10.2 Docking system standardization

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10.2.1 Introduction

Until the most recent decade, sourcing of docking systems was limited primarily to Russia and the United States. Today, this is no longer the case as multiple commercial companies and a few national space agencies have undertaken docking system development activities in support of the ever-growing human spaceflight economy. Standardizing of docking system interfaces has become critically important to support global cooperation in low earth orbit (LEO) and beyond for missions involving international and commercial developers. Additionally, with standardization of docking interfaces, greater flexibility and the potential for response to emergency situations (crew aid or rescue) across the various program campaigns and the world is enabled.

While there is still currently skepticism about the need and feasibility of crew rescue missions, events over recent years have highlighted the potential benefits of ensuring spacecraft interoperability by, as minimum, equipping vehicles with compatible docking interfaces. Although an in-space crew rescue mission has not been performed yet, it is only a matter of time until a rescue mission is needed to aid a crew in distress, as more nations, agencies, and commercial entities develop and fly new vehicles. For example, during the first unmanned demo flight of the Boeing Starliner crew transport vehicle in 2019 an anomaly of the on-board Mission Elapsed Time clock (off by 11 hours) caused the spacecraft to fire thrusters erroneously. By the time the ground controllers intervened, the spacecraft had reached the wrong orbit and expended too much propellant. The unmanned craft failed to complete its demo mission and according to published accounts almost reached the point where it could not nominally reenter the Earth's atmosphere either. In such instances if the vehicle cannot reenter and is outfitted with a standard docking system, it is conceivable that a second vehicle, similarly outfitted can be sent to rendezvous and provide whatever assistance it is able to deliver.

The idea of using vehicles with compatible docking interfaces for international rescue operations goes back to the Apollo-Soyuz Test Project of 1975, however the decision of establishing an international docking standard is more recent and was born out of collaborative docking mechanisms development work by NASA and ESA, which began under the JSC X-38 program. Despite the X-38 program cancellation, the standardization efforts continued with the ISS International Partners leading to the publication in 2010 of the first International Docking System Standard (IDSS) Interface Definition Document (IDD). The IDD, which strictly specifies the interfaces for in-space (i.e., in flight) mating of spacecraft, is a great success as demonstrated by the use by commercial vehicles servicing the International Space Station, by new commercial LEO platforms, and by NASA Lunar Artemis Program involving the Gateway, Orion, and Human Landing System Programs.

The experience of developing and implementing the IDSS IDD provides valuable insight and lessons learned which will be useful for the creation of a "Surface IDSS", or IDSS-S, as future Lunar surface elements providers pursue the development of modules, vehicles, and other Moon based systems; which similar to the in-space equivalent will require interoperability, permanent, semi-permanent, or temporary element-to-element docking and connectivity for sharing of services like fluids, power, and data, and even crew rescue. As Lunar surface architectures and operations plans develop, it seems appropriate to consider developing standard interfaces for nominal and emergency capabilities. Also worth noting is that there will be additional in-space docking/mating systems, e.g., unpressurized spacecraft-to-spacecraft refueling, will be up for standard definition consideration as these systems and capabilities are developed and commercialized.

10.2.2 In-space docking system standardization

10.2.2.1 History and evolution

As mentioned, the IDSS idea evolved out of the cooperation between NASA and ESA for the development of the docking mechanism of the X-38 vehicle. However, the roots of an interoperable docking system go further back to the 1970's and the Apollo Soyuz Test Program (ASTP), when the United States and the Soviet Union demonstrated that it was possible with the right interface requirements and specifications for two independent docking system developers to design, manufacture, test, and then perform an in-space docking between two different countries' spacecraft. A key point worth highlighting is that prior to the ASTP, in-space docking mechanisms configuration relied essentially on the probe and cone configuration discussed in section 10.1. The geometry of the docking mechanism on each mating vehicle was unique, so the right combination is needed to achieve docking. In as much as ASTP was a geopolitical historical event between two competing superpowers, having the same design on both sides was considered more versatile and symbolic of a relationship between peers, which made the selection of an androgynous 3-petal configuration (i.e., interface geometry which is both male and female at the same time) perfect for the ASTP mission. The major benefit of the androgynous configuration is that it eliminates the need to have the right combination of the docking mechanisms on the two mating vehicles, which is obvious complication for unplanned rescue operations. It should be noted that the male-female configuration is sometimes still in use (e.g., Soyuz, Progress, European ATV).

