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## FIBER-OPTICAL SENSING ON-BOARD COMMUNICATION SATELLITES

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### I. ABSTRACT

Striving constantly to reduce mass, AIT effort and overall cost of the classical point-to-point wired temperature sensor harness on-board telecommunication satellites, OHB System (formerly Kayser-Threde) has introduced the Hybrid Sensor Bus (HSB) system. As a future spacecraft platform element, HSB relies on electrical remote sensor units as well as fiber-optical sensors, both of which can serially be connected in a bus architecture. HSB is a modular measurement system with many applications, also thanks to the opportunities posed by the digital I<sup>2</sup>C bus. The emphasis, however, is on the introduction of fiber optics and especially fiber-Bragg grating (FBG) temperature sensors as disruptive innovation for the company's satellite platforms.

The light weight FBG sensors are directly inscribed in mechanically robust and radiation tolerant fibers, reducing the need for optical fiber connectors and splices to a minimum. Wherever an FBG sensor shall be used, the fiber is glued together with a corresponding temperature transducer to the satellites structure or to a subsystem. The transducer is necessary to provide decoupling of mechanical stress, but simultaneously ensure a high thermal conductivity.

HSB has been developed in the frame of an ESA-ARTES program with European and German co-funding and will be verified as flight demonstrator on-board the German Heinrich Hertz satellite (H2Sat). In this paper the Engineering Model development of HSB is presented and a Fiber-optical Sensor Multiplexer for a more flexible sensor bus architecture is introduced. The HSB system aims at telecommunication satellite platforms with an operational life time beyond 15 years in geostationary orbit. It claims a high compatibility in terms of performance and interfaces with existing platforms while it was designed with future applications with increased radiation exposure already in mind.

In its basic configuration HSB consists of four modules which are the Power Supply Unit, the HSB Controller Module, the Interrogator Controller Module and the Analog Front-End for the fiber-optical interrogation. The Interrogator Controller Module handles both, the electrical and fiber-optical sensor network. For the latter it is to be completed by the Analog Front-End. On this front-end, a tunable laser diode is implemented for the scanning of the FBG sensors. The reflected spectra are measured on multiple fiber channels and are then evaluated by use of a peak detection algorithm in order to obtain a precise temperature measurement. The precise operation of the photonic system on long terms can be guaranteed thanks to an in-orbit calibration concept.

### II. CURRENT STATE-OF-THE-ART-IMPLEMENTATION

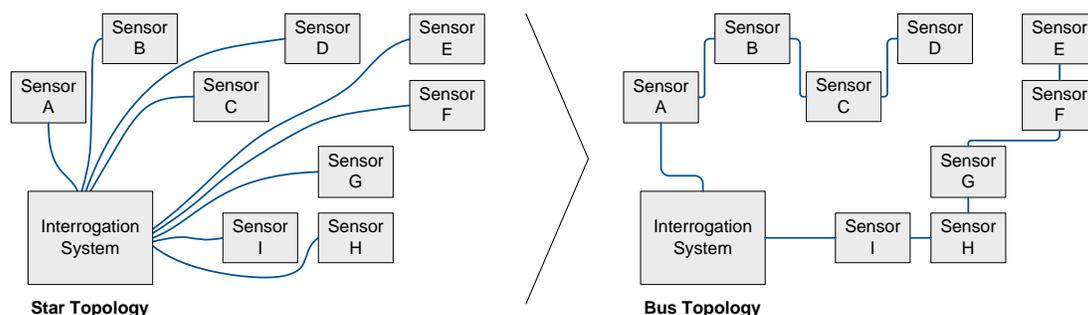
Up to now, satellite sensing systems for housekeeping require a complex wiring harness leading to a high mass and aggravated AIT activities (see Fig. 1). Flexibility and adaptability for different missions is not given with such a measurement system harness. The vast size of the harness mainly results from the point-to-point wiring concept of electrical temperature sensors. The use of sensor busses will result in a flexible system that saves mass and volume and is adaptable to different missions or satellite busses. The number of sensors does not influence the hardware design of the sensor interrogator as long as the maximum number of sensors per channels is not exceeded. Through the modular setup, additional modules can be plugged-in so that the maximum number of overall sensors is only limited by the number of slots in the chassis. The combination of the electrical I<sup>2</sup>C sensor bus with fiber-optic sensing allows to additionally reduce the complexity of the system. Several dozens of temperature sensors can be implemented in optical fibers and connected to the fiber-optical interrogator module.

