MECHANICAL, THERMAL, DATA AND POWER TRANSFER TYPES FOR ROBOTIC SPACE INTERFACES FOR ORBITAL AND PLANETARY MISSIONS - A TECHNICAL REVIEW

Wiebke Wenzel[1]**, Roberto Palazzetti**[2]**, Xiu T. Yan**[2]**, and Sebastian Bartsch**[1]

[1]*German Research Center for Artificial Intelligence - Robotics Innovation Center (DFKI RIC), Robert-Hooke-Str. 1, 28359 Bremen, Germany, Email: firstname.lastname@dfki.de*

[2]*University of Strathclyde, Engineering Faculty, DMEM department, James Weir Building, 75 Montrose Street, G1 1XJ Glasgow, United Kingdom, Email: firstname.lastname@strath.ac.uk*

ABSTRACT

A wide variety of scientific aims have been formulated for future explorations of space and planets. In order to achieve these aims, a need for robotic systems and mission set-ups with increasing complexity arises. The H2020 EU-funded project SIROM (Standard Interface for Robotic Manipulation of Payloads in Future Space Missions), aims to realize an integrated interface for mechanical, data, electrical and thermal connectivity that allows a reliable, robust and multi-functional coupling. The present paper reports an overview of classifications of power, data and mechanical interfaces and thermal transfer methods in current robotic and space applications. Eventually, the paper presents ideas for innovation and development of standard multi-functional interface with the most promising developments expected in the next few years.

Key words: Multifunctional Interface, Robotic Space Interface, Transfer Classifications in Space, Modularity.

1. INTRODUCTION

Connectivity in space is one of the main issues, which engineers and space mission planner have to face nowadays. With the increasing complexity of mission plans and tasks, a need for a standard, multifunctional, scalable and modular interface arise. The SIROM project aims to find a definitive solution for such needs: it aims to realize a set of integrated and inherently optimised interfaces for mechanical, data, electrical and thermal connectivity that allow reliable, robust and multi-functional coupling of payload to robot manipulators, payload to other payload or client to server, in both orbital and planetary environments.

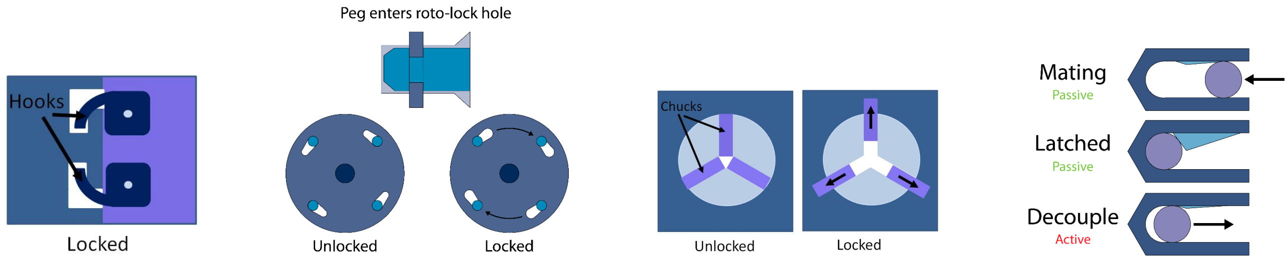
The present paper reports an overview of classifications of power, data and mechanical interfaces and thermal transfer methods in robotics and space applications. All types are described in their functionalities and evaluated for orbital and planetary suitability. While in-orbit systems have to operate in harsh, but repeatable environment, planetary systems have to deal with potentially highly variable environment with, among others, changing temperature and dust level. A comparison among existing interfaces in robotics and space is also presented, with respect to pre-defined mission scenario and requirements. The main focus is on the different transfer possibilities for space and planetary use in order to present a clear overview of the state of the art of the various types of functional connectivity.

Some existing interfaces will present in Section 2. An outline of each type of transfer is given in Section 3. Section 4 includes possibilities and ideas of innovation and development of standard multi-functional interfaces with the most promising developments expected in the next few years. A conclusion and outlook is given in Section 5.

