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# SIF – Yet Another Spacecraft Interconnection Standard

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ABSTRACT: SIF is a Standard InterFace for spacecraft electronics. It combines a number of existing standards: +28 V avionics power, ISO 11898-3 fault-tolerant Control Area Network (CAN), and the CANopen software protocol. Terminals are connected into a closed loop by identical cables. The resulting network is fail-operational and is easy to modify even late in satellite integration.

SpaceQuest experience building a large spacecraft with SIF avionics has demonstrated the cost and schedule savings inherent in standardized interfaces. This paper contains all of the information required for the reader to build and use SIF devices. The small satellite community is invited to make use of SIF, in the belief that widespread utilization of standards benefits all of the players.

### **INTRODUCTION**

It has long been recognized that spacecraft construction can be made simpler if many of the component modules share a common electrical interface. A standard interface can accelerate schedules and reduce mission cost. Standards were the theme of the 2005 Small Satellite Conference, and many excellent papers were presented that expand upon this idea.

The summer of 2005 also saw SpaceQuest's USA and Canadian offices hard at work on a space mission that demanded low cost and rapid schedule. Furthermore, the satellite was significantly larger in scale than SpaceQuest's previous efforts, impacting the ability to reuse previous hardware. With the necessity to design much of the vehicle avionics from scratch, a perfect opportunity arose to build them all to a common interface. The result is the Standard InterFace, or SIF.

SIF borrows liberally from existing standards. Power distribution is accomplished using unswitched +28 V busses common to many aircraft and spacecraft. Data communications uses a fault-tolerant variant of the Control Area Network (CAN) bus, often used in the trucking industry. The higher-level data protocol is CANopen, an open standard found in light rail and factory floor automation.

The primary innovation of SIF is its ring topology. Each piece of equipment has two identical connectors, and is attached to its neighbors by standard cables. This massively reduces the complexity of the spacecraft wire harness. It also allows new equipment to be added to the satellite at the last minute. SIF's capacity for unconstrained expansion is believed to be unique in any of the proposed spacecraft electrical standards.

SIF has already been extremely successful, allowing the avionics for a new satellite bus to be developed in under 12 months. It is hoped that further success will follow. The SIF standard is open, and free for use. This paper contains all of the detail needed for the reader to develop a new SIF device. Spacecraft engineers are encouraged to consider using a SIF bus on new satellites. Component vendors are invited to include SIF in their new devices. The whole industry can benefit from interoperable hardware, reduced GSE, and an increased base of suppliers and customers.

### TOPOLOGY

Existing and proposed spacecraft electrical standards typically fall into one of three topologies: star, daisychain and mesh. Star topologies make use of a central hub to which all of the other terminals are connected. USB is a perfect example of this. Ethernet connections (perhaps carrying power too) will typically also radiate out from a hub or switch. The star topology is attractive for a number of reasons. All of the cables are identical, allowing them to be mass-manufactured. Adding a new last-minute device is easy, provided that the hub has an extra empty port. If the hub is full, however, there is trouble. The star topology is also vulnerable to failure of the hub device which would typically bring down the entire network.



Figure 1: Star Topology

A daisy-chain topology uses continuous electrical busses that are common to all of the connected terminals. SSP, MIL-STD-1553, and most satellite implementations of CAN follow this model. The chief problem with daisy-chain is the complex electrical harnesses that it generates. All of the spacecraft wiring ends up in a single monolithic octopus. Adding an additional terminal to the network requires modification to this wiring, and the satellite cannot be used while this work is being done.



Figure 2: Daisy-Chain Topology

A mesh topology links each terminal to a number of its peers. All cables are identical, but now there is no central hub to serve as a vulnerable limit to growth. Adding additional terminals is easy, and redundant data paths can make the network extremely robust. The SpaceWire standard allows for mesh networks, but unfortunately it does not include provision for power distribution so it is not a complete electrical interface.



Figure 3: Mesh Topology

SIF uses a ring topology that is a cross between a degenerate mesh and a daisy-chain. Each terminal connects to exactly two others, and so the complete

network becomes a closed loop. Within the terminal, the two connectors are wired directly together permitting the use of a continuous signaling medium bus such as CAN. The circular nature of the network provides a redundant path for power and data between any two terminals.