Point-to-point wiring was the favorite concept for a long time, because it isolates faults in such way, that only one sensor is affected by e.g. a connectivity issue. Sensor bus concepts overcome this potential issue by taking care through improving wiring and sensor reliability on the one hand and making use of a redundant sensor bus on the other hand. By ensuring fault isolation in the redundant sensor devices, the sensor bus can be seen as single point of failure free. Additionally, the number of sensors for housekeeping is chosen high enough, so that according to calculated failure probabilities malfunctioning sensors do not impede a sufficient system temperature monitoring.



**Fig. 1:** Cable harness of a satellite with point-to-point wiring results in a complex cable harness.

In Fig. 2 on the left side, a state-of-the-art implementation of a sensor network is shown. The sensors are connected to a central data acquisition box. On the right-hand side, a possible implementation of the proposed sensor bus concept is shown, with the HSB system as central control and evaluation element. The sensors can be used to measure temperatures or any other physical quantity, if an appropriate transducer is foreseen. By using sensor multiplexers, the HSB system can be extended while the harness profits from the more decentralized bus structure because of the new hierarchical level.



**Fig. 2:** Point-to-point wired sensors of a state-of-the art sensor implementation (left) and a modern proposed bus topology (right).

### III. FIBER-OPTICAL SENSING

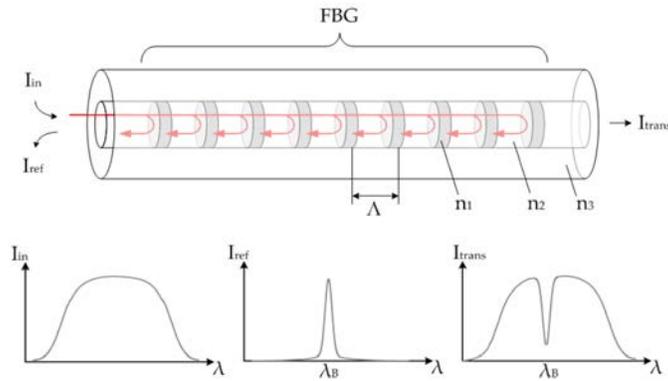
In this section a short introduction to fiber-optical sensing is given. For this type of sensing, a so called fiber-Bragg grating (FBG) is written into an optical single-mode fiber. The FBG sensor allows measurements of temperature and/or strain without any electrical signals. The grating structure, which is physically seen as a modulated refractive index change along the fiber axis, is usually written by a UV-excimer laser (193 nm or 248 nm) in a photosensitive fiber [2, 3]. After the writing process, a wavelength dependent band-stop filter is formed in the fiber, whereof the Bragg-wavelength can be approximated to:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \quad (1)$$

where  $\lambda_B$  is the Bragg-wavelength,  $n_{eff}$  is the effective refractive index and  $\Lambda$  is the grating pitch.

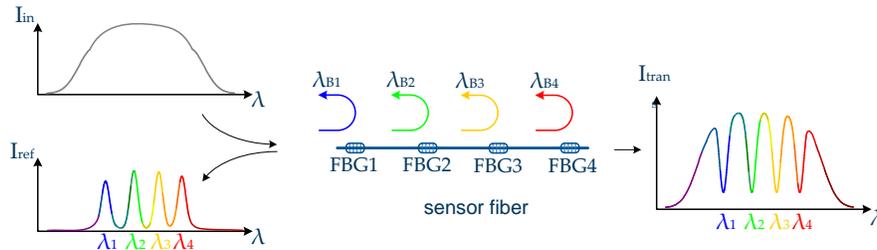
Only light with a wavelength close to the Bragg-wavelength  $\lambda_B$  is reflected back, the rest of the spectrum can pass the FBG without any noticeable loss. This is illustrated in Fig. 3.

