Entwicklung eines drahtlosen und energieautarken Sensorsystems in industriellen Anwendungen für eine hohe Anzahl von Sensormodulen

Development of a wireless and self-sustaining sensor system in industrial applications for a high number of sensors

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Kurzfassung

Im industriellen Umfeld von Fertigungsanlagen bietet sich für eine Vielzahl von Messaufgaben zur Prozessüberwachung die Nutzung eines Thermoelektrischen Generators (TEG) zur Energieversorgung eines drahtlosen Sensormoduls an. Dieser Beitrag beschreibt die verschiedenen Aspekte bei der Entwicklung eines energieautarken Systems am Beispiel Kühlmittelüberwachung. Dabei soll eine kontinuierliche Druck- und Temperaturmessung an jedem Spritzgießwerkzeug eines Kühlmittelverteilsystems erfolgen. Weiterhin ist eine drahtlose Übertragung der Daten zu einer zentralen Steuerung erforderlich, wobei sich über 50 Sensormodule einen Funkkanal teilen müssen. Die Energie zum Betrieb des Sensormoduls liefert ein TEG aus der Temperaturdifferenz am Kühlmittelrohr und der „warmen" Umgebung. Zur Erreichung der stabilen Energieversorgung wurden verschiedene TEG und Aufbauweisen mit kontrolliertem Wärmefluss evaluiert und optimiert. Zusammen mit einem spezifischen Powermanagement ist eine robuste und industrietaugliche Lösung entstanden.

Abstract

The industrial environment of a manufacturing plant is a suitable field of application for a variety of measuring tasks for process monitoring on the use of thermoelectric generators (TEG) for the power supply of wireless sensor modules. This paper describes the various aspects of the development of a self-sustaining system using the example of coolant monitoring and control. Subject is a continuous pressure and temperature measurement at each mold of a cooling system. Furthermore, wireless transmission of data to a central base station is required, wherein more than 50 sensor modules have to share one radio channel. The energy for operation of the sensor module is provided by a TEG using the temperature difference between the coolant tube and the "warm" environment. To attain a stable energy supply, various TEG and construction practices with controlled heat flow have been evaluated and optimized. In combination with a specific power management a robust, industry-compliant solution has been realized.

1 Introduction

Self-sustaining wireless sensor systems supporting process measurement technology have the advantage that they are maintenance free and easy to install in a process environment. Nevertheless such systems have to fulfil high demands on availability, measurement interval, communication security and data throughput.

The presented development addresses the monitoring and control of a cooling fluid within the manufacturing process for producing parts by injecting material like elastomers, polymers, metals or glasses into a mold (injection molding). The principle of the process is given in [1]. As parameters to be observed pressure and temperature of the coolant were given. The coolant is used to shorten the time between injection and opening the tool. Controlling the reflowing coolant allows to open the mold (figure 1) as early as possible.

The task of the development was to design a sensor system for a high number of about 50 measuring points spread over an area of about 2000 square meters. Due to occasional exchanges of machine parts, e.g. molds, handlers etc., a wired installation did not come into account. Furthermore the difficult access to measuring points for maintenance, a battery driven approach was prohibited. So it was obvious to implement wireless and self-sustaining sensor modules.

Figure 1 Photograph of typical mold
(Source Fraunhofer IMS)

In principle two sources for local energy supply were usable for energy harvesting: the flow of the coolant or the temperature difference between the coolant and the ambi-

ent surrounding. The use of the flow energy would require a kind of a micro turbine and in order to that rotating parts with restricted life time. Therefore the choice falls on a thermoelectric generator as an energy harvester.
The considered temperature range is defined from -20 °C up to 125 °C.

2 Concept Design

2.1 System architecture

The system consists of a PC as control computer, one or more base stations and a large number of self-powered sensors. As shown in figure 2, each sensor is assigned to a dedicated base station.