2. RELATED WORK

Terrestrial examples of robotic connection interfaces are commonly seen in modular robotics, where homogeneous or heterogeneous modules interconnect to satisfy some functions, either mechanical, thermal, electrical or computational. Modular platforms make the creation and the operation of large structures easy, hence why they are being considered for large scale space operations [1]. A large range of space interface has been found in literature [2] [3]. Figure 1 summarise the selected existing interfaces, based on the presence or absence of a number of given features.

Each interface has basic properties, as for example the possibility of passive docking, genderless principle, rotational orientation, fails-safeness, possibility of power or data transfer, rigid connection, fuel valve, element redundancy, mechanical transfer, tracking, thermal transfer, reusability and marker.



(a) Hook (b) Roto-lock (c) Clamp (d) Carribena

Figure 2. Latching mechanism

	Passive dock	Genderless	Rotational Orientation	Fail-safe	Power Transfer	Data Transfer	Rigid Connection	Fuel valve	Redundancy	Mechanical Transfer	Tracking	Thermal Transfer	Reusable	Marker	Amount of Orientations	Latch type
MTRAN		X	X		X	X			X				X		4	Magnetic
SINGO		X	X	X			X		X				X		4	Clamp
CAST	X		X				X				X		X		2	Hook
CEBOT	X						?				X		X	X	1	Hook
ATRON							X			X			X		1	Hook
Telecube	X	X	X		X	X			X				X		2	Magnetic
PolyBot	X	X	X		X		X		X				X		4	Rotational
AMAS			X				X		X				X		4	Hook
Sproewitz			X				X		X				X		4	Hook
SMORES		X	X	X									X		2	Magnetic
GENFA		X	X	X	X		X		X	X			X		4	Rotational
ACOR				X					X						1	Hook
SWARM / SPHERES		X			x		X		X				X		1	Rotational
Phoenix Tool	X		X		X		X		X	X			X		1	Hook
Phoenix Satlet			X		X	X	X		X				X	X	~	Clamp
SRMS	X				?								X		1	Snare
SSRMS	?				X	X			X		X		X	X	1	Snare
DEXTRE (OTCM)					X	X	X			X			X		1	Clamp
iBOSS		X	X	X	X	X			X			X	X		4	Rotational
TransTerrA EMI			X		X	X	X		X	X			X	X	4	Clamp
Berthing and Docking	X		X				X		X	X			X		~	Hook
EM-Cube	X	X	X						X				X	X	4	Magnetic
UBot			X										X	X	1	Hook
Hand-like manipulator			X							X	X		X			Clamp

Figure 1. Basic properties of existing interfaces

3. TYPE OF TRANSFER

3.1. Mechanical

Latches are used to lock or restrict movement after the initial interface contact; they can be activated automatically once the connectors have been firmly pushed together or engaged. Sometimes latches are not necessary, but they are strongly recommended to ensure rigid connection. Latching can be achieved physically or magnetically. Mechanical latching is any means of physical connection that maintains itself by interference of motion upon an object, developing a connection that mates two objects. Mechanical latches are often motor driven, but can also be initiated in other ways, such as Shape Memory Alloy, even if they require high current to be activated [4]. Among the various methods of physical connection, in order to help identifying the core functionality of each one, these are classified in groups that share properties or traits. The literature review highlighted four latch classes: hook, rotational, clamp and carribena. Figure 3 shows advantages and disasvantages of these four mechanical latch classes.

Hook The hook latch is perhaps the simplest of the mechanical latches, it involves one side of the connector rotating hook-like appendages into position around the other face of the connector, interfering in any translational movement perpendicular to the face, as well as rotational movement around that axis if possible. Figure 2(a) shows an example of a hook latch. Locking is possible in passive manner (with e.g. springs) or in active manner with actuators.

Roto-lock A rotational locking mechanism is a motor-powered type of lock, that requires a male/female interface to operate. It usually works by first having the male side of the connection coupled with the female side; then the roto-lock engages, rotating around the centre of interface, tightening the female side, or latching into groves on the male side. This concept is almost exclusively used with the Peg-in-hole system, expanded further in Figure 2(b). The main benefit of a roto-lock system is that it only involves one moving part, which is highly beneficial for space applications.

