A Universal Interface for Modular Spacecraft

Lennon Rodgers
rogers@mit.edu

Nicholas Hoff, Elizabeth Jordan, Michael Heiman, David W. Miller
nhoff@mit.edu, ejordan@mit.edu, michaelh@mit.edu, millerd@mit.edu

Space Systems Laboratory, Department of Aeronautics and Astronautics, MIT
Cambridge, Massachusetts 02139, USA

ABSTRACT: For any modular spacecraft design that allows for reconfiguration once in orbit, there is a need for an interface that acts as a common connection between the modules. The interface must provide autonomous docking, undocking and communication, in addition to transferring mechanical, electrical and thermal loads through each of the modules. This study focuses on the requirements and design of an interface developed as part of the SWARM spacecraft test bed at MIT. The key features include its simple, compact and universal design. It also houses the metrology subsystem and allows for autonomous docking and reconfiguration of the modular components.

1. INTRODUCTION TO MODULAR SPACECRAFT

1.1. Modularity
A modular spacecraft design is defined as one that is composed of standardized, reconfigurable components. More specifically, it is a system that consists of multiple de-coupled subsystems, with the ability to re-use common modules across separate missions. This is in contrast with a common spacecraft design, which involves using identical but non-reconfigurable designs, or a heritage spacecraft design, which is heavily based upon previous designs. A modular spacecraft design holds promise for reducing the amount of time required for design, manufacturing, integration and testing.

The commercial, military and science communities would directly benefit from modular designs by having the option of replacing only particular subsystems of a spacecraft. For example, a failed propulsion subsystem could be replaced instead of the entire spacecraft. Another benefit of a modular design is the ability to launch large spacecraft by stacking modules within one or more launch vehicles. Once in space, the modules could be autonomously deployed and assembled. The spacecraft could then be reconfigured to accommodate various mission objectives. Lastly, standardization gives rise to compatibility across organizations and allows for more domestic and international collaboration. As space technology advances, there is a need for standardization and modularity if space technology is to follow a similar path as other successfully advanced technologies such as automobiles, aircraft and electronics.

However, the major drawback with modular spacecraft design is the need for each subsystem to function independently except through the connections available through one or more interface. Because of this, the modular design will most likely be sub-optimal and performance may be sacrificed. The interface is a critical component of any modular spacecraft design, and will be the primary focus of this paper.

1.2. SWARM
SWARM stands for Self-assembling Wireless Autonomous and Reconfigurable Modules. SWARM is a test-bed developed as part of an undergraduate design course at the Massachusetts Institute of Technology. The project demonstrates the use of modular spacecraft, which are capable of self-assembly and reconfiguration while utilizing wireless communication. While the lab prototypes closely resemble an actual space system, they are not designed for the space environment. The SWARM spacecraft system consists of the following separate modules (the quantity is in parenthesis):

- Computer (1)
- Attitude Control System (ACS) (1)
- Propulsion (2)
- Mother Ship (1)
Each module performs a set of subsystem functions and is supported by the following common components (the quantity is in parenthesis):

- Structural Package/Containment (1)
- Power Supply and Distribution Bus (1)
- Field Programmable Gate Array (FPGA) (1)
- Metrology Sensors (4 sets)
- Interface (up to 4)

The computer module is the central processor, and gives commands wirelessly to the local FPGA on each module using the standard Bluetooth® protocol. A laptop is currently used as the computer module. By using wireless communication, the modules are able to communicate in both docked and formation flown architectures. The ACS module provides rotational torque and is capable of storing angular momentum for the entire spacecraft. This module is essentially a motorized flywheel with a gyro and microprocessor that are used to perform all local sensing and low-level commands. The ACS module receives a commanded change in angle from the computer module, and by integrating the on-board rate gyro, executes the commanded angle change by applying torque against the flywheel. The propulsion module provides the thrust for rotation and translation. Each propulsion module has a firing circuit and six thrusters, which use a supply tank of CO₂ and a pressure regulator. This module converts thrust commands into a series of firing circuit on-times via a pulse width modulation scheme. The mother ship module acts as a much larger vehicle that provides electrical power charging.

The ACS and propulsion modules are mounted on air-carriages and float on a flat surface. For simplicity, the mother ship and computer modules are stationary and not contained within the standard module packaging (Figure 1).