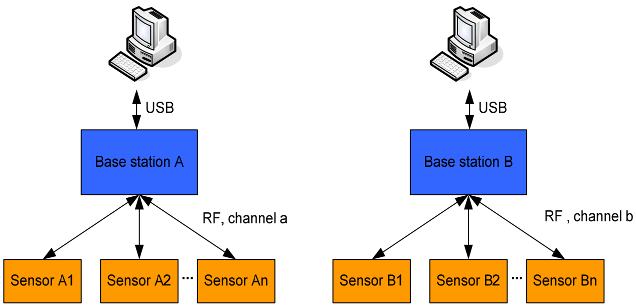

Figure 2 System architecture

Limited by the wireless protocol, a base station can manage up to 80 participants. If more sensor nodes are needed for a special application, a second base station for further 80 participants must be added. In that case a new communication cell is created with its own carrier frequency similar to the technique known from mobile phone systems.

2.2 RF link and protocol

Very high demands are made on the wireless communications in industrial applications. The communication, especially in case of process control tasks, has to perform real-time operation. Although the amount of data per sensor is small, a large number of participants have to share the limited capacity of a channel.
For such applications stochastic primitive multiple-access methods, such as "Aloha" or "slotted Aloha" [2] are not suitable because of their high probability of collision with many participants in the system and the consequent lack of real-time capability.
From mobile phone systems synchronized time slot management (TDMA - Time Division Multiple Access) is known that results in guaranteed time slots for many participants by collision avoidance methods [2]. The system presented here shows the implementation of this technology, which is dimensioned for a large number of participants and a fixed data throughput. Due to the fixed allocation of time slots (see figure 3), this approach has real-time capability and is well suited for industrial applications that exceed sporadic data communication, such as continuous transmission of parameters for monitoring and control purposes.

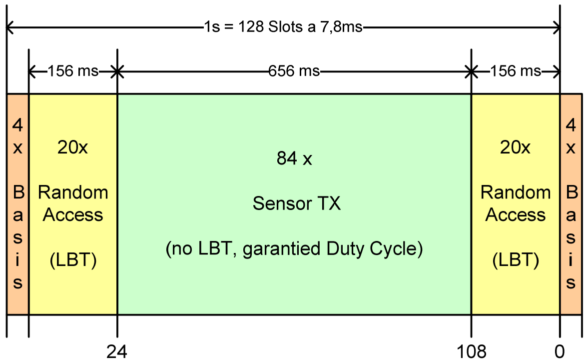

Figure 3 TDMA frame structure of the RF protocol

Within the "basis" slots (figure 3) the base station sends a synchronization message containing additional information and configuration data. The "Random Access" slots are used as allocated time slots for the following transmission of sensor data. For time critical measurements, the base station can allocate several slots to one sensor modules in the "Sensor TX" phase. A second "Random Access" phase was added to the frame structure. Within this phase sensor modules can join the communication to a later point in time due to power aspects in power management. Especially during startup it is possible, that sensor modules need longer periods for recharge of the buffer capacitors.

2.3 Power consumption of an energy self-sufficient module

In wireless sensor systems a carefully energy management has to be designed in order to achieve the best performance of the system. Figure 4 shows the involved building blocks in a block diagram.

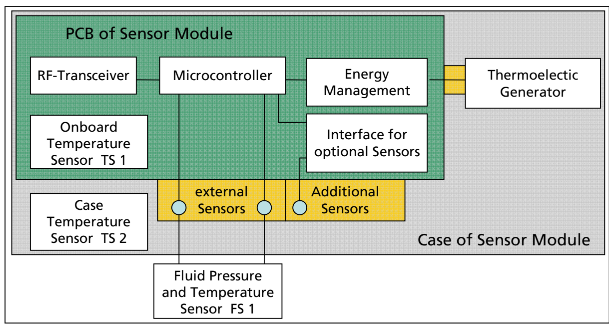

Figure 4 Block diagram of the sensor module

The largest consumers of energy are the radio front-end and the sensor. The total energy demand has to be calculated from the demand of one measuring and transmission cycle and the cycle rate itself. Therefore high-efficient components and a low sampling and transmission rate are advantageous for the design of an energy-independent system. But in this case of a process monitoring application high measurement and communication rates are required.
Based on the hardware concept the following figures for energy consumption can be made. The measurement and

transmit phase (Sensor TX) is estimated with a duration of 100 ms, where:

- the measurement takes 80 ms,
- the sending takes 10 ms and
- the remaining jobs take 10 ms; this includes set-up, calculation and storage tasks of the micro-controller.