Figure 4: SIF Ring Topology

Expanding a SIF network is simple. Disconnect the SIF cable from between two terminals to open the loop, and then add the new terminal along with two SIF cables to once-again close the ring. During spacecraft assembly it may be useful to keep the ring open, and thus operate without redundancy. This eliminates the need to continually re-close the ring as more and more terminals are added.



Figure 5: Adding a SIF Terminal

Adding a new node requires two new SIF cables of an appropriate length, shown in brown in Figure 5. On a mechanically large satellite it may be possible to use standardized cable lengths: 50 cm, 75 cm, 100 cm, and so on. A small satellite will usually need to have a new length of cable custom fabricated. In either case, the effort to add a new terminal is small compared to reworking a harness (daisy-chain) or upgrading a hub (star).

### THE SIF SPECIFICATION

### SIF Cables

SIF cables shall be terminated at both ends with 9-pin plug (male) D-subminiature connectors. The connectors are wired straight through, as shown.

Pin	Wire	Signal
1	24 AWG Gray	CAN_L
2	20 AWG Black	Power Return
3	No connect	
4	20 AWG Red	+28 V A
5	20 AWG Orange	+28 V B
6	24 AWG Violet	CAN_H
7	20 AWG Brown	Power Return
8	Cable Shield (optional)	
9	20 AWG Yellow	+28 V C

**Table 1: SIF Cable Pinout** 

Spools of SIF cable can be purchased from Weico Wire & Cable Inc. (<u>www.weicowire.com</u>). Ask for part #9745.

#### SIF Terminals

Each SIF terminal shall have two 9-pin socket (female) D-subminiature connectors for its SIF connection. The signals from one connector shall be routed to the other connector within the terminal. In addition, the two Power Return signals shall be connected together and the Cable Shield signal shall be connected to the terminal's chassis. The internal connections must have current-handling capacities equivalent to the wire gauge used in the SIF cable.

#### **Electrical Signals**

The three +28 V busses are used to distribute power through the network, together with the Power Return signal. MIL-STD-461E shall be used to define and test the voltage ripple and spike levels on these busses.

The CAN\_L and CAN\_H signals carry a fault-tolerant CAN data bus. The physical layer is governed by ISO 11898-3. The data link layer is CAN 2.0B, at 125 kbps. Higher protocol layers are supplied by the CANopen standard. For more information on CANopen, visit http://www.canopen.org/.

### **IMPLEMENTATION DETAILS**

#### **Power Consumers**

Most SIF terminals will draw all of their operating power from the SIF bus. This can be done most simply with a fuse and diode-OR circuit, such as shown in Figure 6. An electronic circuit breaker may be used to protect the fuses and to provide a more graceful response to overcurrent events.



#### **Figure 6: Power Consumer Interface**

### **Power Producers**

Power must be supplied to the SIF bus somehow, typically through one or more specialized terminals that have external connections to the satellite's battery or solar panels. The power producer terminals are responsible for turning the SIF bus on and off at appropriate phases of the mission. A simple fuse scheme for a power producer is illustrated in Figure 7.



**Figure 7: Power Producer Schematic** 

#### CAN Interface

There are a variety of CAN chips that will meet ISO 11898-3. Look for the words "fault tolerant" in the product description. Be sure to choose a part with controlled slew rate. The closed loop of the SIF bus does not provide any provision for impedance matching at its (nonexistent) ends, so sharp edges may travel many times around the ring before damping. This must

be mitigated by using parts that switch slowly and thus avoid edges. SpaceQuest has had good success with the Maxim MAX3055 part.

ISO 11898-3 uses distributed termination resistors in each terminal. A value of 2.2 k $\Omega$  for each resistor works well for SIF networks ranging in size from two to twenty nodes.

Occasionally it may be desirable to interface a legacy ISO 11898-2 CAN product to the SIF network. This can be done, provided that the device's 100  $\Omega$  termination resistor is disabled. Watch out for premade CAN cables that have the resistor built in. The two CAN standards will directly interface, provided that the bus has not experienced an open- or short-circuit failure. If this does occur the ISO 11898-3 parts will still be able to intercommunicate but the ISO 11898-2 devices will stop functioning.