The fact that light which does not correspond to the Bragg-wavelength can pass the FBG sensor, is used to build a multi-sensor wavelength-division multiplexing (WDM) system. In this way such a system, many sensors can be read out with a single interrogator module and without any additional active fiber-optical components. The Bragg-wavelength of each sensor in the fiber must differ from each other and must be adequately spaced in wavelength to avoid a mixing of the sensor responses due to strong differences in sensor temperatures. The principle of forming a WDM FBG sensor array is shown in Fig. 4.



**Fig. 3:** FBG with a pitch period  $\Lambda$  and reflected light  $I_{ref}$  (top). A broadband optical light  $I_{in}$  is coupled into the FBG, and only light with the Bragg-wavelength  $I_{ref}$  is reflected. The transmitted light  $I_{trans}$  shows a dip at the wavelength position where the reflection occurs (bottom).

The number of embedded FBGs is limited by the optical broadness of the illuminating light source and by the necessary spectral bandwidth of each sensor. The laser can be tuned within a bandwidth of approximately 40 nm. By taking into account the fact, that one sensor needs (margins included) a bandwidth of approximately 4 nm to cover the full temperature range from  $-100^{\circ}\text{C}$  to  $+100^{\circ}\text{C}$ , the maximum number of sensors per string is given to ten sensors.



**Fig. 4:** FBG sensor array is illuminated with a broad light source (top left) and the transmission (right) and reflection spectra (bottom left) are shown.

The shift in Bragg-wavelength according to equation (2) can be split up in two terms. The first term is affected by the applied strain to the sensor and the second term is affected by changes in sensor temperature. In silica fibers, the temperature-dependent change in the Bragg-wavelength is given per 95 % by the temperature-sensitivity of the refractive index  $dn/dT$ , whereas the change in the fiber length due to the thermal expansion coefficient  $\alpha$  amounts only to  $\approx 5\%$ .

The presented design uses a laser with a central wavelength at 1550 nm, so the shift from the initial Bragg-wavelength due to strain changes  $\Delta\varepsilon$  and temperature changes  $\Delta T$  can be computed to [2]:

$$\Delta\lambda_B [pm] = 1.209 \frac{pm}{\mu\varepsilon} \cdot \Delta\varepsilon + 10.338 \frac{pm}{K} \cdot \Delta T. \quad (2)$$

When the sensor is mounted on a strain insensitive platform on which only temperature changes affect the shift in the Bragg-wavelength, then a conclusion with respect to the temperature at the sensor location can be made. An appropriate transducer design is introduced in [7].