The calculated power consumption for this cycle is 3.1 mWs.

For the evaluation of the system two sample rates should be considered: 1/second and 1/minute. With a standby power of 36 µW and the used sample rate the average power consumption can be determined. The power for the operation of one hour results in dependency to the sample rate to:

a) 1/second: $E_{sec} = 7.67$ Wh
High sample rate for operation in injection operation and low latency requirements.

b) 1/minute: $E_{min} = 0.25$ Wh
Low sample rate in other operation phases, e.g. after ejection and handling.

Compared to the capacity of a primary battery cell - about 5 Wh for a AA size type – it is obvious, that a battery based approach is less promising.

2.4 Power supply by TEG energy harvesting

For the use of energy harvesting various technologies such as rectification of radio waves, conversion of kinetic energy by piezoelectric transducers, conversion of rotational energy by dynamos, solar cells or thermoelectric generators are available. For the application considered here a temperature difference provided by the process to be monitored was chosen as an appropriate energy source. A thermoelectric generator (TEG), also known as seebeck generator, converts the temperature difference between the cold coolant and the warm environment directly into electric energy for the supply of the sensor node. Reference [3] gives a comprehensive survey of the seebeck effect and the function of thermoelectric generators. Figure 5 shows the embedding of a TEG in the power supply of a sensor module.

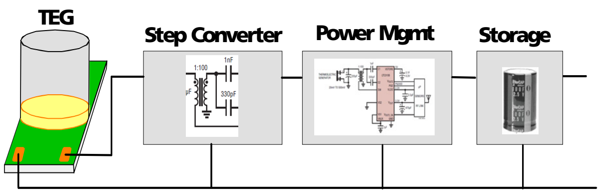

Figure 5 Embedding of the thermoelectric generator (TEG) into the sensor modules power supply.

The output voltage of the TEG has to be transformed to one or more stable DC operating voltages. Depending on the used components, typical values for these voltages are 1.8 V, 3.3 V or 5.0 V. The power management unit supervises the operation voltages and indicates the power status to the processing unit.

A storage unit is optional for sensor modules. It is used to bridge either current peaks or power gaps and has to be designed carefully due to side effects. Especially in the startup phase, the storage unit can cause undesired behavior because of delays in charging.

During the concept phase of the presented development two TEGs were evaluated:

i) TGP-751 supplied by Micropelt [4]:

The TGP-751 is a packaged TEG in thin-film, solid state technology. The package is easy to be integrated into the mechanical design of the housing and mounting into the application environment (see figure 6).

Seebeck voltage is $V_{sbi} = 110$ mV/K.

Thermal resistance: $R_{th} = 18$ K/W.

Size (l * w * h): 15 mm * 10 mm * 15 mm.

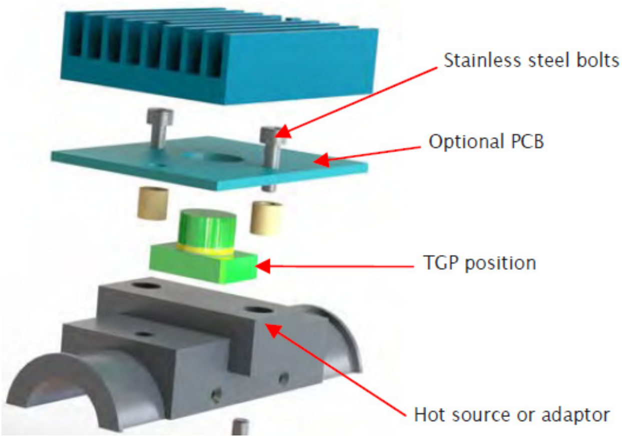

Figure 6 Example of integration of the TGP-751 (Source: Micropelt)

ii) Power-Strap supplied by O-Flexx [5]:

The used sample of Power-Strap is an unpackaged TEG in thin-film, solid state technology with 20 TEG chips. The TEG chips are bonded on a flexible stripe (see figure 7). The TEG can easily be adapted to the demand of power by cutting the length of the stripe, the number of determine the power. The package design and mounting into the application environment is more complex.

Thermal resistance per chip: $R_{th} = 124$ K/W.

Thermal resistance per meter: $R_{th} = 0.7$ K/W.

Size of used strap (l * w * h): 250 mm * 20 mm * 1 mm.

(values were taken from Preliminary Data Sheet O-Flexx "Power Strap" not published till press time of this article)

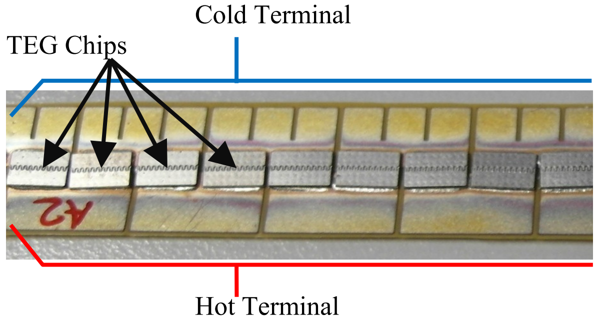

Figure 7 "Power-Strap" TEG (Source: O-Flexx)

The following figures 8, 9 and 10 are showing the test setup for the Power Strap evaluation. The stripe is fixed at the hot and cold side by pressing the thermal contacts against hot and cold heat conductors between the tube for coolant fluid and a dissipator. The dissipator is not shown in the figures.

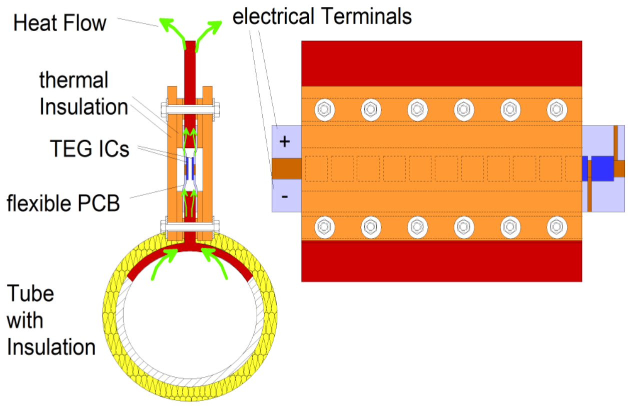

Figure 8 Example of integrating the “Power-Strap” test setup as cross section and side view

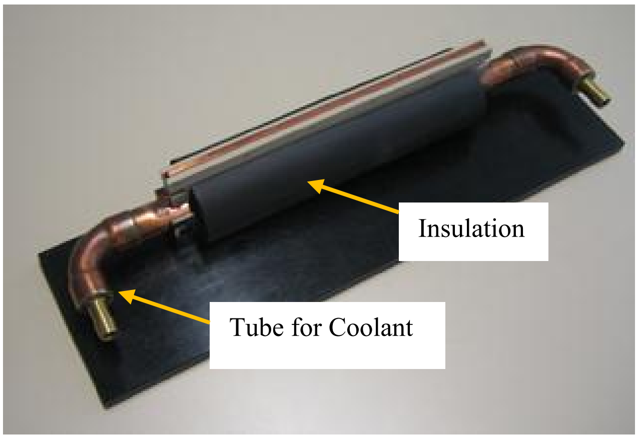

Figure 9 Photograph of “Power-Strap” test setup (Source: Fraunhofer IMS)