Fig. 10.2-1: Artist's conception of the Apollo and Soyuz docking using the 3-petal androgynous mechanism (Credit: NASA)

Fast forwarding through the 1980’s, 1990’s and into the 2000’s, both the U.S. and Russian had retained the androgynous docking system configuration for some of their programs. The Russians’, who had gotten farther along in their development than the U.S., had already certified their androgynous docking system - Androgynous Peripheral Assembly System (APAS). The APAS evolved from the original version used for the ASTP (APAS-75) to APAS-89 used on Shuttle-MIR program, to APAS-95 for Shuttle-ISS. 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 the basic interfaces specification and the standardized critical dimensions. While NASA had used the latest technology for the NDS development, it was decided that the International Docking System Standard would be based on the APAS-95 procured from Russia. Having a flight proven, certified, design made selecting a standard design baseline easier for everybody. Over the last decades, slight tweaks were made to improve the IDSS specification to address some changes needed to accommodate an expanding set of missions and environments, but the basic core design remained unaltered.

10.2.3 Standard basic geometry and keep out zones

As discussed in section 10.1, the androgynous mechanism consists of a circular docking ring with 3 equally spaced guide petals The IDSS IDD details the physical geometric mating interface and design loads requirements. Theses geometric interface requirements must be strictly followed to ensure physical spacecraft mating compatibility and includes both defined components and areas that are void of components. The IDD also identifies common design parameters in Section 3.0, for example, docking initial conditions and vehicle mass properties and mass pairing. This information represents a recommended set of design values enveloping a broad set of design reference missions and conditions, which if accommodated in the docking system design, increases the probability of successful docking between different spacecraft.

Since docking results in a final controlled and aligned state, it enables locating very precisely secondary docking interfaces such as resource transfer connectors or umblicals, which can be used to share power, data, and fluid resources between the two mated spacecraft. The IDSS Interface Design Document (IDD) prescribes keep-out-zones (KOZ) 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 NASA programs, by specifying and controlling the KOZ, mission planners are able to use these zones for mating of connectors and transferring of resources across the interface to meet specific program needs. Currently there is little commonality of resource transfer technology across the industry, but as industry applications grow, further standardization should occur over time. Until this occurs, the KOZ requirement and the requirement that all spacecrafts umbilical connectors remain retracted below the seal plane out of the way, ensure the achievement of the docking system primary purpose will be unhindered. After mechanical mating, resource connectors and umbilicals would be connected, and conversly disconnected prior to undocking.

