking system which had been procured from Russia and used for the Shuttle-Mir Program. Having a flight-proven, certified, design made selecting a design baseline easier for NASA Managers. While the APAS was chosen, there have been slight tweaks made to improve the IDSS design over the last decade to address changes needed to accommodate an expanding set of missions and environments, although the basic core design of the standard has not changed. Likely the biggest overall change from the original APAS design was a recent change to require recessing the power resource umbilical/connector below the mating sealing interface plane; which will be discussed more in a section below.

Basic Geometry and Keep Out Zones

While the term androgyny is used to describe the actual geometric arrangement of the interfacing features, in terms of physical implementation this means a circular docking ring with 3 equally spaced guide petals as depicted in Figure 2. During initial docking contact, in what is generally referred to as "docking soft capture", two 3-petal ring interfaces are guided into alignment with each other. Each petal on one ring is guided between the edges of two petals on the opposing ring very effectively provides a means of guiding the two 3-petal interfaces from a completely unconstrained state to a precisely aligned, fully constrained state. At the point of maximum meshing a trip latch similar to a simple door latch is used to hold the two rings together.

Given human spacecraft are typically larger in volume with significant masses, it is difficult to precisely control them in-space primarily due the precision and magnitude of thruster control authority coupled with real-time knowledge and accuracy of relative position and state vectors. To overcome this, the standard IDSS mechanism design requires one of the two 3-petal soft capture rings to be mounted on a 6 degree-of-freedom mechanism which when extended enables capture ring orientation compliance for matching the orientation of the second mating guide ring; as well as providing "stroke for attenuation" when fully meshed after capture. After this compliant "soft capture system" achieves soft capture and motion is attenuated, the active ring is fully retracted into final alignment bringing the two docking structural and sealing interface together, which is called "hard latching". Hard latching nominally involves inserting large diameter close tolerance "guide pins" which provide both the final precise positioning required for the high strength hook latching as well as an interface shear load reacting feature. The action of fully latching and preloading these two structural interfaces compresses the docking seals which are required for pressurization of the vestibule/passageway to enable crew and logistics transfer after hatch opening. These high-strength latch hooks and the docking tunnel are designed to hold the two docking interfaces together and resist the forces trying to separate them (e.g., internal cabin pressure or any external loads applied be either of the two mated vehicles result from thruster firing or from internal disturbance like crew exercise).

Since docking results in a finally controlled and aligned state, it enables locating very precisely secondary docking interfaces; such as resource transfer connectors or umbilicals which can be used to share power, data, and fluid resources between spacecraft. The IDSS IDD prescribes keep out zones around the circular docking interface like the numbers arranged around the edge of a clock face to further aid with docking resource standardization. While there is currently not much in the way of standardization of the "connectors" themselves between the various existing NASA Programs, by specifying and controlling the keep out zones, mission planners are able to use these zones for mating of connectors and transferring of resources across a mated interface meeting the specifications of their specific Program needs. Although, today there is little commonality of resource transfer technology across the industry, as the industry grows it is expected that further standardization will occur over time. Until this occurs, the IDSS IDD implementation will use the keep out zones and the requirement that all spacecrafts umbilical connectors remain retracted below the seal plane out of the way and unable to prevent the primary functions of docking which is the minimum required for crew rescue. After docking is complete, resource connectors/umbilicals can be actuated to extend and mate with connectors mounted on the other side and conversely retracted prior to undocking..