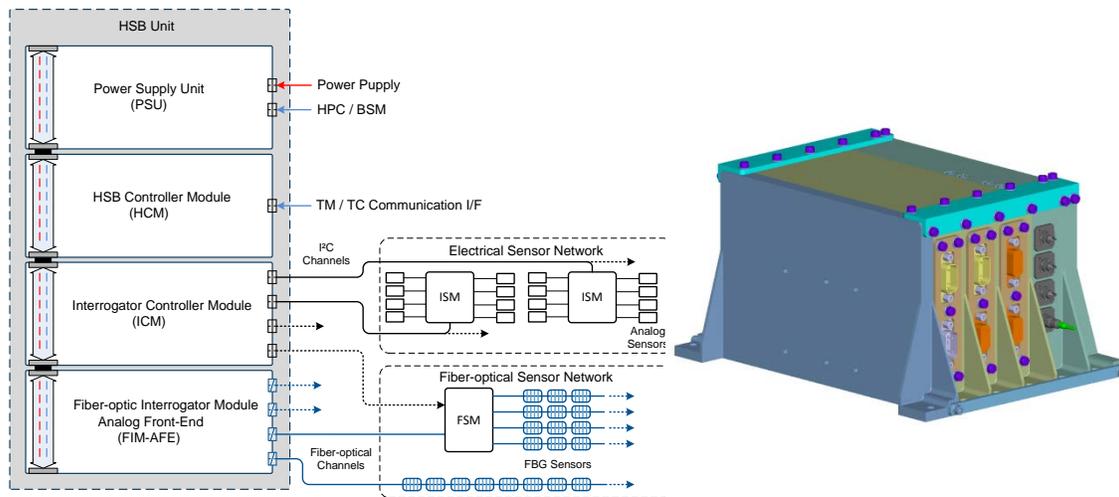
#### IV. HYBRID SENSOR BUS SYSTEM

##### A. System Description

The Hybrid Sensor Bus (HSB) is a modular sensor system [1, 4] which is able to read out electrical sensors over the PC bus and fiber-optical sensors based on FBG sensing technology. The system itself consists out of four different modules as can be seen in the block diagram Fig. 5. The system is supplied with power from the satellite bus over the power supply unit (PSU) which is also responsible for the handling of the standardized high power command (HPC) for on/off switching. The communication with the platform is directly handled by the HSB controller module (HCM) over the MIL-STD-1553B bus. The address of the HSB system can easily be changed by an external MIL-STD address connector which makes the system more flexible. The interrogator controller module is the core of the HSB system, it is firstly responsible for measuring the four PC bus channels and for managing the corresponding sensor data and secondly it is responsible for interfacing with the fiber-

optical analog front-end (AFE) module controlling the digital-to-analog converters (DAC) and analog-to-digital converters (ADC). For querying fiber-optical sensors, the FIM analog front-end board is indispensable. This module holds the laser diode, acting as light source for the spectral measurements, the photodiodes for the detection of the, by the FBGs, reflected light a polarization switch for the compensation of birefringence effects of the FBGs and other passive optical components such as isolators and couplers. The functionality and most important properties of each module is explained in the next sections. The HSB system is a modular system, which means that also other modules with other functionality could be implemented. The single modules are stacked together and are mechanically fixed onto the base plate and on the top side of the frames. To increase the number of sensors, further modules can be added.

The HSB system uses the RS485 bus for internal module communication. The data transported over the bus are mainly measurement data which are queried by the HCM from other modules. The system uses a single master concept. The internal RS485 system bus foresees the usage of a fully redundant system, so each module can be doubled for use in a redundant, single point of failure free configuration.



**Fig. 5:** HSB system overview with the four different modules (left) and a picture of the 3D CAD model (right).

The electrical and mechanical properties are summarized in Tab. 1. The maximum power consumption is the worst case value which is expected at warming up from the minimum temperature of  $-40^{\circ}\text{C}$  and is primarily caused by the temperature controller of the laser diode. The target mission is planned to be in a geostationary satellite orbit, so the lifetime of 15 years and a high reliability figure for a redundant configuration were the design goal. For the system design, a detailed radiation analysis was carried out, to identify the maximum radiation loads inside the HSB box.

Parameter	Value
Mass	3.5 kg
Envelope Dimension	160 mm x 118 mm x 224mm
Number of IPC sensor strings	4 strings with 25 sensors each
Number of fiber-optical sensors	2 strings with 10 to 12 FBGs
Measurement rate	1 Hz nominal, 10 Hz fast mode for single sensors
Resolution	$\pm 0.5^{\circ}\text{C}$
Operational Temperatures	$-20^{\circ}\text{C} \dots +65^{\circ}\text{C}$
Lifetime	15 Years
Radiation load	$< 100\text{krad}$ (inside box, 15 a)
Power Avg	16.7 W
Power Max	27 W

**Tab. 1:** Electrical and mechanical properties of the HSB system

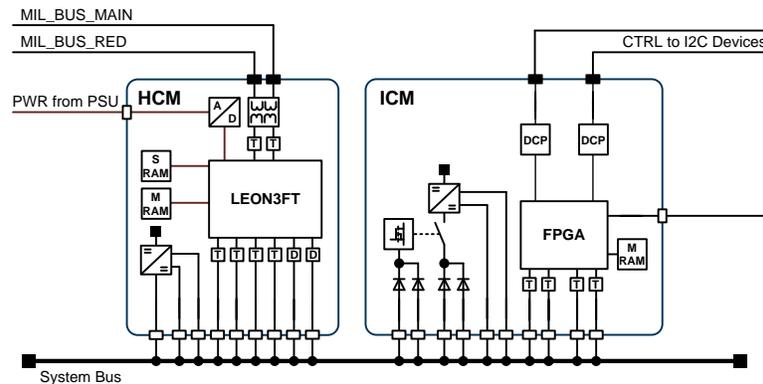
#### B. Power Supply Unit (PSU)

