Research on Integrated Interface Design of Small Modular Spacecraft

Wanxin Man, Xinhong Li, Zhibin Zhang, Jiping An, Guohui Zhang, Junwei He

ABSTRACT

Modularity in space provides a solution to the scale-constrained problem of space systems, while providing other benefits in terms of flexibility, sustainability and affordability. In the system, modules are added and removed through interconnect interfaces, which transfer mechanical load, data, electrical power, and heat from one module to another. The current research tends to integrate multiple functions into a single device or equipment to reduce costs and improve standardization. This article will explore the design requirements and constraints that need to be satisfied in the design of this standardized, extensible, multi-functional (mechanical, electrical, data, thermal), modular interface, and compare the realization of each function to provide a design consideration.

KEYWORDS
Modularity, Integrated Interface, Multi-functional.

INTRODUCTION

The traditional spacecraft is designed as a highly integrated "stovepipe" system[1], which the morphology of the spacecraft remains unchanged for a long period of time. With the deepening of the mission, the complexity, cost, design period are constantly increasing, and the mass and volume of the spacecraft have become very large. At the beginning of the design, the continuous changes in long-term missions were not foreseen, making the spacecraft unable to adapt to the changes well, let alone repairing malfunctioning systems. In the 1970s, NASA Goddard Space Flight Center proposed the design concept of multi-mission modular spacecraft(MMS)[2], and on this basis, it proposed a modular, adaptive, and reconfigurable system concept (MARS)[3]. The Air Force Research Laboratory of US proposed a plug-and-play system for aerospace and designed a spacecraft PnPSat with plug-and-play functionality[4]. The “Phoenix Project” aims to realize the modular function of satellite architecture by applying cellular satellites with the concept of cellularization and morphological reconstruction[5]. The iBOSS project of the German Aerospace Center (DLR) draws on the idea of Lego bricks and implements a modular and repairable design method through the "building blocks" model to improve the performance of the spacecraft[6].

Wanxin Man, Xinhong Li, Zhibin Zhang, Jiping An, Guohui Zhang, Junwei He
College of Space Science and Technology, Space Engineering University Beijing, China
Spacecraft can be designed into modules with independent functions through space modularization. These functional modules can be easily packaged and launched into space. The space robot or the module itself has the function of autonomous assembly, which assembles these modules into independent spacecraft with target function. These modules need interfaces to connect, and these interfaces may not only transfer mechanical forces or moments, but also some such as electrical power, data and thermal. These requirements force the interface to be designed as a standardized, extensible, modular universal connection interface with multiple functions (mechanical, electrical, data, and thermal). This kind of interface can satisfy the multi-functional coupling among spacecraft modules, platforms, payloads, client servers and robot end effectors in orbit and planetary environments[7].

![Figure 1. Small spacecraft docking mechanism (A) MIT SPHERES universal docking port (B) ARCADE experiment main units (C) iSSI model of iBOSS (D) Orbital Express capture and mating mechanism (E) AMDS docking mechanism.](image)

At present, the large-scale docking mechanisms used in manned spaceflight mainly include Probe-drogue Mechanism, APAS-75, APAS-89, Hybrid Docking Mechanisms, and Common Berthing Mechanism, etc. Small docking mechanisms for on-orbit services have gradually been developed in recent years. The representative ones are MIT SPHERES docking system[8]; the three-finger docking mechanism of Orbital Express Program[9]; the Autonomous Rendezvous Control and Docking Experiment (ARCADE) project[10] led by the University of Padova; the Autonomous Micro satellite Docking System (AMDS)[11] developed by Michigan Aerospace Corporation (MAC); the iSSIs docking interface of iBOSS project[12] designed by the German Aerospace Center (DLR). Below some key design requirements that need to be met in the design of the modular spacecraft integrated connection interface are described in detail.
DESIGN REQUIREMENTS OF SPACECRAFT MODULE INTEGRATED DOCKING INTERFACE

The modular platform facilitates the creation and operation of large-scale aerospace structures in space, and reduces manufacturing and maintenance costs. The module connection interface enables homogeneous or heterogeneous modules to establish rigid connections and transmit various types of resources. Due to the small mass of the module and high rendezvous accuracy, the docking collision energy is small, and the design of the buffer system is relatively simple. Generally, an integrated capture-lock design can be adopted. The design of interface type is usually based on some vital properties. Studies have shown that rotational symmetry, redundancy, rigid connection, and androgyny are some of the ideal design traits of module interfaces. This section will discuss the interface design requirements and constraints, and provide useful help for interface design.