![Figure 1. A SPHERE, two propulsion modules and an ACS module, sitting on air-carriages rigidly connected using the SWARM interface.](image)

2. THE INTERFACE DESIGN

For a cluster of independent modules, there is a need to connect all of them together autonomously. The common component required to connect the modules is the interface, which must be placed at each node where the modules are to be rigidly connected. This section describes in detail the design of the SWARM interface and begins with the general requirements.

2.1. Design Requirements

The interface must be capable of performing the following functions between each module:

- **Autonomously Dock/Undock:** This provides the ability for the modules to be assembled and reconfigured without human intervention. Thus allowing the modules to perform complex docking maneuvers such as capturing a tumbling satellite.²
- **Transfer Mechanical Loads:** By mechanically connecting the modules, separate propulsion and ACS modules are able to control the translation and rotation of the entire module cluster.
- **Transfer Electrical Power:** This allows the modules to share electrical power. Thus, a central power module (such as a solar panel) could distribute power to the entire module cluster.
- **Transfer Thermal Loads:** This allows the modules to have a centralized thermal system, and thus separate systems are not needed on each module.
- **Provide a Connection for Data and Communication:** Communication between modules is necessary for docking/undocking, transferring range data, and general system control.

A very critical requirement is that the interface be universal, meaning all are identical in design and fabrication, yet have the ability to dock together. This requirement is very subtle, but imposes large restrictions on the design. The interface must also compensate for alignment error during docking (Figure 2); For SWARM, an alignment error of two centimeters off-axis with a 5° angle was assumed. The last major functional requirement is for a capture mechanism to pull the modules fully together once they are within docking range (Figure 2). The docking range is defined as the closest distance the modules can be brought together in a controlled manner using the metrology sensors and propulsion subsystem; The SWARM docking range is approximately two centimeters. Other more general design requirements include:

- Must be capable of mass production.
- The over-all size should be minimized.
- Should not deplete the module batteries when operated.
The following are other practical requirements that restricted and governed the final SWARM interface design:

- Non-professional machinists (students) must be capable of producing each of the components using the tools available. Thus, the design should not rely on professional machining.
- Assembly and disassembly must be simple. Thus the number of parts should be minimized and the design should avoid press-fits, etc.
- Use off-the-shelf parts if possible.
- The number of moving parts should be minimized for general simplicity.

The next section takes these requirements and discusses two high-level interface designs and concludes with the basic design used for the SWARM test bed.

2.2. Interface Design Iterations

The design requirements were initially used to form two different interface architectures. The first, Type A, has an extendable and retractable concentric core (Figure 3). The extended core on one interface would be inserted into an interface with a retracted core. A locking mechanism, using both the inner and outer core, would then be used to form a rigid connection. One weakness in this design is the need for a re-configuration change before it can dock. Thus, the initial step of retracting or extending the central core induces an additional mode of failure to the docking procedure; if one of the cores was unable to fully retract, docking would be impossible. This architecture also requires a gearing mechanism or a linear actuator, which adds complexity. Lastly, this design requires the interface to be long enough to contain the entire length of two cores, which increases its overall size.

The second architecture considered, Type B, uses a protruding pin and an entrance hole (Figure 4). The protruding pin is rigidly attached and thus does not extend or retract. This architecture allows for a much more compact design since nothing is being retracted. In addition, the protruding pin is off-axis, which provides more rotational rigidity ($M_z$).

The schematic shows only one pin and hole, though multiple pins could be used as long as the pin pattern is matched with holes through the center vertical axis of the interface (Figure 5). The symmetry through the vertical axis keeps the port universal. One advantage to adding pins is an increase in possible docking orientations. For example, the interface has one docking orientation with one pin; similarly, there are two docking orientations with two pins. However, it should be noted that a turntable-type device could be used to rotate the interface about the x-axis into the proper position before docking. This would allow the interface to dock in any orientation in the y-z plane.
Both the Type A and B interface were designed and built for comparison (Figure 6 and Figure 7). For the Type B, it was determined that there was no real advantage to using more than one pin for the SWARM application since one pin held test loads adequately and using multiple pins made docking and undocking more difficult. The comparison showed that the Type B interface is superior to the Type A mostly because it has a simpler and more compact design. It is more compact because it uses counter-rotating disks for locking instead of a translational device. The details of the locking device are discussed in Section 2.4.2. For these reasons the Type B design was chosen to develop into a final interface design.

Figure 6. A CAD model (left) and the prototype (right) using the Type A architecture.