Clamp The clamp mechanism involves two or more chucks (jaw like contraptions) closing together connect the two interfaces. In a typical male-female interface arrangement, the clamp may be on the female side, but there are ways to produce a hermaphroditic clamp connection, where the clamps are the main points of contact on both faces. Figure 2(c) shows a three chuck clam In this example it’s important to note that regular chucks are simply holding the rod as a “push fit” and with enough force, Z axis and rotation can happen. With modified notches in the chucks and male piece, this can be removed.

Latch type	Advantages	Disadvantages
Hook	Rigid Connection	Naturally male
	Small misalignment correction	Multiple moving parts
	Passive retention	Point contacts
		Active (de)couple
Roto-Lock	Rigid Connection	Little / no lateral misalignment correction
	One moving part	Active (de)couple
	Passive retention	
	Potentially fail-safe	
Clamp	Rigid Connection	Multiple moving parts
	Naturally male or female	Active (de)couple
	Fail-safe	
	High strength	
	Passive retention	
	High misalignment correction	
Carribena	High misalignment correction	Naturally female
	Passive couple	Multiple moving parts
		May require push part
		Active decouple

Figure 3. Advantages and disadvantages of mechanical latch classes

Carribena This latch involves having a mechanical interference piece in a passive locked state on the female side, and on the male side one crossbar piece. The male part pushes into the female part to disengage the interference piece using low amounts of force. Once the male piece is past a certain threshold, the female piece returns to its default position either through active (actuator, electromagnet) or passive (spring, static magnet) means. The lock can only be disengaged using an active unlock sequence, but the translational motion required opens up many options for automatic alignment. Figure 2(d) shows the Carribena mechanism.

3.2. Electrical

The functionality of transferring electrical load in a spacecraft is similar to terrestrial applications, but the cold vacuum of space adds some challenges to the process; in particular the high temperature range makes on-purpose space-designed cables necessary. The power transfer is a common function for modern an dated interfaces, and few designs have been devloped for the purpose: each one of them have pros and cons that need to be considered an are here highlighted. Four types for power transfer interfaces have been indentified and here described: pin, tabs, slip rings and wireless power transmission. Advantages and disadvantages of these four types are shown in Figure 5.

Pins Pin connections are a versatile way of interlocking and maintaining electrical contact between two interfaces. It involves the use of, commonly long and cylindrical, male/female inserts (see Figure 4(a)). This type of connection prevents lateral movement but axial movement is still allowed without a latching mechanism. The arrangement of pins determines redundancy, rotational symmetry and gender of the interface. Pins are affected adversely by particles, and depending on their thickness, may be easy to break.

Tab Tab contacts (see Figure 4(b)) are spring loaded metal component that acts as a simple touch interface for power. They are not designed with any form of latching, but the spring load gives the interface excellent angular and axial tolerance, enabling the connection even before the latch has fully closed. Tabs need to be sized carefully to compensate for high power loads and other space environment effects.

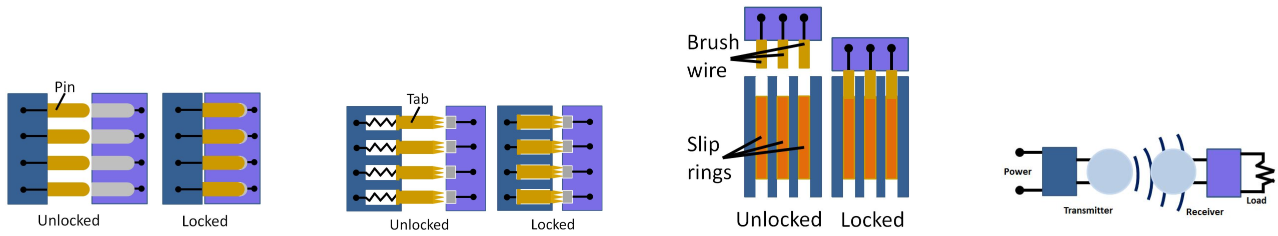
Slip rings Slip rings are electrical contacts in ring form, allowing for theoretically infinite number of rotational allowances (see Figure 4(c)). They demand much more space than other methods of power conduits, but provide a more flexible solution for abstract rotation connections.