### **CANopen Software**

There are a number of embedded CANopen software packages available that can be used in SIF terminals. SpaceQuest ultimately chose to write a custom CANopen implementation for those terminals with 8-bit microcontrollers. SIF terminals running Linux use a modified CANFestival stack.

Just as important as the embedded software is the ground test software. PCANopen Magic is a commercial program that will run on a Windows PC. Together with a USB-to-CAN adaptor from PEAK it allows a user to debug and command CANopen networks. It is not cheap, but is less expensive than developing such an application from scratch.

# FAULT TOLERANCE

A SIF bus is extremely robust. It is tolerant of any single fault, and in practice is usually able to survive several serious faults while remaining functional. Table 2 shows some of the potential faults, and their effects on a SIF bus.

As with any redundant spacecraft device, it is good practice to include built-in-test features to ensure that no failures have occurred before launch. SpaceQuest devices telemeter the states of all of their fuses, and read the ERROR bit from the ISO11898-3 transceivers to detect CAN wiring faults.

### **Table 2: SIF Fault Recovery**

Fault	Recovery
Open-circuit in wire	Ring topology provides
open encut in wite	any two nodes.
	Power producer fuses
Short-circuit from +28 V	blow. Two other +28 V
to Power Return	circuits remain
	operational.
Short circuit from CAN	ISO11898-3 transceiver
signal to +28V Power	automatically detects
Return or other CAN	these conditions and falls
signal	back to single-ended
signal.	transmission mode.
	Each message protected
Electrical paise on CAN	by 16-bit CRC, with
bug	automatic retransmission
bus	that is transparent to
	software.
Mishebaying software on	CAN controller hardware
terminal	prevents a node from
termina	'jamming' the bus.

# EXISTING SIF HARDWARE

SpaceQuest and its partners have developed a number of SIF-compliant devices. These are available for use on future missions, and will freely inter-operate with SIF devices from other vendors.

# General Purpose Terminal

The GPT is a generic interface between the SIF bus and spacecraft sensors, actuators and payloads. Large satellites may require a dozen GPTs, while a microsat can make do with one or two. The GPT provides a wide variety of I/O, as well as a modest onboard processor that can close some local control loops. A flexible current source/sink multiplexer allows direct connection to a variety of analog devices without need for any additional 'glue' components. All of the I/O is available on a single 50-pin D-subminiature connector.

Analog Inputs	Up to 12 channels (8 shared with digital), unipolar or bipolar, 16-bit ADC, 1 MHz sample rate
Glue-free	YSI thermistor, AD590 temp
interface to	sensor, RADFET, potentiometer
Analog Outputs	One 12-bit DAC
Digital I/O	8 bits of general purpose I/O
Sorial Duggog	Two RS-485 half-duplex
Serial Busses	One SPI
Power Output	Six half-H bridge +28 V switches
r ower Output	One adjustable DC/DC output

### **Table 3: GPT Capabilities**



**Figure 8: General Purpose Terminal** 

Figure 8 shows a GPT box, with the lid removed for clarity. Two SIF cables, with their distinctive purple patterned jackets, are also shown.

### **Deployment Terminal**

The deployment terminal can fire up to eight pyrotechnic cutters. It can also be used for other safety critical operations such as motor igniters and one-shot valves. In accordance with generally accepted practices there are separate PRE-ARM, ARM and FIRE inhibit devices and additional protections at the software layer.

A unique feature of the deployment terminal is its extensive built-in-test capability. Upon command it will execute a test and detect failed inhibit devices, open-circuit pyro wiring and pyros that are shorted to +28 V or to ground.



**Figure 9: Deployment Terminal** 

Figure 9 shows the deployment terminal PCB. The military circular connector carries the pyro ARM and

FIRE signals. The turrets on the left of the board attach to the SIF connectors (not shown).

# **Battery Charge Regulator**

This terminal connects to a spacecraft's battery and solar panels, and supplies power to the SIF bus. The battery charge state is monitored with onboard software, allowing different charging curves to be commanded on-orbit. Surplus electrical power is dissipated in the solar panels using four separate PWM shunt devices. The BCR connects to the satellite's separation switch, and keeps the SIF bus turned off until launch.