Gender

![Figure 2. Gender interface categories: (A) Gendered and (B) Bi-gendered.](image)

The gender of the interface coupling mechanism is closely related to the difficulty of mechanical design and directly affects the reconfigurability of the system. The interface of the docking subsystem is usually divided into male, female, and androgyny. The male connector is usually convex in structure, while the female connector is concave. Androgynous interface combines the male and female connectors on a surface to establish a connection between two antisymmetric interfaces. The gender-mating interface is very simple, but it can only be mating with the opposite gender port, which greatly reduces task reconfiguration and flexibility. Androgyny is a good choice and its advantages are enough to make up for the disadvantages of simplicity.

Rotational Symmetry

If the docking mechanism is axially symmetric with respect to its longitudinal axis, the rotational degree of freedom around the axis is free, which can reduce the alignment requirements of the connection, greatly simplify the docking process and reduce the fuel consumption. At the same time, rotational symmetry also helps to integrate the redundancy of the interface components.
Simplicity

The simpler mechanical design means the lower probability of component or mechanism failure. Simplicity may conflict with other design constraints. Simple design requirements may mean complete redesign and development of new solutions. For simplicity, it can be measured by the number of active components and actuators.

Mechanical Transmission

![Figure 3. Load transfer model (A) docked modules geometry and (B) loads on the docking ports.](image)

The docking port should transfer loads and make the connection interface fit tightly without interrupting the mechanical and electrical contact, allowing separate attitude control and orbit propulsion to act on the whole modular structure. To simplify the model, the docking port is considered on the line between the mass centers of the two modules. If module 1 provides control force and control torque, the dynamics equations of module 1 can be written as follows:

\[
\begin{align*}
    m_1\ddot{x}_1 &= F_{AC} - F \\
    I_1\phi_1 &= T_{AC} - T
\end{align*}
\]

The dynamics equations of module 2 can be expressed as follows:

\[
\begin{align*}
    m_2\ddot{x}_2 &= F \\
    I_2\phi_2 &= T
\end{align*}
\]

When the two modules are mated, the center of mass acceleration of the combination is the same. Therefore, in the first order approximation, the maximal loads on the docking subsystem can be calculated:

\[
\begin{align*}
    F &= F_{AC} \frac{m_2}{m_1 + m_2} \\
    T &= T_{AC} \frac{I_2}{I_1 + I_2}
\end{align*}
\]

Tolerance to Misalignment

In the process of docking, there may be slight errors in position, direction, inclination and speed that will affect the mating procedure. Sufficient values should be set for tolerable misalignments during the design.
Latches

Latches are used to lock or limit the movement of the mechanism after initial contact. They can be activated automatically once the connector is firmly pushed or engaged. The latch can be actuated by mechanical or electromagnetic. Common actuation methods include electric motors, electro/permanent magnets and Shape Memory Alloy (SMA) wire. Generally, the driving mode is selected according to the size of the driving object.

Transmission Types

Not only need to establish a mechanical connection between the two modules, the realization of other functions is also essential. For example, electrical connections enable the distribution and sharing of power between modules, and data interfaces allow modules to communicate and transfer data. It has to be said that the establishment of thermal connection interface, modules may be stacked in different forms to establish spacecraft. The tight mating between the modules will inevitably affect the thermal control of the modules. It is necessary to ensure that the modules have the ability to exchange heat in order to operate normally.

Redundancy

Once the spacecraft into the space, it is difficult to repair. The system must be able to withstand the failure of components. Redundancy requires that the system must have other facilities to compensate for the failure after some components fail.

Space Environment

Interfaces exposed to the space environment, materials, mechanisms and electronics are easily affected and must be specially designed to ensure the normal operation of the interface until the end of the mission.

There are specific conflicts between most of the requirements of the interface, which are difficult to fully satisfy. These aspects need to be considered comprehensively in order to establish a good solution to make the task flexible enough.

INTERFACE TRANSMISSION FUNCTIONS

The internal optimized integrated connection interface needs to realize the transmission of mechanical, electrical, thermal and data. It is necessary to introduce various types of interface forms and analyze their advantages and disadvantages in order to guide the interface design.

Mechanical Interface

Mechanical connection design of the interface can be roughly divided into four main types according to its connection methods: pin and hole, hook, lock and key,
shape matching[13]. The pin and hole connector uses another locking mechanism to lock the pin in place to prevent accidental detachment after inserting the pin into the corresponding hole. The hook connector incorporates a hook or gripper on one side of the connection and a hole, groove or rod on the opposite side. One side of the connector rotates the hook attachments to a position around the other side of the connector that interferes with any translational motion perpendicular to the surface and with rotational motion about the axis. The lock and key connector is to insert a specially designed key into the cavity on the surface of the female connector and rotate the key to be embedded into the channel in the cavity to lock the connection. Shape matching connector is usually of the same shape and is connected together by interlocking specially designed geometric shapes to prevent relative motion between them.