Wireless power transmission Wireless power transmission is a very high specific power electric propulsion enabled by disassociating the power generation from the transfer vehicle. First, power is acquired on the power-beamers through the use of solar arrays. This DC power is then converted to RF power so that it may be transmitted to the rectenna (rectifying antenna) on the transfer vehicle. A rectenna captures incident RF power and transforms it to DC power by a diode based converter. This system increases, by one order of magnitude, the actual specific power transferred to spacecrafts.

3.3. Data

On-board bus requirements are currently driven by the need to move from fully centralized processing towards distributed processing. A modern spacecraft bus will need to be able to acquire synchronous data frames from sensors with controlled latency, transmit synchronous to actuators with controlled latency, transfer asynchronous and isochronous data packets between nodes, and provide a symmetric medium access control service to nodes (i.e. each node can access the bus on demand), accurate distribution of time data and time reference pulse, and a safe implementation for a cross-strapping mechanism. Many industry-standard serial data communications methods are in use in space. The limiting factor is often the availability of space-qualified supporting hardware for a given hardware bus, though software protocols may remain the same. Although I2C, SPI, PCI, and even USB have been long tested and used as board-level data buses in space, with appropriate redundancy and software support, a Modular Data Interface is expected to use a communications bus suitable for reliable long-range wired links. Eight main data buses have been highlighted from literature review and are here briefly presented.

Milbus With the ECSS-E-50-13C standard for use on board spacecraft, the Mil-Std-1553B Manchester code bus (Milbus) was one of the first military-spec data buses, adopted by the ESA. It is time-division multiplexed, very



(a) Pins (b) Tab (c) Slip ring (d) Wireless

Figure 4. Electrical transfer types

robust, and been used in many space applications being self-clocking and capable of detecting many types of communications error. However, the use of Manchester encoding introduces frequency related issues at high data rates, and it may not be suitable for operations that requires high data rate.

CANbus The Controller Area Network is a very popular and common message-based half-duplex bus in robotics and automotive applications, and has been used in several space applications. ECSS-E-ST-50-15C describes the use of CAN bus in space hardware, with CANOpen chosen as standard protocol layer for ESA missions. The current development towards low power rad-hard ISO 11898-2 CAN transceiver hardware and CAN can be implemented over twisted pairs also. The main limitation of CAN is the bit rate, with a maximum of 3.7Mbit/s in the CAN FD standard.

SpaceWire One of the newest and most space-centered buses is SpaceWire, which focuses on connecting processing nodes via reliable full-duplex switched serial packet links. The SpaceWire communications standard ECSS-E-ST-50-12C from 2003, has been supplemented by protocol identification in ECSS-E-ST-50-51C, remote memory access in ECSS-E-ST-50-52C, and packet transfer in ECSS-E-ST-50-53C, and adopted by ESA, NASA, JAXA, and RosCosmos. As a decentralized network, it is well suited to redundancy and multi-node robotic systems and is much simpler and more reliable than traditional spacecraft backplanes. SpaceWire is typically limited by hardware design to 50Mbit/s, but the underlying LVDS standard can perform much faster with up to 3Gbit/s possible in concept on terrestrial hardware.

Standardized Serial Interface The RS-422/423 ANSI standards were created as industrial serial bus standards, and have proved vastly superior performance that the previous RS-232 due to the use of lower voltages and differential signalling for higher bit rates. The RS-485 also defines an enhanced RS-422 standard that enables very flexible multiple-point networking options in both half- and full-duplex configurations on a differential bus.

Time-Triggered Bus Four time-triggered common bus architectures are the SAFEbus, TTA (Time-Triggered Architecture), SPIDER (Scalable Processor-Independent Design for Electromagnetic Resilience) and FlexRay. SAFEbus interfaces (Bus Interface Units, BIUs) are duplicated, and the interconnect bus is quad-redundant. Its data rate is limited to 60MB/s. TTA is unique in being used for aircraft, where a mature tradition of design and certification for flight-critical electronics provides strong scrutiny of arguments for safety. SPIDER is a research platform dedicated to explore recovery strategies for radiation-induced high-intensity radiated fields/electromagnetic interference (HIRFEMI) faults, and the interconnect is composed of active elements called Redundancy Management Units (RMUs). SPIDER uses a different topology and a different class of algorithms from the other three types of busses. FlexRay operation is divided between time-triggered and event-triggered activities. Its mixture of time- and event-triggered operation is potentially important.