The power supply unit is responsible for the generation of the intermediate power of 12 V used by the other modules. Each module generates its own necessary low voltage power rails, so the PSU holds only one main DC/DC converter with a maximum power of 35 W. The nominal input voltage of the PSU is 50 V, but also other bus voltages such as 28 V are possible with minor modifications. Also included in the PSU are the input and output filter for the converter and a housekeeping unit for the 12 V power rail and temperature monitoring

of the converter. The module is controlled by the platform over high power commands to switch the HSB system on or off. For status feedback to the platform, main and redundant binary switch monitoring (BSM) signals are implemented.

### C. HSB Controller Module (HCM)

The HSB controller module holds the functional blocks to control the entire HSB system in terms of operational states and data transfer. In this module, also the MIL-STD-1553 decoding hardware is implemented, which interfaces with the satellite platform. The HCM controller is a powerful LEON3FT-based processor using a real time operation system (RTEMS). The module generates all necessary power rails local onboard from the 12 V supplied from the PSU. A schematic overview is given in Fig. 6 (left).



**Fig. 6:** Functional block diagram of the HSB controller module (HCM, left) and the interrogator controller module (ICM, right).

The most important functional properties of this module are summarized here in short:

- LEON3FT processor
- MRAM acting as boot loader storage
- MRAM for application software storage
- Gold / Silver Image for application software
- SRAM
- All memories are EDAC protected
- MIL-STD-1553B interface logic with external address selector
- Firmware upload possibility over MIL-STD-1553B

### D. Interrogator Controller Module (ICM)

The interrogator controller module is responsible for reading out the I<sup>2</sup>C sensor lines and controlling the analog frontend's ADCs and DACs to perform spectral measurements. Again, all necessary power rails are generated onboard from the 12 V intermediate voltage. The core of the ICM is space-proven, radiation tolerant and single event upset immune field programmable gate array (FPGA), which holds the state machine for controlling both types of interrogator, electrical and fiber-optical.

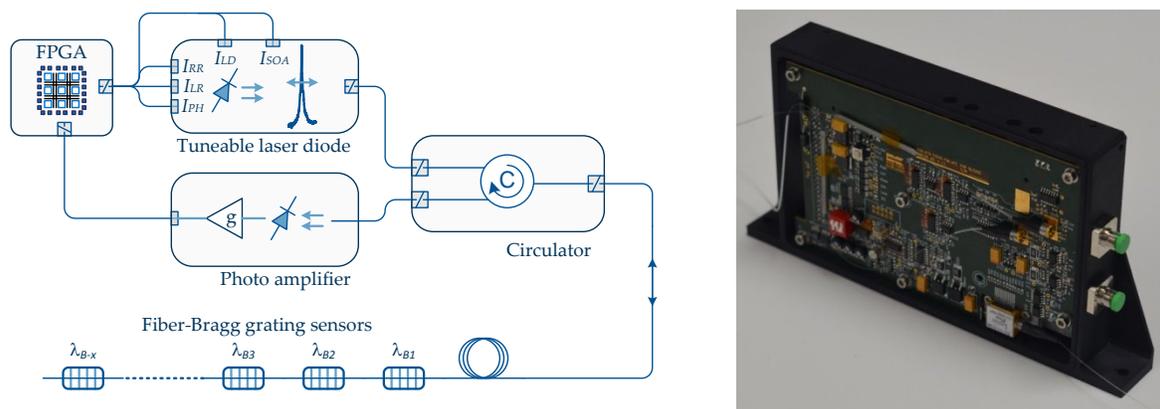
For the electrical sensor bus, four I<sup>2</sup>C channels are implemented onboard the ICM. Each channel has a supply voltage rail of 5 V for powering external sensors. The power rail is protected inside the HCM against overcurrent events by a latch-up circuit. The sensor address and the dedicated commands to read out the sensor are stored in lists, which can be configured on ground as well as in orbit. In addition, the module also has an interface to the fiber-optical interrogator analog front-end board (FIM-AFE). In this way, both sensor busses, the I<sup>2</sup>C-bus on the one side and the fiber-optical bus on the other side are controlled efficiently by a single FPGA solution. The laser diode is controlled in wavelength by the use of data stored into a look-up table (see next section).