Figure 4. Mechanical Connection (A) pin and hole (B) Hook (C) shape matching (D) lock and key.

| Mechanical connection classes | Advantages and disadvantages |
|-------------------------------|-------------------------------|
| Pin and hole                  | Good tolerable misalignments, Easy to orient, Simple structure | Need additional latches, Power consumption, Low efficiency |
| Hook                          | Adaptable to the environment, Flexible orientation, Simple structure | Hard to control, Multiple moving parts, Naturally male |
| Lock and key                  | One moving part, Potentially fail-safe, Passive retention | Little/no lateral misalignment correction, Complicated structure |
| Shape matching                | Potentially fail-safe | Complicated structure, Need additional latches, Weak generality |
Electrical Interface

The cold vacuum environment of space brings some challenges to power transmission. At the same time, the electrical interface should be compact and reliable, light weight, short circuit protection, and reusable. The existing electrical connection design forms mainly include: pin, tabs, slip rings, and wireless power transmission. Male pins are inserted into female inserts to form multi-point contacts, thereby interlocking and maintaining electrical contact between the two interfaces. The electrical tab is a spring-loaded metal component without a special locking device, and the electrical connection can be realized only through the touch of the tabs. Slip ring is a kind of circular electrical contacts, which can realize signal and current transmission between two relative rotating mechanisms. The wireless power transmission obtains DC power through the solar array, and then converts it into radio frequency power and transmits it to another module's rectenna, which is then converted to DC power through a diode-based converter. It can be seen from Table II that the electrical tabs have self-adjusting ability and are not sensitive to particles, which are very suitable for the electrical connection interface between modules.

![Figure 5. Electrical interface types (A) Pins (B) Spring-loaded tabs (C) SWARM brass tabs (D) EMI tabs (E) Cylindrical slip rings (F) A cast slip ring assembly with carbon brush system (G) Wireless power transmission components.](image)

| Electrical connection classes | Advantages and disadvantages |
|------------------------------|-----------------------------|
| Pin                          | Good contact<br>Prevent lateral movement | Particles sensitivity<br>No or little self-adjustment capability<br>Easy to damage |
| Tabs                         | Excellent angular and axial tolerance<br>self-adjustment<br>Tolerance against particles | No latching after connection<br>Sizes dependent on environment |
## Electrical connection classes

|                  | Advantages                                      | Disadvantages                              |
|------------------|-------------------------------------------------|--------------------------------------------|
| **Advantages**   | Rotating connection                             | Wear of sliding contact                    |
|                  | Low starting current                             | High assembly space                        |
|                  | High overload capacity                           |                                            |
| **Disadvantages**| Wear of sliding contact                          |                                            |
|                  | High assembly space                              |                                            |

### Slip rings
- Rotating connection
- Low starting current
- High overload capacity
- Wear of sliding contact
- High assembly space

### Wireless power transmission
- Non-contact transmission
- Resistance to particle influence
- Insensitive to interference
- Loss of energy
- Large surface for energy absorption
- Weight penalty

## Data Interface

At present, as the spacecraft system transforms from completely centralized processing to distributed processing, higher requirements are put forward on the onboard bus. Because of the need to process a large number of different types of data, the data rate has been difficult to satisfy the requirements. With the requirements of on-orbit services, real-time control has become a difficult point. In Table III, several commonly data buses used in space are compared and briefly described. It can be seen that SpaceWire and Firewire will dominate the aerospace field at present. In the future, with the development of aerospace system to network and intelligence, the communication mode with bus as the mainstream will gradually transition to the communication mode with network. Fiber channel and Real-time Ethernet will be the focus of space data transmission development.