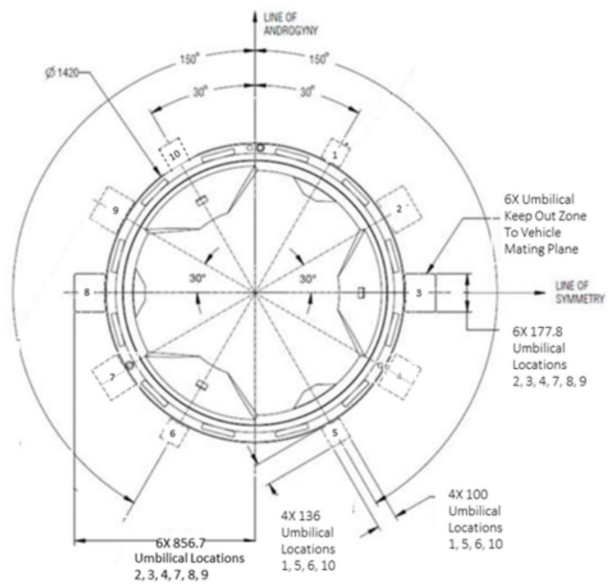

Figure 2. IDSS umbilical connector Keep-Out Zones

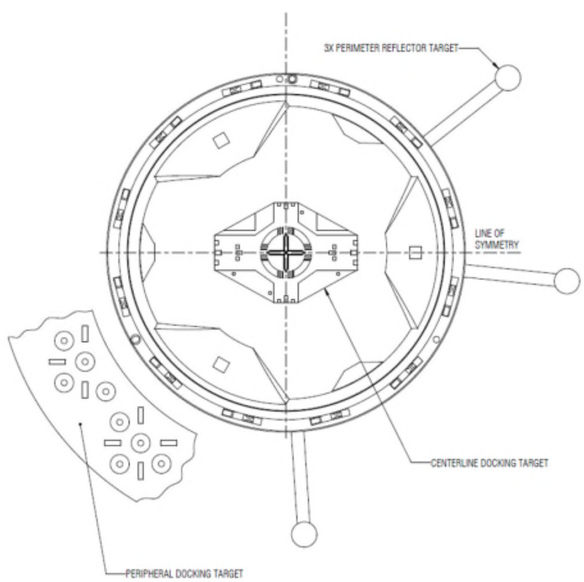

Figure 3. The 3 Types of IDSS Navigation aids (CDT-Cenerline Docking Target, PDT-peripheral Docking target, PRT- peripheral Reflector Targets) combination of which provide navigation support for active vehicle operations at long, mid, and short ranges

In Space Docking Challenges

Besides resource transfer connectors, there are two other related capabilities that also may influence the primary function of docking/mating. One is the placement of rendezvous navigation aids in or around the periphery of the docking interface. These are required by the active spacecraft to be able see/sense their alignment and positional accuracy as the spacecraft move closer and closer into proximity with each other for docking. Currently there are difference types of technologies, (e.g., cameras, lidar), each with its strengths and weaknesses and while industry continues to improve and promote various technologies in this area, like resource connectors, there is still not any consensus on the navigation target and aids required to enable rendezvous, proximity operations, and docking (RPOD). However there are separate standards in-place or in development by both Human Space Flight and satellite refueling spacecraft developers and is a discipline where things are evolving quickly.

Another factor which offers challenges for the design of docking systems and their operations is the use of docking systems/interfaces for “berthing” operations. Berthing is another category of spacecraft attachment which differs from docking in that instead of two “free flying” spacecraft, a robotic manipulator system (RMS) or robotic “arm” is used to reach across from one craft to grapple the other. This robotic arm then provides the positional and closing initial contact conditions for mating. For example, after the now retired Space Shuttle had docked with the ISS, the Shuttle RMS could retrieve large modules from its payload bay and plug them into specialized “berthing ports” on the ISS. Another example of this is the ISS Cygnus resupply vehicle when fly’s up close the ISS and “station keeps” (i.e., floats within a small navigation box) as the Station RMS reaches, grapples, and berths the craft to a Common Berthing Mechanism port. Since the beginning of the IDSS there have been efforts to improve commonality between docking and berthing mechanisms, and the primary way for docking to not preclude berthing is to ensure that the force/velocity requirements for docking system to achieve compliance and capture are such that they don’t exceed the capabilities of a robotic arm.

Like navigation aids and resource umbilicals, berthing compatibility is an area where further definition and standardization needs definitization to better ensure all of these RPOD and berthing disciplines work together rather than have incongruous or competing requirements. Standards like the IDSS IDD are intended to enable cooperation and collaboration between space agencies, industry, and programs and highlight that it is important to consider a broader view of envisioned architectures in a functioning space infrastructure and the benefits of further standardization on global collaboration.

The Case for Surface Docking Interoperabilty

As human space exploration continues to mature and expand, mission planners and architects have already turned their attention to the eventual occupation and exploitation of other Solar System surface destinations, like the Moon and Mars. Once initial Lunar-return missions get beyond the Apollo-style ‘visit and live out of your lander’ paradigm, focus will turn to long-term, sustainable, infrastructure emplacement, and just like was demonstrated for the ISS assembly, long term Lunar or Mars surface occupation will require an equivalent of rendezvous, docking and resource transfer connectivity. As attention has returned to surface missions in recent years, so has the attention of NASA docking system discipline organization to begin to understand what it will take to develop the systems and capabilities to docking of grounded surface vehicles. At first glance it may seem this is easier than in-space docking but that is not necessarily the case. In the case of the Moon, lunar dust presents a formidable challenge when it comes to sealing and mechanisms. For any surface mission, the mass constraints for landing every ounce of mass are more stringent meaning systems need to be designed to be even more mass efficient. Also, unlike its in-space equivalent, surface docking will be “constrained” due to surface elevation variations as most likely any two surface modules will never be able to be brought into perfect final alignment like they can easily be done in-space. This is called “fixed-fixed” connectivity and is a challenge to existing docking system designs. A potential solution for dealing with the “fixed-fixed” challenge of surface docking of two pressurized elements involves the use of a pressurized tunnel to extend the reach of the docking interface between misaligned vehicles. In effect, this is like elongating the soft capture system of its in-space equivalent and forgoing the action of bringing the two mating halves together into perfect alignment with no gap. Besides overcoming misalignment, a connecting pressure tunnel can also aid in meeting potential “planetary protection” requirements of a future