### E. Fiber-Optical-Interrogator Module, Analog Front-end (FIM-AFE)

The interrogator module is based on a modulated grating Y-branch (MGY) tunable laser. This type of laser diode can be tuned from a wavelength of 1528 nm to 1568 nm with the help of three input currents. In the digital control system, a look-up table is stored wherein the relation between laser wavelengths and reflector currents is implemented. During a measurement cycle, the tunable laser scans through the full spectrum and the reflected light from the FBG array is measured by a photodiode. The reflected intensity signal is assigned to the

output wavelength again in terms of a look-up table (LuT). Afterwards, the setup wavelength and the reflected signal are evaluated in the FPGA by dedicated algorithms. First, a peak is detected and the sample points which are relevant for the further processing of the data are buffered. Then a second algorithm computes the Bragg wavelength of the detected peak. When the shift in Bragg wavelength in relation to a reference value is determined by the FPGA, the assignment to a physical temperature can be performed [8].

The current design of the analog front-end (AFE) is shown on the right-hand side of Fig. 4. The tunable MGY laser diode is controlled by the FPGA which is implemented in the Intelligent Controller Module (ICM). Dedicated DACs convert the digital control signals to sweep the MGY laser diode through the wavelength band in order to cover the optical spectrum spanned by the FBG sensors. Two ADCs with multiplexed inputs convert the analog signals measured by the photo diodes of the external FBG channels on the on side and provided by MGY laser diode as reference signals on the other side. For stable operation the MGY laser diodes internal thermo-electric cooler is controlled by a bipolar temperature controller circuit.



**Fig. 4.** Fiber-optical interrogator based on a tunable laser with control FPGA, optical circulator, fiber-Bragg grating sensors and photo amplifier (left), FIM-AFE breadboard in prototyping frame (right)

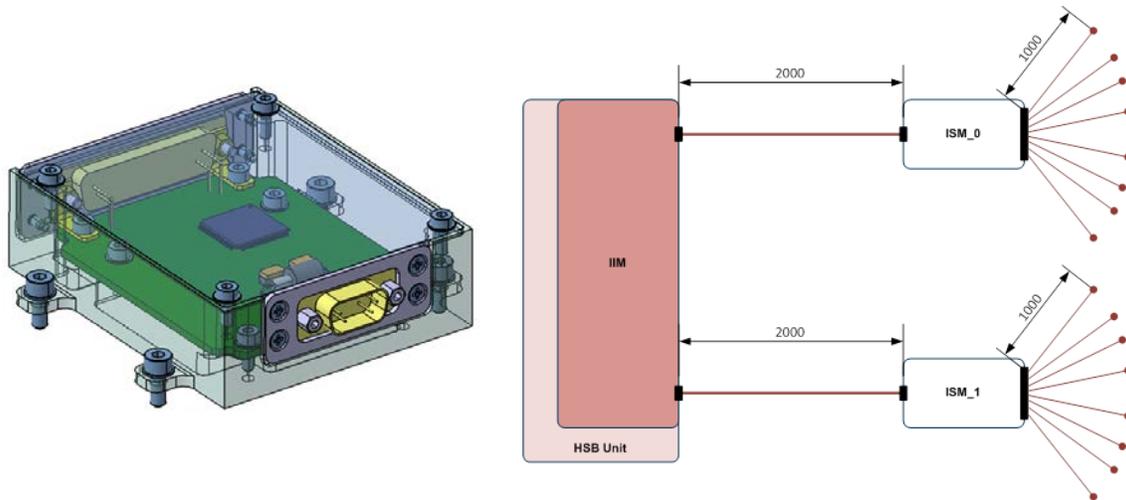
A long term wavelength drift of the MGY laser diode caused by radiation and other sources is to be compensated for stable operation. In the HSB breadboard phase, the use of the internal etalon of the laser diode was foreseen to be used for drift compensations. The etalon curves do not show any wavelength shifts due to radiation and could therefore be used for the calibration of the MGY laser diode [5]. In addition the laser was tested against radiation with gamma rays (up to 100 krad TID) and neutrons up to  $(10^{12} \text{ n}_0/\text{cm}^2)$  showing only a shift of about 50 pm [6], which can be corrected by recalibration.