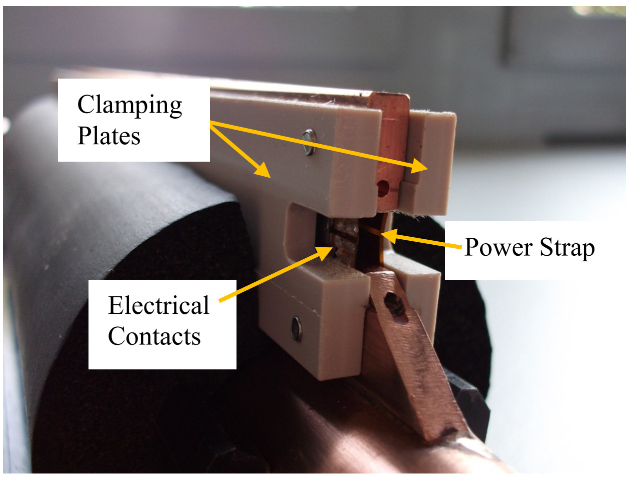

Figure 10 “Power-Strap” clamped between hot and cold terminals (Source: Fraunhofer IMS)

The subject of the mechanical design is to concentrate the heat flow between the fluid (source) and the ambient surrounding (sink) through the chips of the TEG. In practice a part of the heat flow goes parallel to the TEG chip path from source to sink. The behavior can be modelled in an equivalent circuit.

To limit the not usable heat flow in parallel to the flow through the TEG chips a careful mechanical design with selection of suitable materials has to be done. For the “Power Strap” the design is shown in figures 8 to 10, where figure 8 shows the heat flow in principle and figure 9 and 10 the realization with insulation materials.

After setup of both TEG test installations the open circuit voltages were measured over temperature difference. Figure 11 demonstrates the characteristics of the TEGs. The Micropelt TGP-751 indicates a good representation of the theoretical linear relationship between temperature difference and voltage output. The internal apparent resistance and the voltage level allow an easy impedance matching to the following circuitry. The input voltage of the DC-DC converter should cover a range from 0.15 V to 2.5 V. This range enables the design of an energy efficient converter.

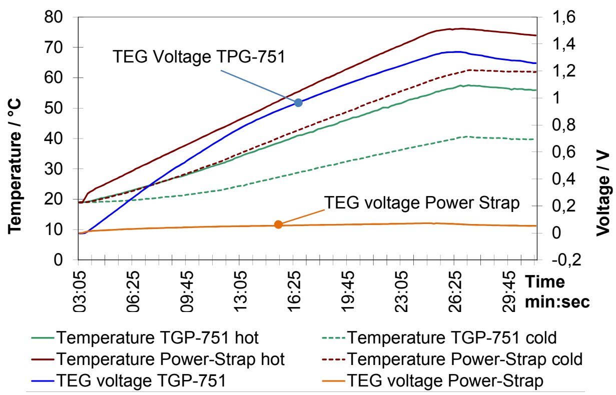

Figure 11 Comparison of open circuit voltages of TEGs

The “Power Strap” TEG is initially planned to be used for medium power applications in the power range of a few watts. So the internal apparent resistance is designed for higher currents and the output voltage results in the sum of TEG chip output voltages. The short stripe used here comprises a relative low number of chips and so the output voltage of the TEG is low as well. For the further development the TGP-751 was chosen because of its higher output voltage.

3 Realization

3.1 Mechanical design

Due to the harsh environment in industrial applications, a housing with a protection class better than IP 65 is designed. The cold-side temperature provided by the process medium (coolant) is fed from the bottom to the thermal generator; the heating of the warm side of the generator is realized by capturing the heat radiation of the environment using a special shape of the housing itself (see figure 12).