### TABLE III. PERFORMANCE COMPARISON OF SOME DATA BUSES.

| Classes  | 1553B | RS485 | CANBus | Firewire | SpaceWire | Fibre Channel | Real-time Ethernet |
|----------|-------|-------|--------|----------|-----------|---------------|-------------------|
| Data rate| 1Mb/s | ~10Mb/s | ~3.7Mb/s | 100Mb/s| 100Mb/s | 100Mb/s | 100Mb/s |
| Topology | Linear bus | Star Tree Ring Bus type | Bus type | Serial bus Tree Daisy-chaining | Point-to-point | Point-to-point | Point-to-point |
| Arbitration mechanism | Controller | | | | | | |
| Transmission mode | Half-duplex | Full-duplex | Message-based half-duplex | Half-duplex | Full-duplex | Full-duplex | Full-duplex |
| Coding mode | Manchester encoding | | | | | | |
| Bit-error rate | $10^{-4}$ | | | | | | $10^{-12}$ |
| Transmission protocol | Command response | Asynchronous serial communication protocol | Can protocol | CANOpen | RAAP | SDDP | STUP |
| Transmission distance | 10m | 100m | 10km | 72m | 10m | 100m |
| Medium | Shielded twisted pair | Twisted pair | Twisted pair | Optical fiber Unshielded twisted pair | Optical fiber Twisted pair | Optical fiber Twisted pair | Optical fiber Twisted pair |
| Characteristics | High reliability | Simple in structure | Low bandwidth | Low tolerance | Limited error | Uncertainties | High reliability | Low efficiency | Strong calculation ability | High throughput | Easy expansion | Easy maintenance | High reliability | Low power consumption | High bandwidth | Low latency | Lowered error rate | Flexible network construction | High data volume | Strong real-time communication | High safety | Strong fault tolerance mechanism |
Thermal Interface

When the spacecraft is exposed to the space environment, it needs to bear extreme temperature conditions and experience large temperature fluctuations. Modular spacecraft are connected together in the form of stacking, and the interfaces between modules are closely attached, which requires the function of heat transfer between independent module interfaces. Due to the particularity of space environment, heat transfer methods are mainly conduction and radiation. Heat switches are used to control the on-off of thermal connections between components, fluid heat transfer devices and special thermal functional materials are used to realize heat transfer. The connection of the modules determine that the thermal control of the structure is distributed, which requires a reliable and efficient thermal control strategy to meet the thermal balance adjustment and thermal load distribution. At present, there are relatively few studies on the heat transfer between this connection interface. The main reports that have been reported are: a special carbon nano-copper alloy composite material used in the iBOSS project, and the pumping fluid circuit in the SIROM project[14]. The Table IV briefly introduces some performances of the three thermal control methods: thermal switch, heat pipe and thermal coating.

### TABLE IV. THE PERFORMANCE OF THREE TYPES OF THERMAL CONTROL METHODS.

| Classification | Heat switch                                                                 | Thermal control methods | Heat pipe                                                                 | Heat coating                                                                 |
|----------------|------------------------------------------------------------------------------|-------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Work principle| A thermal control device that can control the thermal connection between components according to the demands. | A heat transfer element that uses fluid phase change and capillary action for heat transfer. | By adjusting the solar absorption ratio, and the infrared emissivity to control the radiation heat transfer material inside and outside the satellite. | Erlastic assembly, high limit heat flux density, low thermal resistance anti-gravity, etc. |
| Typical classes| Micro expansion heat switch, shape memory alloy actuators heat switch, self-actuated heat switch, phase transition driven heat switch, etc. | Loop heat pipe, capillary pumped loop, pulsating heat pipe, variable thermal conductive heat pipe, vapour-dynamic thermophore, micro miniature heat pipes, sorption heat pipes, etc. | Quartz glass aluminized second surface mirror, aluminum alloy/gold plating coating, Parylene aluminum-coating second surface mirror, thermochromic coating, etc. | The thermal coating can obtain different thermal equilibrium temperature, adjust the temperature gradient of the surface, strengthen the internal radiation between the satellite skin and the instruments. |
| Characteristics| It has a wide temperature control range. The high switching ratio mainly depends on the heat transfer surface material and the operating performance. Reliability depends on the performance of the actuator. | Flexible assembly, high limit heat flux density, long distance transportation, low thermal resistance, anti-gravity, etc. | - | - |

CONCLUSIONS

This article focuses on the design of integrated interfaces for small modular spacecraft, mainly discusses the requirements that need to be satisfied in the interface design. After that, the transmission modes of mechanical, electrical, data and thermal between modules are simply compared. Most of the requirements are often in conflict with each other, so we need to choose a compromise solution according to the actual situation. Among them, rotational symmetry, redundancy, rigid connection, and androgyny are some of the ideal design traits of module interfaces.

Mechanical connection design of the interface can be roughly divided into four main types: pin and hole, hook, lock and key, shape matching. The existing electrical connection design forms mainly include: pin, tabs, slip rings, and wireless power transmission. The spring-loaded electrical tab is suitable for the electrical
connector between modules due to its adjustability and particle resistance. In data transmission, SpaceWire and Firewire will dominate in the future, but the development from bus to network communication will make fiber channel and real-time Ethernet become the development priorities. For the heat transfer between modules, it will mainly rely on heat pipes and thermal functional materials. The heat switch will assist in controlling the on-off of the thermal connection. At the same time, it is necessary to study new control strategies for heat balance adjustment and heat load distribution.

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