Figure 7. The SWARM interface design, which has a Type B architecture.

Figure 8 shows some of the key features of the final interface design; these features include a steel core and aluminum channel for an electromagnet coil, which acts as the capture mechanism, two brass tabs to transfer electrical power, and an angled pin and chamfered hole to increase docking tolerances given the SWARM docking range and alignment error. Also, a motor is used as part of the locking mechanism. Lastly, since wireless communication is used, a wire connection is not needed to pass through the interface. Table 1 summarizes the key specifications of the design, and Figure 9 and Figure 10 show the interface mounted to two SPHERES and a SWARM module, respectively.

This final interface design came after much iteration. Manufacturing considerations drove many of the iterations, since mass production was a requirement. Also, because non-professional machinists manufactured each of the components, many iterations were needed to bring the fabrication within reach given the limited machining abilities. Many previous designs were complex, and thus were immediately eliminated. Thus a simple design was chosen with a minimum number of parts, which could be easily made given the available resources. For example, many of the parts were made on a 2-dimensional water-jet. This machine is almost 100% automated, easy to use and cost effective for creating 2-dimensional parts. The remaining parts were made on either a lathe or mill, and when possible were simplified using jigs and automated using computer programs.

Lastly, it should be noted that the requirement to pass thermal fluid was removed early in the design process. This was done because thermal issues were not large enough to necessitate a thermal control system in the

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<th>Table 1. Key Specifications</th>
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<td>Dimensions</td>
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<tr>
<td>Protruding Pin Length</td>
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<tr>
<td>Entrance Hole Diameter</td>
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<tr>
<td>Mass</td>
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<tr>
<td>Electromagnet Wire</td>
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<td>Electromagnet Resistance</td>
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<td>Electromagnet Voltage</td>
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<td>Electromagnet Wire Turns</td>
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laboratory environment. Also, the difficulty of passing thermal fluid through the interface in a no-drip manner was difficult to implement given the time and machining limitations of the project.

![Figure 9. Two SPHERES locked together using two interfaces.](image)

![Figure 10. A SWARM Module with an interface. Notice the metrology sensors mounted around the interface (green boards).](image)

2.3. **Concept of Operation**

The general docking and undocking operations of the interface are summarized in Figure 11. The docking sequence is initiated once the metrology sensors have brought the modules within docking range. The computer gives commands via the FPGA to enter docking mode, and the docking begins by activating the electromagnets on each of the interfaces. Sensors are used to determine when the interfaces are ready to be locked and when a successful lock has been achieved.

![Figure 11. Flow-chart showing the docking and undocking sequence.](image)

2.4. **Design/Hardware Details**

This section provides the details of the interface design. The outline follows the functional requirements discussed in the Design Requirements section. Lastly, a summary of the testing and validation is given.

2.4.1. **Requirement: Autonomously Dock and Undock**

The electromagnet and other supporting sensors are required to provide autonomous docking and undocking. Also, a chamfered entrance hole and special protruding pin are used to compensate for alignment error during docking.

The electromagnet is required because the metrology sensors become ineffective once the interfaces are brought within a few centimeters of each other. Instead of using a blind final trajectory, electromagnets are used for a final attractive pull during docking. Also, the electromagnet force is used to hold the modules together during locking. The front of the interface is made of steel with a concentric aluminum channel (Figure 8). The steel enhances the magnetic field, and the channel houses the wrappings of coated copper wire that form the electromagnet. The two disadvantages of using an electromagnet are an increase in weight from the steel core and the additional power consumption when the electromagnet is activated. It should be noted that an entire aluminum core was tested, but the magnetic field was not sufficient.
A sensor is used to detect when the two modules have made contact, which is when the interface can be locked. To accomplish this, an interrupt-type optical sensor was used. Once the pin is sufficiently inside the entrance hole, the protruding pin blocks the sensor beam, which sends a low signal to the FPGA (Figure 12). A second sensor is used to detect when the locking mechanism is completely closed. When the motor has stalled, the sensor detects a current spike, and relays a high signal to the FGPA; this signifies that the interface is locked.

![Figure 12](image-url)  
**Figure 12.** The pin blocks the sensor. The sensor is mounted directly behind the second rotating ring.

An electronics circuit was designed to receive the high and low signals from the sensors, relay FPGA commands and distribute bus power to the interface. The functions of the interface circuit are shown schematically in Figure 13.