Firewire Among the major contender for data busses, there are the Firewire (IEEE1394) and the Time-Triggered (TT) Ethernet. Bus IEEE1394 has been firstly introduced in 1995 for real-time high-speed data transmission, and has recently been updated to a real-time standard satisfying space and military avionics interconnect needs. It is a high versatile system, because of its variable channel sizes, bandwidth on demand, hierarchical addressing, and the 1600 Mbps data rate with a 64-bit wide data path.

Time Triggered Ethernet TT Ethernet is intended to support all types of applications, from simple data acquisition, to multimedia systems up to the most demanding safety-critical real-time control systems which require a fault-tolerant communication service that must be certified. It distinguishes between two traffic categories: the time-triggered traffic, that is temporally guaranteed, and the standard event-triggered Ethernet traffic which is handled in conformance with the existing Ethernet standards.

Type	Advantage	Disadvantage
Pin	Prevent lateral movement	Easily breakable (depending on thickness
	Large electrical connection surface	Affected adversely by particles
	Latching after connection	Precise guiding while connecting necessary
	Transfer of energy and signals	
Tab	Large amount of angular and displacement tolerance	Dimensioning is dependent of power loads and other space environment effects
	Power is available before final connection	
	Tolerance against particles	
	Transfer of energy and signals / data	
Slip ring	Applicable for high power	Long initial phase
	Transfer of energy and signals	Not appropriate of permanent use, because of wear of sliding contact
	High torque at start	Unsutiable for short term operation
	Low starting current	Need more assembly space as other methods of power conduits
	High overload capacity	
	Rotating connection (at least one rotating part. Rotating over 360° possible, no contortive cables...)	
Wireless power transmission	Non-contact transmitter receiver	Need large surface for energy absorption
	Resistant against affecting by particles	Loss of energy
	Insensitive to electromagnetical propagation material interference, good stability	Need large electronic compoonents for transmitting

Figure 5. Advantages and disadvantages of electrical connections

3.4. Thermal

The following section aims to present a review of the state-of-the-art of the thermal interfaces used in spacecraft. The table in Figure 7 shows advantages and disadvantages of six different possibilities of thermal transfer methods.

Heat Pipes Loop heat pipes (LHPs) are among the most common thermal transfer methods used in spacecraft. They transfer heat by two-phase heat transfer devices that utilize the evaporation and condensation of a working fluid, which circulates due to the capillary force developed in a fine porous wick. The advantages of LHPs are best manifested at large capacities and heat-transfer distances. Furthermore LHPs are particularly suitable when it is necessary to ensure efficient transfer at any orientation of the gravity field. The LHP principle allows creating ramified heat-transfer devices including different numbers of evaporators and condensers situated at different orientations, making themselves particularly suitable for thermoregulation systems of spacecraft, reducing mass and increasing compactness.

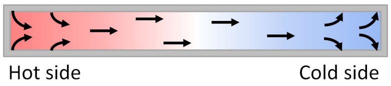
Fluid Loops Mechanical Pumped Fluid Loop (MPFLs), in conjunction with a deployable radiator, is one of the technologies that has enormous potential to meet the demands of future spacecraft thermal control. It is used to transmit a large amount of heat between two regions separated by large distances. The working fluid does not undergo any phase change as it flows through various components.

Water Sublimators Those spacecraft working in warm environments can use water sublimators, which offer simplicity, reliability, small volume, high efficiency and excellent work performance in zero gravity. In sublimation mode water freezes in the pores of the plate and heat is removed from the system by sublimation to the vacuum of space. Ice will generate some heat as it freezes from liquid to solid form due to the heat of fusion. Water has an unusually high latent heat of evaporation/sublimation which is enough compensate the heat generated upon fusion (freezing), as well as any heat that might be generated by friction as the water moves through the plate. The availability of space vacuum allows for water to go from the solid to vapour state on the surface of a porous plate, which is sensitive to trace contaminants that can impede the sublimation process. If a plate is adversely impacted by trace contaminants, it cannot maintain the required heat rejection properties. The intermediate porous plate approach has a good chance of resulting in a sealed porous plate, but the risk is a reduction in cooling capacity.