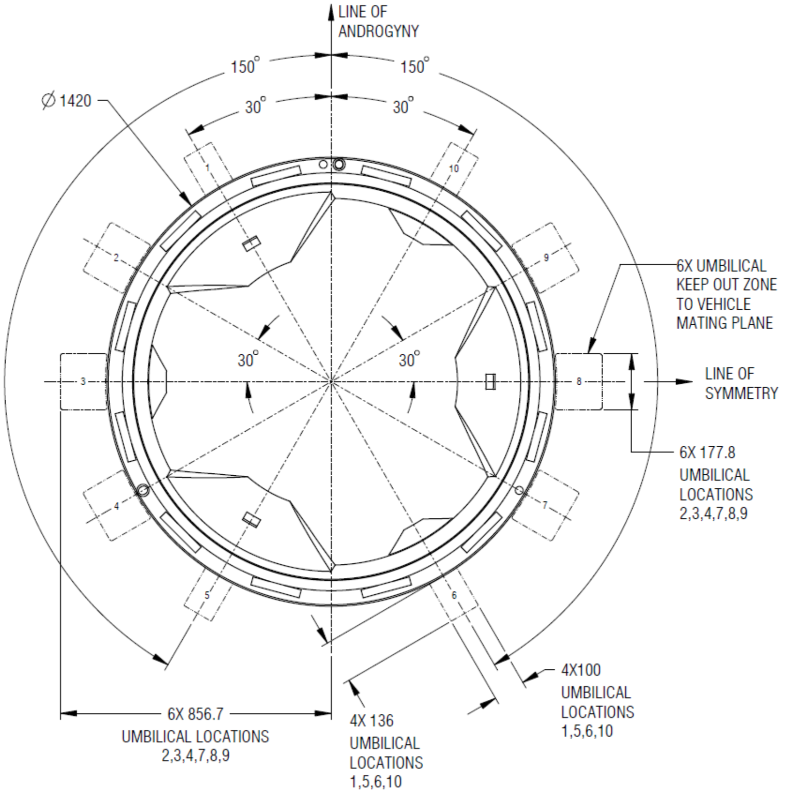

Fig. 10.2-2: IDSS umbilical and connectors Keep-out Zones

10.2.3.1 In-space docking challenges

Besides resource transfer connections, there are two other capabilities that can influence the performance of the primary function of the standard docking system. One is the placement of rendezvous navigation aids on or around the perphriphery of the docking interface. These are required by the active spacecraft to "see and sense" the alignment and positional accuracy as the spacecraft move closer and closer during rendezvous, proximity operations, and docking (RPOD). There are different technologies, (e.g. cameras, lidar etc), each with its strengths and weaknesses and subjected to continue improvement efforts by industry, however as for resource connectors there is still no consensus on the navigation target and aids requirements.

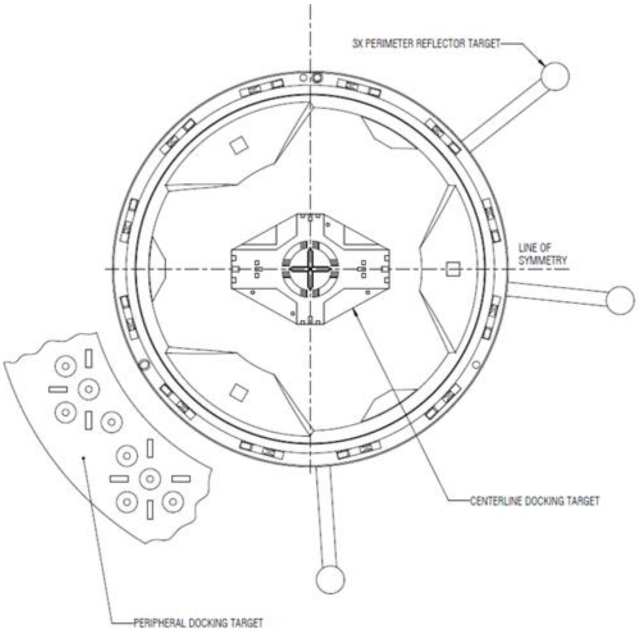

Fig. 10.2-3: The 3 types of IDSS navigation aids (CDT- Centerline Docking Target, PDT-Peripheral Docking Target, PRT-Perioheral Reflector Targets) combination of which provide navigation support for active vehicle operations at long, mid and short ranges.

The other issue is the commonality of berthing and docking mechanisms. The term “docking” refers specifically to autonomously performed mating of two free flying spacecraft, while the term “berthing” is used when the mating operation is performed by a robotic manipulator system (RMS) or robotic “arm” that reaches across from one craft to grapple and move the other into the mating capture envelope. During berthing operations it is the robotic arm that provides the positional and closing initial contact conditions for mating. An example is the Cyngus resupply vehicle that flies up close to the International Space Station and “stationkeeps” (i.e. floats within a small navigation box) as the station RMS reaches, grapples, and “berths” the craft to a Common Berthing Mechanism (CBM) port. Since the beginning of the IDSS development, there have been efforts to improve the commonality between docking and berthing mechanisms by keeping the force/velocity requirements for the docking system to achieve compliance and capture within the capabilities of a robotic arm. Berthing compatiblity is an area where futher definition and standarization is being pursued.

10.2.4 Surface docking interoperability

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 and later Mars missions will require surface rendezvous, docking and resource transfer connectivity. At first glance surface docking may seem easier than in-space docking but that is not necessarily true. In the case of the Moon, lunar dust is 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 the 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. This is called “fixed-fixed” connectivity and is a challenge to existing docking system designs. A possible solution for the “fixed-fixed” challenge of surface docking of two pressurized elements is the use of a pressurized tunnel to extend the reach of the docking interface between misaligned elements. Essentially, this is 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. Operational techniques to define the effects of pressurization of a flexible docking tunnel with respect to final module-to-module alignment have been defined as a critical area of study.

The current NASA Mars reference mission shows the crew descending to the Mars surface on a Mars Descent Vehicle (MDV), along with a Pressurized Rover (PR) which would serve as the crew habitat on Mars. The crew would perform Extra-Vehicular Activities (EVAs) via a Suitport (SP) which is a special EVA suit-sized docking interface with the PR. Crew and cargo transfer would be enabled by a pressurized tunnel pre-positioned to Mars Ascent Vehicle (MAV) for surface departure and ascent to the orbiting Mars Transit Vehicle (MTV) for return to Earth. Such pressurized transfer capability, also known as “shirt-sleeve transfer”, would be great aid between the Mars PR and the MAV. The MAV would 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 PR to dock with.