### Figure 10: Battery Charge Regulator

Figure 10 shows a BCR mounted in a SpaceQuest standard 10" tray. The two connectors on the lower right side carry the SIF bus. The circular connector on the left attaches to the battery. Solar panels plug into the four connectors at the bottom of the picture.

### **Dual-Speed Modem**

The dual-speed modem can connect up to three onboard computers to two radio transceivers. The low-speed transceiver typically operates at 9600 bps for command and telemetry, while the high-speed link can run up to 1.4 Mbps for payload data.

The modem also contains a discrete command decoder. When a particular bit sequence is detected on the lowspeed uplink, one of several pre-stored messages is transmitted on the CAN bus. This is useful for emergency resets and power cycles, or to switch between redundant strings.



Figure 11: Dual-Speed Modem

### **Power Conversion Distiller**

The distiller is so named because unregulated SIF power flows into the bottom of this modular stack, and clean switched regulated power comes out of the top. A distiller stack can hold up to nine modules, each of which can contain a DC/DC converter. The distiller can be used to supply regulated power for bus systems and payloads. It can also be reconfigured as a power producer terminal and used as a battery charge/discharge regulator. An onboard processor gathers telemetry from all of the power conversion modules and manages polyphase synchronization.



Figure 12: Distiller Stack (5 modules)

# Linux Computers

Two independent high-performance computer systems have been developed for SIF. The one computer is based on an industrial PC104 stack, while the other is a rad-hard custom design. Both run the Linux operating system, offer several gigabytes of solid-state memory, and interface to Ethernet and HDLC communication links in addition to CAN.



Figure 13: PC104 Linux Computer

# HARDWARE-IN-THE-LOOP TESTING

HITL testing is a very powerful technique for validating the control systems of an integrated spacecraft. It can be used to investigate attitude control, power control, and thermal control loops. In all of these cases it is difficult to put the satellite in its correct environment before launch. Instead, a simulation model of the environment and dynamics of the spacecraft is run on a special test computer. The outputs of the spacecraft's actuators are fed into this computer in real-time, and the model is used to generate simulated sensor readings which are passed back into the spacecraft to close the control loop.

On a traditional spacecraft, spoofing the on-board sensors can involve complex and expensive GSE. Using CANopen, however, a SIF-based spacecraft can easily implement a HITL test that will validate the onboard computer, software and communications in an environment indistinguishable from flight.

The key is the CANopen Process Data Object (PDO). A full description of this communication mode is outside the scope of this paper, but PDOs are fully described in the CANopen specification. In brief, PDOs allow a virtual connection between software variables on different terminals. When the variable is updated on one terminal, a CAN message is transmitted that sends the new value to the other linked terminals. This protocol operates at a low level and can be invisible to the application software.

Onboard control loops should use PDOs for data exchange between sensors, controllers and actuators, as shown in Figure 14. PDO links can be used even if two or more of these processes exist on the same hardware. For example, an ACS computer may have a direct link to an attitude sensor, but should nevertheless send the data out on the CAN bus as a PDO, and then reinterpret that same message as an input to its control algorithm.



Figure 14: Onboard Control-Loop

Figure 15 shows how a hardware-in-the-loop test can be easily performed on an integrated spacecraft. A test computer is plugged into the CAN bus, through the spacecraft test port. A CANopen command is issued to break the PDO connection between the sensor and the controller, and to replace it with a PDO connection between the controller and the test computer.



Figure 15: HITL Computer Connection

The test computer maintains a simulation model of the control system plant, be it the satellite's attitude, battery state of charge, or temperature. PDO messages from the controller to the actuators are monitored, and are used to update the simulation. For example, if the controller sends a "turn on" message to a heater, the simulated satellite's temperature should begin to increase.

The test computer transmits PDO messages containing the outputs of simulated sensors. These messages are received by controller, which continues the cycle by transmitting more command PDOs to the actuators. Meanwhile the actual sensors on the spacecraft continue to transmit their readings but are ignored by the controller.

HITL testing has proven to be a very useful way to understand the behaviour of onboard computer systems under representative loading and realtime constraints. SpaceQuest has used this testing to validate attitude control software. It has also proved useful to investigate power system response to simulated failures.