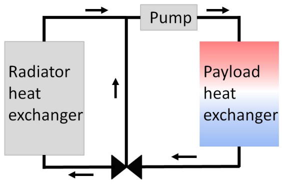
Pulsating Heat Pipes Pulsating heat pipes (PHPs), or oscillating heat pipes (OHPs) are one of the latest type of highly efficient heat transfer systems. The state-of-the-art of experimental investigations on PHPs are mainly focused on the applications of nanofluids and other functional fluids, aiming at enhancing the heat transfer performance of the PHPs.

Self-rewetting Fluids Some studies have been conducted on thermal management devices, such as wickless heat pipes, using the so-called “self-rewetting fluids” (dilute aqueous solutions of high carbon alcohols) as a working fluid. Most of the liquids show a decrease in the surface tension with increasing temperature, while self-rewetting fluids exhibit the opposite behaviour.

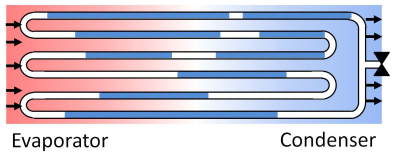
Hybrid single-phase, two-phase and heat pump thermal control system This system is designed to accommodate three different operational modes: single-phase, two-phase and heat pump. The single-phase and two-phase modes are used in cold environments, while heat



(a) Heat pipe



(b) Mechanical Pumped Fluid Loop



(c) Pulsating heat pipe

Figure 6. Thermal transfer types

Type	Advantage	Disadvantage
Heat Pipes	Great efficiency in transferring heat	Not feasible for long distance heat transfer
	Most reliable	
	Less components (and therefore most failure-free)	
	Well suited for small assembly space	
	Well-founded experiences	
Fluid Loops	Carrying large amount of heat at a long distance	Leakage
		Needs some components and therefore and must be dimensioned accordingly
Water sublimators	Ideal for working in space environment	Sensitive, because of the porous plate
		Dimensioning (need maybe more space as required for the whole interface)
		Unsuitable for planetary interface because of environmental condition
Pulsating Heat Pipes	Two possible geometries (open loop and closed loop). Maybe especially suitable for docking interfaces.	Less experiences
		Only a couple of small companies produce them
Self-rewetting Fluids	Better thermal resistance and higher dry out limit	
	Supplement to heat pipes (?)	
Hybrid thermal control system	Highly variable for different temperature conditions	Needs many components and therefore and must be dimensioned accordingly

Figure 7. Advantages and disadvantages of thermal transfer types

pump is applied in hot environments, where a compressor is needed to raise the fluid temperature above that of the heat sink.

4. KEY INNOVATIONS

This section will cover proposed standards to use for power and data, as well as methods for thermal transfer and mechanical latching, suitable for space and planetary applications, in particular to the mentioned SIROM project. The table in Figure 8 shows the technology readiness level (TRL) of the transfer types described in Section 3.

The suitability of each transfer types is noted in the columns ”for orbits” and ”for planets” of the table in Figure 8. For this evaluation, influences of space and planetary environments have been considered. There are influences as a wide range of temperature differences, effects on materials, atomic oxygen erosion, radiation, single event effects (SEEs), gravity and magnetism, atmosphere, high vacuum and contamination (dust particles and space debris).

4.1. Proposed latching methods

Meaningful archetype of connection interface design, which would work best within the context of the project SIROM, are either the rotational lock or clamp type latches. Both methods do not require physical translated force against the target interface to latch and offer the ability of androgynous design. In addition, both methods are inherently fail-safe and offer significant misalignment correction. The clamp latch can offer component redundancy, but rotational locking can offer simplicity.

Useful examples of these interfaces are the androgynous, self-correcting clamp geometry from SINGO [5] and iBoss [6] a simple rotational locking mechanism.

4.2. Proposed power transfer methods

Power transfer interface aims compactness and robust design, low weight, protection against short circuit, multiple usage and space environment robustness. Due to its high tolerance for dust particles and compounded by the popularity of the method in existing interface designs, spring loaded contacts (tabs) are recommended as the electrical interface’s point of contact [7]. The popularity and continuing extensive use of 100V/100A/10kW platforms leads to the conclusion that these should be the minimum requirement benchmark for the electrical interface design.