## V. SENSOR EXTENSION

### A. I<sup>2</sup>C Sensor Multiplexer (ISM)

The I<sup>2</sup>C Sensor Multiplexer (ISM) is an intelligent interface between the analog electrical temperature sensors and the I<sup>2</sup>C bus handled by the ICM. Since no qualified digital temperature transducers are available yet, the ISM is introduced in the HSB design for the in-orbit verification of the electric sensor bus based on the I<sup>2</sup>C protocol. Up to 12 analog electric sensors as e.g. NTC or Pt1000 sensor signals are read out and digitized by the ISM. The digitized temperature values are then provided to the central HSB system via I<sup>2</sup>C bus. The module works as a sensor concentrator, one ISM for example can be attached on a payload, monitoring up to 12 sensors and sending the data back to the HSB system. The harness from the ISM to the HSB system contains only four wires, so the mass impact and routing effort are very low. The resolutions is planned to be better than  $\pm 0.5 \text{ }^\circ\text{C}$  for an operational temperature range between  $-40 \text{ }^\circ\text{C}$  and  $+65 \text{ }^\circ\text{C}$ . The envelope dimension is given to  $100.1 \text{ mm} \times 95.0 \text{ mm} \times 30.5 \text{ mm}$ .

A picture of the 3D model of the ISM is given in Fig. 6 on the left. The sensors are connects over D-sub shell connector on the back side, whereas the I<sup>2</sup>C interface is connected on the front of the ISM. A possible usage of the ISM on a scientific payload where two ISMs are used is shown on the right of Fig. 6.

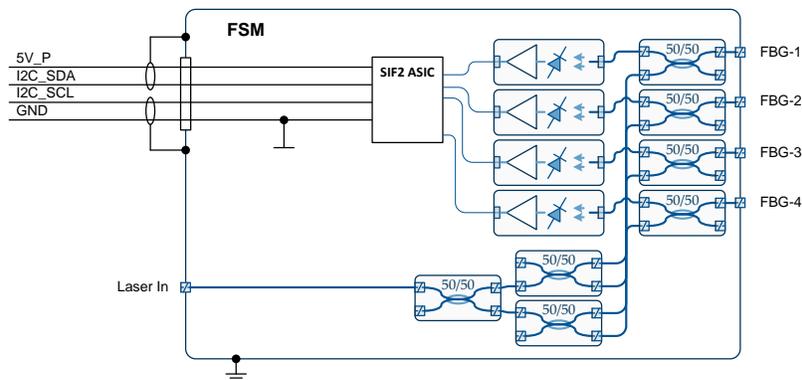


**Fig. 7:** Picture of the 3D model of the ISM (left) and possible usage of the module in combination with the HSB system (right)

**B. Fiber-Optical sensor Multiplexer (FSM)**

The fundamental architecture of the FSM is shown in Fig. 6. To increase the number of sensors to be interrogated by HSB and to enhance the bus network capabilities, the fiber-optical sensor multiplexer has been introduced. The multiplexer is an HSB-independent data concentrator for sensor network extension, e.g. in exposed parts of the satellite. The laser light generated by the analog front-end is guided to the multiplexer wherein it is split to multiple fiber channels, each allowing up to ten FBG sensors. In the multiplexer, a mixed signal ASIC digitizes the FBG peak reflections measured by the photo-diodes of each channel. The digital spectrum is then read via PC by the Interrogator Controller Module whereon the temperatures are calculated and packed for telemetry to the platform.