Mars missions. Enabling surface mating and pressurized transfer tunnel would minimize exposure to the planetary surface and mitigate the potential of human and Martian biological/hazardous cross-contamination between internal and external environments.

The current NASA Mars reference mission publicly available shows the crew descending to the Mars surface on a Mars Descent Vehicle, along with a Pressurized Rover which serves as the crew habitat for their mission. Nominally the Mars crew would perform Extra-Vehicular Activities (EVAs) via Suitport which is a special EVA suit-sized docking interface with the Pressurized Rover. However crew and cargo transfer can be enabled by using a pressurized tunnel pre-positioned Mars Ascent Vehicle (MAV) for their surface departure and ascent to the Mars Transit Vehicle for their return to Earth (Figures 4 and 5). This pressurized transfer capability, also known as "shirt-sleeve transfer", would be great aid between the Mars Pressurized Rover and the MAV. The MAV will also likely need a deployable tunnel with a standard docking interface extending from the higher MAV elevated deck height down closer to the surface for the Pressurized Rover to dock with.

Figure 4. Mars Rover docked to Mars Ascent Vehicle utilizing Pressurized Transfer Concept (source is JSC in-house modeling/rendering)

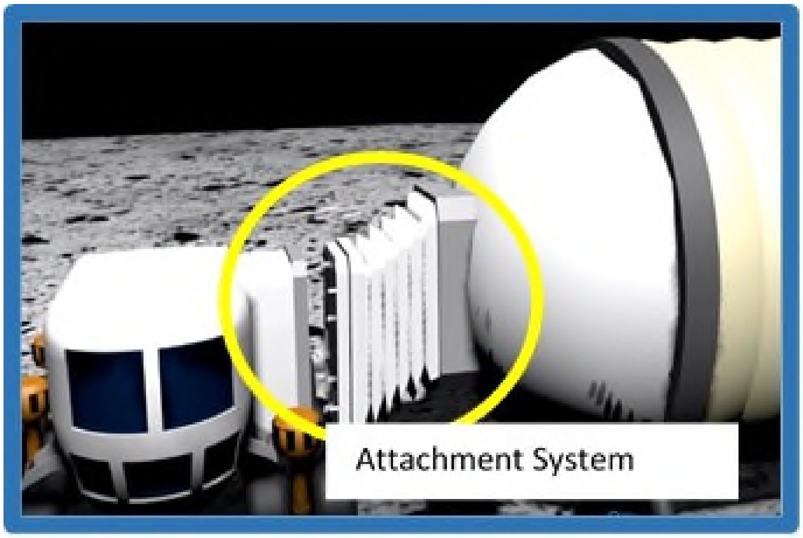

Figure 5. Illustration Depicting Lunar Rover Docked to Surface Module Active - Active Docking Adapter utilizing Pressurized Transfer Concept with misalignment (source is JSC in-house modeling/rendering)

The surface docking capability for Mars could be demonstrated on the Lunar surface as part of a certification process and lessons learning experience. In addition to lunar proving ground demonstration benefits there are additional advantages for lunar sustained operations including efficiencies gained for shirt-sleeve crew and cargo transfer and the possibility of a large logistics carrier that can be landed and then docked to the habitat for use as a cupboard, closet, or even for trash management. Having such a capability in a sustained lunar environment would help minimize lunar EVAs for housekeeping and logistics transfer activities, while conversely increasing the percentage of EVA time for science and maintenance, and/or reducing the overall frequency of EVA suit maintenance and the effort and time required to do so.

Overcoming Surface Docking Challenges - Study Activities to Date

As previously described, for surface missions involving multiple modules and rovers, vehicle and element misalignments will require a mating systems and tunnels which will help accommodate some residual final alignment offsets due to the presence of lunar gravity and uneven terrain. At JSC, some low-fidelity, non-flight hardware is currently under study for use in helping develop requirements; and to help buy down future risks to surface docking articulation, latching, and sealing which are the essential elements required to enable a pressurized, shirt-sleeve, transfer passageway between vehicles and elements.