4.3. Proposed data standards

Main requirements for the data interface are compactness and robustness, low mass, mutliple usage, compliance with space environment conditions and the highest possible data rate desirably should be 100 Mbit/s.

In terms of the physical interface, recommended features to fulfill these requirements are open-drain signalling, robust for short distances/low data rates, to achieve high data rates differential-driven signalling will be needed (e.g. LVDS). Synchronous and clocked (or self-clocking) operation to prevent timing variations. Using of redundant pairs (at least two) in a given data link in case of a bad contact. Full-duplex operation (potentially using redundant pairs) is desirable. Connectors must ensure correct polarity and positive contact locking against vibration. Connectors must be made of materials that will not corrode or accumulate nonconductive layers in planetary or vacuum environments. Voltage must be high enough to overcome radiation and static buildup effects but not high enough to be hazardous in the space environment. External contacts and wiring must be electrically isolated at the transceiver by means of optical or pulse transformer coupling to ensure protection against static discharge.

Considering the specified requirements and recommended features as well as the review presented in Section 3.3, it may be advisable to make use of the LVDS SpaceWire interface standard [8], but without the requirement that only SpaceWire protocol be transmitted over it, and with the addition of robust isolation.

4.4. Proposed transfer methods

Thermal transfer between modules is not a well traversed knowledge area, thus further detailed research is recommended to build confidence. While consideration of low weight, compactness, robustness, multiple usage and low complexity, heat pipes [9], fluid loop [10] and self-rewetting fluid technology [11] are meaningful. Heat pipes represent the most reliable thermal interface, already applied in several spacecrafts, fluid loop technology is capable of carrying on the largest amount of heat at the longest distance and the self-rewetting fluid technology appears to be the most promising one in future perspective.

5. CONCLUSION AND OUTLOOK

This review aimed to present the state-of-the-art and the future perspective of robotic space interfaces, with focus on thermal, data, electrical and mechanical functionalities. The main conclusions are here summarized:

1. Many existing interface designs target small modular robots, but the design principle can be up scaled

Classification	Type	TRL	Remark	For orbits	For planets
mechanical transfer	Hook	7-9	already developed, prototyped, tested, and flown into space	suitable	suitable
	Rotational	7-9		suitable	suitable
	Clamp	7-9		suitable	limited
	Carribena	7-9		suitable	limited
electrical transfer	Pins	7-9	already developed, prototyped, tested, and flown into space	limited	limited
	Tab	7-9		suitable	suitable
	Slip ring	7-9		suitable	limited
	Wireless power transmission	3-4	preliminary studies to prove technology's feasibility	suitable	suitable
data transfer	Milbus	7-9	already developed, prototyped, tested, and flown into space	suitable	suitable
	CANbus	7-9		suitable	suitable
	SpaceWire	7-9		suitable	suitable
	Standardised Serial interface	7-9		suitable in some configurations	suitable in some configurations
	Firewire	7-9		suitable	suitable
	Time Triggered Ethernet	7-9		suitable	suitable
	Time-triggered Bus	7-9	used in aircraft only	limited suitable	limited suitable
thermal transfer	Heat pipe	7-9	already developed, prototyped, tested, and flown into space	suitable	suitable
	Fluid loops	7-9		suitable	
	Water sublimator	7-9			not suitable
	pulsating heat pipes	7-9	tested in various environment. Never flown into space	suitable	suitable
	self-rewetting fluids	7-9	tested in parabolic flights		

Figure 8. Basic properties of existing interfaces

   - The iBoss is the closest existing prototype that integrates all the 4 main functionalities described here
   - Rotational symmetry, internal redundancy and hermaphroditic connection are common and basic requirements.
   - Additional design effectiveness is achieved with particle mitigation, 6-DoF misalignment tolerance and fail-safe docking and undocking

2. Latching methods consist of four archetypes; hook, clamp, carribena and rotational lock
   - Clamping/rotational locking methods are recommended for low force/torque