Assuming that the FBG sensors are mounted on or embedded in a satellite panel, the FSM acts as a data acquisition unit for these sensors. The reflected light is measured, converted inside the FSM and sent to the HSB system. The laser light is generated by the FIM-AFE. With the FSM, an additional 4x10 FBG sensors can be measured, which opens up new possibilities for the sensing system.



**Fig. 8:** Fiber sensor multiplexer (FSM) block diagram

**VI. BENEFIT OF THE HSB SYSTEM AGAINST THE STATE-OF-THE-ART IMPLEMENTATION**

**Handling Harness Handling:** In state-of-the-art satellites, lots of temperature and slow varying signals for housekeeping have to be measured. The number of sensors can reach up to 1000 sensors, redundant sensors included. This increases the harness complexity and the weight. The complexity renders the harness very inflexible in case of design changes. By introducing a sensor bus system the harness would be dramatically decrease because no point-to-point wiring is used.

**Mass Effect:** In a standard telecommunication satellite, a temperature measurement point is often measured by four sensors due to redundancy and reliability requirements. So a three out of four weighting is done for which four sensors are necessary. Assuming a median wire count per sensor of 2.6 wires/sensors (for high-precision measurements, Kelvin probes are used), this results in a worst case of 10.4 wires per sensor position. In a sensor

bus configuration, the length between each sensor is smaller than in the point-to-point wiring concept, reducing the mass impact dramatically.

**AIT Effort:** The high number of sensors and the resulting increase in wire count makes the harness integration more complex and increases the effort. Adding a new sensor or changing the sensors position comes along with a partial or complete disassembly of the harness. Also sensors for ground testing must be assembled and integrated. In a sensor bus topology, the implementation of additional sensors is less time-consuming and the sensor can be attached to any position in the sensor string.

**Low Flexibility:** As mentioned before, adding additional sensors is nearly impossible due to the strict harness design and the point-by-point wiring topology. This low flexibility has a negative impact on the satellite design. This flexibility can highly be improved by adding intelligent, decentralized sensor multiplexers to the electrical sensor bus. The configuration inside the HSB system is based on digital sensor lists, so adding sensors or changing conversion factors is very easy.

**Integration:** In sum, an exemplary target platform requires up to 500 cables for standard point-to-point wiring of the sensors. For a smart panel with integrated FBGs only 16 fibers (wires) would be necessary. The wire count is reduced by more than 90 %. The average length of a point-to-point wired sensor in a satellite is assumed to be 4 m in comparison to the length of 0.8 m in a bus configuration. Less wire length will reduce the integration effort additionally. The integration effort is assumed to be reduced by a factor of 50 %.

**EMI/EMC Problems:** Fiber-optical sensors and fibers can be considered immune to EMI problems due to insensitivity of light to the electrical fields present in a satellite.

## VII. IN-ORBIT VERIFICATION APPROACH

The HSB system will fly onboard the German In-Orbit-Verification satellite “Heinrich-Hertz” (H2Sat) funded by the German Aerospace Agency. For this mission, the current engineering model will be rebuilt as a proto-flight model to prove the concept of sensor bus topologies and fiber-optical sensing onboard geostationary satellites. A sensor network consisting out of 16 fiber-optical sensors divided into two strings and two ISM modules will be implemented in addition to the presented HSB system. The sensors which are read-out by the HSB system will be mounted next to the platform sensors to allow a comparison between both sensor types. The fiber-optical sensors will be mounted on special developed transducers given in [7].

In addition the HSB system will be able to supervise temperatures within a certain range and trigger alarm functions when values are seen out of range. Also averaging functions will be tested. This is a further outlook into future, where the satellite management unit might be unloaded from the task of housekeeping measurements, taking over this task to decentralized units such as the HSB system.

## VIII. ACKNOWLEDGEMENT

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