#### LIMITS OF SCALE

SIF networks are applicable to a wide range of satellite sizes, but there are bounds. As a satellite grows larger, the limited power handling capacity of the SIF cable and the limited data rate of the CAN bus may become a constraint. For very small satellites the physical size of the SIF connectors and the requirements for +28 V may be onerous.

Table 4 shows the maximum current that the SIF bus can deliver to a terminal. Most D-subminiature connectors are limited to 5 A per pin, although there are some that advertise a 7.5 A capacity. There are two power return conductors in each SIF cable, and they set the allowed current limit. Finally, the capacity is doubled because current can travel on one of two possible paths between the power producer and the power consumer terminals – either clockwise or counter-clockwise around the ring.

### Table 4: SIF Current Capacity

Conductor Current Limit	5 A
Power Return Conductors	2 / cable
SIF Cables	2 / terminal
Maximum SIF Current	20 A

The CAN bus runs at a baud rate of 125 kbps. This is mandated by the fault-tolerant physical layer. While ISO11898-2 CAN will typically run at 1 Mbps, ISO11898-3 parts are restricted to slower speeds. There is a large protocol overhead associated with CAN and CANopen. Table 5 shows the best case throughput of the bus. For transferring large amounts of data, the longest possible messages are used in order to reduce the overhead of header and CRC. The most efficient transfer mode available in CANopen is Block SDO, which carries data in 7 out of the 8 message bytes. Transactions using the simpler Segmented SDO protocol can expect only half of this throughput. Short telemetry and command requests will see even worse performance.

### **Table 5: CAN Data Throughput**

CAN Baud Rate	125 kbps
Maximum Message Length	108 bit periods
Message Rate	1157 Hz
CANopen Message Payload	7 bytes
Bus Data Throughput	8 kBytes/sec

The largest spacecraft to date that has used SIF has a length on the order of 5 meters and a peak power consumption of  $\sim$ 300 W. A dozen SIF terminals (half GPTs, half special-purpose) were used. The power handling was augmented by providing one power producer terminal at each end of the spacecraft, linked to the central battery with heavy-gauge wire. The CAN bus was more than adequate for control, but high-speed Ethernet busses were used to carry payload data.

On the small end, SIF has been successfully used within the traditional SpaceQuest microsatellite tray stack architecture. Future applications are being considered for spacecraft in the 20 kg range.

### MAGNETIC DIPOLE

The ring structure of the SIF bus makes it extremely robust against wiring and connector failures. However, it does raise the specter of current loops. There is no guarantee that the +28 V current and the Power Return current are balanced in a particular SIF cable. Slight differences in contact resistance may make more of the +28 V current flow through one branch of the ring, with the return current flowing through the opposite branch. This will create a DC current loop, and thus a magnetic dipole that may interfere with the spacecraft ACS system.

The simplest mitigation of this problem is to run both branches of the SIF ring physically close to each other. While keeping the topology of a circle, the physical projected area can be reduced and thus the magnetic dipole quenched. For satellites with more stringent requirements a specialized power producer terminal is required. This would either drive only one end of the SIF loop (and thus halve its current capacity) or transformer couple into both ends (with a complexity and efficiency penalty).

# CONCLUSION

Spacecraft electrical standards have been much discussed in recent years, as they hold the potential to reduce mission schedule and cost. A number of standards are already in common use: SSP, CAN, MIL-STD-1553, and SpaceWire to name a few. SIF is yet another standard, but it has unique features that merit its future use.

SIF provides a complete interface with both power and data. Its ring architecture eliminates the monolithic spacecraft harness and replaces it with a number of identical cables. Additional equipment can be easily added, even late in the satellite integration process. The SIF network is robust against failure. It is inherently easy to test, both because of its HITL capabilities and because only one type of GSE is required.

The benefits of SIF are not just theoretical. SpaceQuest has built a large spacecraft with a SIF backbone and has seen first-hand the time and cost savings. A large pool of off-the-shelf SIF hardware now exists to be used on future satellites.

SIF is an open standard, and is freely shared with the small satellite community. The reader is encouraged to implement it, to expand upon it, and to help put more SIF networks on-orbit. Cooperation in standards benefits us all.

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