3. Electrical power transfer methods included tabs, slip rings, pin arrangements and even wireless
   - Scoop proof and spring loaded tab contacts are recommended physical means of power transfer
   - 100V bus minimum requirements are recommended as a benchmark
   - Slip rings can also be taken if a pseudo-infinite orientation design is pursued

4. Data transfer protocols ranged fro CANbus to SpaceWire and Firewire
   - The use of redundant twisted pairs and fullduplex is recommended

5. Thermal exchange methods are rarely applied in such a way, but usually took the form of heat pipes or fluid loops
    - Heat pipes represent the simplest method, but fluid loops/rewetting fluids have the most potential
    - Only one design with integrated thermal interface has been found, and it still needs further development

In conclusion, the path toward a development of a standard space interface with integrated multiple functionalities, has still a long way to go, but the current developments are moving in the right direction. The current SIROM H2020 project aims to develop the current state of the art and to integrate the most promising technology and develop a product with the ambition of becoming the standard for the next 10-year space missions.

ACKNOWLEDGMENTS

The authors would like to thank all Partners (SENER, AIRBUS DS LTD, AIRBUS DS GMBH, TAS ITALIA SPA, Leonardo SPA, Strathclyde University, DFKI GMBH, TELETEL, SPACEAPPS, MAG SOAR S.L.) and supporting staff of the SIROM Project. The project results presented in this publication are derived from the conceptual phase.

SIROM is part of the project "PERASPERA", which is funded, as part of the Horizon 2020 Space Work Programme 2014, a Programme Support Activity (PSA) for the implementation of a Strategic Research Cluster (SRC) on Space Robotics Technologies. The project leading to this publication has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730035.

REFERENCES

[1] Thomas M Roehr, Florian Cordes, and Frank Kirchner. Reconfigurable integrated multirobot exploration system (rimres): heterogeneous modular reconfigurable robots for space exploration. *Journal of Field Robotics*, 31(1):3–34, 2014.

[2] Carl Glen Henshaw. The darpa phoenix spacecraft servicing program: Overview and plans for risk reduction. In *International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS)*, 2014.

[3] M. Oda, M. Nishida, and S. Nishida. Development of an eva end-effector, grapple fixtures and tools for the satellite mounted robot system. In *Intelligent Robots and Systems '96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on*, volume 3, pages 1536–1543 vol.3, Nov 1996.

[4] B. Khoshnevis, P. Will, and Wei-Min Shen. Highly compliant and self-tightening docking modules for precise and fast connection of self-reconfigurable robots. In *2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422)*, volume 2, pages 2311–2316 vol.2, Sept 2003.

[5] W. M. Shen, R. Kovac, and M. Rubenstein. Singo: A single-end-operative and genderless connector for self-reconfiguration, self-assembly and self-healing. In *2009 IEEE International Conference on Robotics and Automation*, pages 4253–4258, May 2009.

[6] M. Goeller, J. Oberlaender, K.Uhl, A. Roennau, and R. Dillmann. Modular robots for on-orbit satellite servicing modular robots for on-orbit satellite servicing. In *Proceedings of the 13th Symposium on Advanced Space Technologies in Robotics and Automation - ASTRA*, June 2016.

[7] A. Dettmann, Z. Wang, W. Wenzel, F. Cordes, and F. Kirchner. Heterogeneous modules with a homogeneous electromechanical interface in multi-module systems for space exploration. In *2011 IEEE International Conference on Robotics and Automation*, pages 1964–1969, May 2011.

[8] Steve Parkes, Albert Ferrer, Stuart Mills, and Alex Mason. Spacewire-d: Deterministic data delivery with spacewire. In *International SpaceWire Conference, St Petersburg, Russia*, 2010.

[9] Yu.F. Maydanik. Loop heat pipes. *Applied Thermal Engineering*, 25(5–6):635 – 657, 2005.

[10] Prashant Kumar Rai, Simhachala Rao Chikkala, Abhijit A Adoni, and Dinesh Kumar. Space radiator optimization for single-phase mechanical pumped fluid loop. *Journal of Thermal Science and Engineering Applications*, 7(4):041021, 2015.

[11] Yoshiyuki Abe, Akira Iwaski, and Kotaro Tanaka. Thermal management with self-rewetting fluids. *Microgravity - Science and Technology*, 16(1):148–152, 2005.