Fig. 10.2-4: Mars rover docked to Mars ascent vehicle utilizing pressurized transfer concept (Credit: NASA-JSC)

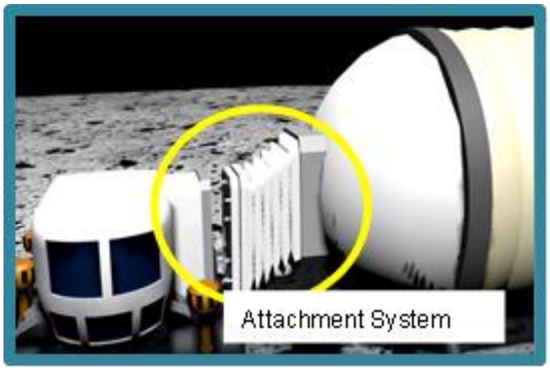

Fig. 10.2-5: Lunar rover docked to surface module active – active docking adapter utilizing pressurized transfer concept with misalignement (Credit: NASA-JSC)

10.2.4.1 Overcoming Surface Docking Challenges

Various on-going development activities indicate that most of the future lunar surface architectures are counting on surface docking and shirt sleeve transfer capabilities for planetary surface activities. Research and development of articulating variants, interfacing size and characteristics, is needed to explore, document, and reach consensus of the features and requirements of a future international surface docking standard to enable further collaboration among participating commercial and international stakeholders.

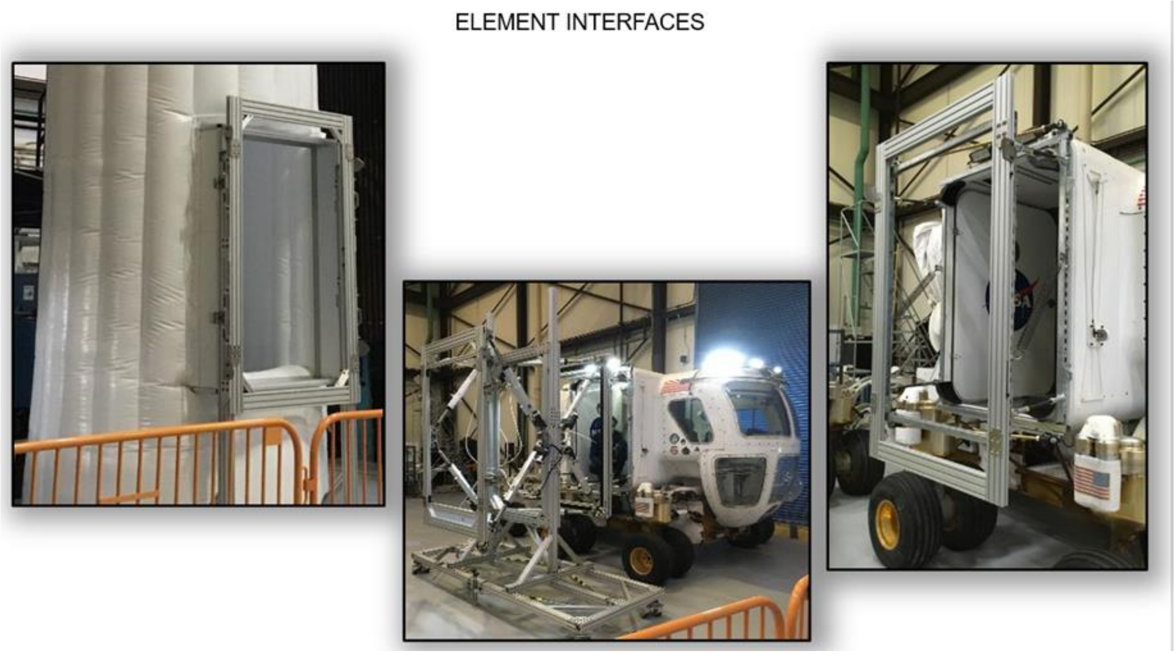

Fig. 10.2-6: Proof of concept for surface docking and pressurized transfer hardware under development at NASA intended to feed most notional lunar surface architectural roadmaps and near-term development activities for future commercial development and deployment.

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