The docking discipline team at JSC has on-going development activities exploring docking and shirt sleeve transfer capabilities on planetary surfaces. Articulating variants that will perform the docking function for two pressurized elements are being developed and tested. A primary objective for the NASA team is to explore and document the features and requirements of a potential international interface standard. It is a goal in the next year to create a draft of this new surface docking standard as well as begin collaboration with commercial and international stakeholders towards baselining this standard in the next few years. The timing of this is critically important to support anticipated surface mission development activities leading to sustainable lunar operations. While it would be best to implement the right standard early on, timing, funding, and maturity may limit this from happening. A fall back strategy would be to scar early elements/vehicles for potential retrofit of a docking interface or system in the future for later implementation.

Figure 6 shows images of concept hardware currently under development at JSC intended to feed most notional lunar surface architectural roadmaps and near-term timely development activities for future commercial development and deployment. Efforts are currently underway by JSC Engineering seeking substantial active partnering with Industry with the expectation to accelerate work in this area to the benefit of enabling lunar surface sustainability sooner and with less cost.

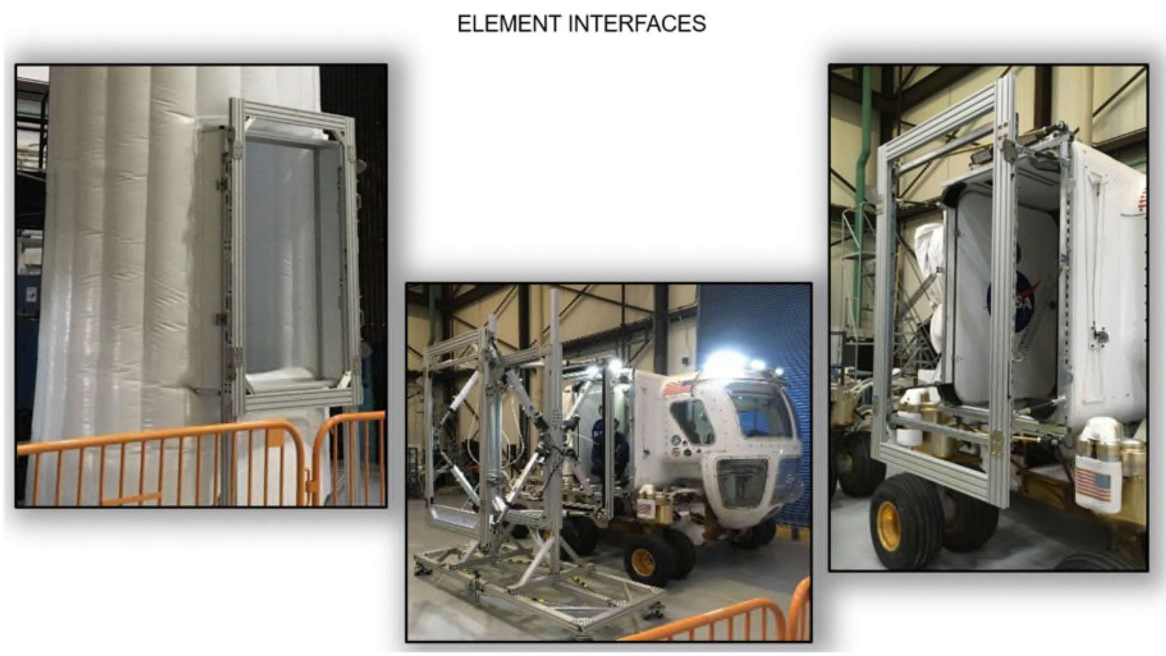

Figure 6. Proof of Concept Surface Docking and Pressurized Transfer Concept Hardware

Conclusion

This paper has intended to highlight the significance of in-space and surface docking standardization in hopes of conveying the importance of standardization which in turn enables interoperability, crew rescue, more sustainable crew and logistics transfer, and planetary protection. Careful consideration of exploration architectures as well as implementation of interface standards can support not only the planned but the unplanned, providing greater flexibility to reconfigure and sustained operations over time.

As new platforms and vehicle are developed for LEO, deep space, and surface activities, it is critical for space agencies, programs, and commercial developers to recognize the great benefits of standardization but be committed to compliance to implementation and be willing to overcome any disadvantages that may come with less optimized solutions. A true world view of space exploration, docking standardization supports a greater efficiencies, encourages global cooperation, and enables inherently safer and sustainable missions and operations.