![Figure 13](image-url)  
**Figure 13.** A schematic of the interface circuit board.

Lastly, large docking tolerances are required for autonomous docking because it increases the chances of a successful docking maneuver. Making the entrance hole very large while making the protruding pin thin and short will increase docking tolerances. To determine the diameter of the entrance hole, simple calculations were made based on the desired docking tolerances and then validated through experimentation. The docking tolerances were improved by adding a chamfer to the entrance hole and an angle to the head of the pin.

### 2.4.2. Requirement: Transfer Mechanical Loads

Since SWARM operates on a 2-D air-table, there are two types of mechanical loading scenarios that were considered when designing the interface. The first type is the cantilever load, which occurs when one module is cantilevered off another module that is mounted on an air-carriage (Figure 14.a). The second type of loading is caused by the centripetal forces that occur when the module cluster is rotating about its common center of gravity (Figure 14.b).

![Figure 14](image-url)  
**Figure 14.** (a) Cantilever loading. (b) Centripetal loading.

To mechanically connect the modules, a locking mechanism is required. This mechanism uses two counter-rotating disks, which are used to both pinch and wedge the protruding pin (Figure 15). Once each of the pins has been inserted into the opposing interface, the motor is activated, which begins closing both disks onto the pin. The ramp on the back of the pin head creates a wedge effect, which draws the two modules together and forms a tight mechanical lock.

![Figure 15](image-url)  
**Figure 15.** This illustrates how the counter-rotating disks are used to lock the pin. The pin is both pinched and wedged.

The disks are counter-rotated by pulling a pin along a curved slot (Figure 16). The two disks are identical, but one is flipped, so they counter rotate equally in opposite directions. This greatly simplified the design and has been proven effective for the SWARM test bed. Figure 17 shows how a threaded motor rod is used to translate the pin along the curved slot. By using a threaded motor shaft, the shaft is locked in place once the motor stops turning.
2.4.3. Requirement: Transfer Electrical Loads

Two brass tabs are used to pass bus voltage through the interface (Figure 8). The top tab is the positive and the bottom is the negative. When the two docking interfaces are connected, the opposing tabs create a closed electrical connection, and electricity can be passed between the modules. For SWARM, multiple bus voltages are required, thus a power circuit was necessary in each module to provide the other voltages. The need for this additional power-card is considered a drawback of the decision to pass a single bus voltage through the interface, versus having multiple voltages passed. It should be noted that the power tabs are mounted on a plexiglass insert to isolate the electrical connection from the surrounding steel. The wires from the power tabs need to be fed through the interface from the front to the back, so they can be connected to the interface card (Figure 18).

2.4.4. Requirement: Provide a Connection for Data and Communication

Bluetooth® wireless units provide wireless communication between each module and the central computer module. The communication range is 10 meters and data transfer rates on the order of one MBPS. Currently, a baud rate of 115200 KBPS is the highest used by SWARM, but actual bandwidth is influenced by factors such as error checking modes and signal interference.

2.4.5. Testing and Validation

Tests showed that two modules could be commanded to autonomously dock and undock. Two docked modules were then flown manually and docked to the mother ship module. Thus, it was shown that three modules could be autonomously connected.

Table 2 summarizes some of the tests performed on the interface. The “Weight Supported” results are not maximum values, but rather the operational values of SWARM; it is likely that the interface could support much larger mechanical loads.

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<thead>
<tr>
<th>Table 2. Summary of Interface Tests</th>
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<tr>
<td>Maximum Docking Range</td>
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<tr>
<td>Time for Final Capture (EM pull)</td>
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<tr>
<td>Time to Lock</td>
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<tr>
<td>Weight Supported, Cantilevered</td>
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<td>Weight Supported, Tensile</td>
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Lastly, tests showed that two interfaces can be locked together and then pass electrical current. However, the ability for one module to charge the batteries of another module has not been tested, though future plans exist to test such capabilities.

3. CONCLUSIONS AND FUTURE WORK

It has been shown that an interface can be designed for autonomous docking that is simple, compact and robust. The biggest constraints on the SWARM interface design were the small size and the requirement for it to be simple and mass-produced by non-professional machinists (students).

Future work includes adding thermal fluid transfer, and investigating other radically different interface designs. Lastly, further development of error resistant docking algorithms will be created and implemented at both the FPGA and central computer levels.
4. REFERENCES