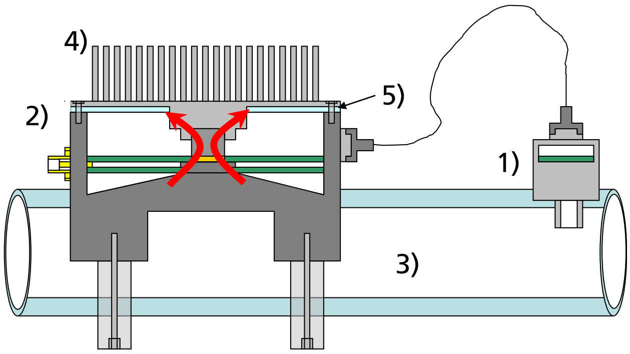

Figure 12 Mechanical assembly of the sensor module

1. Pressure and temperature sensor
2. Electronics and thermoelectric generator (TEG)
3. Coolant (heat sink)
4. Ambient temperature (heat source)
5. Thermal insulation and seal

The two housing halves are thermally decoupled from each other by means of a thermal insulator, which also ensures the tightness of the housing. The sensor is mounted externally to the measuring point using a separate housing. The use of an external sensor results in the possibility of an easy system expansion to other measurement scenarios by adding further external sensors.

3.2 RF communication protocol

The radio protocol between a base station and the sensors is designed for a capacity of up to 80 nodes that can transmit measurement values every second. The realization of the time slot assignment method for this number of participants is a great challenge because of the very small amount of energy provided by the thermal generator and the temperature drift of the internal clock sources. The system shall be able to be used at a maximum ambient temperature of 125 °C, which greatly restricts the selection of usable components.

The implementation of the radio protocol includes special low-power synchronization algorithms which guarantee an optimum load profile matching with the current power generation. The protocol structure and other security measures make sure that after the synchronization phase any clock frequency drift is compensated over a temperature range from -20 °C up to 125 °C and thus each participant maintains its dedicated time slot for the wireless communication telegrams. With respect to the strong limitations and boundary parameters such as poor energy allocation, large number of participants, high measuring and transmission rate of up to 1 Hz and a wide temperature range of up to 125 °C the total system obtains its real-time capability and functionality.

4 Results

During the verification the system is tested on a specially built test environment. Figure 13 shows the results of such a measurement performed with realistic environment parameters. Due to easier setup the hot and the cold side were swapped and fluid delivers the heat energy. In the red curve the monitored temperature of the medium is shown; the dark blue curve shows the ambient temperature. The difference of these two temperatures is shown in the green curve.

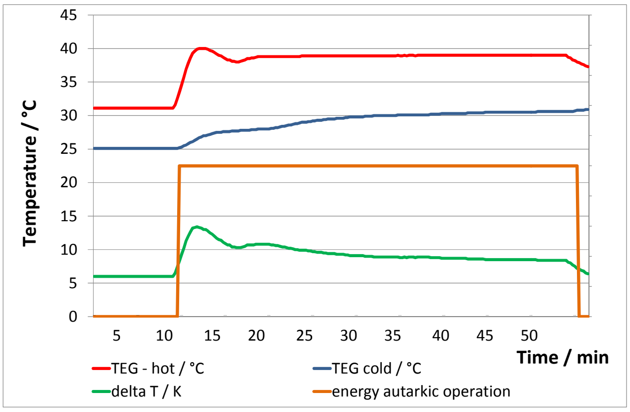

Figure 13 Operation test results

Based on the orange curve showing an internally generated signal that indicates the self-powered operation it is evident that a self-sustaining operation is possible if the temperature difference has an amount of at least 8 Kelvin. This value refers to a measurement and communication interval of 30 seconds. If the application provides a higher temperature difference, the number of measurements and transmissions can increase to more than one measurement per second.
In order to evaluate the startup phase and to monitor the charging of the buffer capacitors as well as the transmission rate, an auxiliary power source in form of a battery was temporary added to the sensor module. Figure 14 shows the startup sequence of the sensor module operating with a higher sample and transmission rate of 1 sample per second.

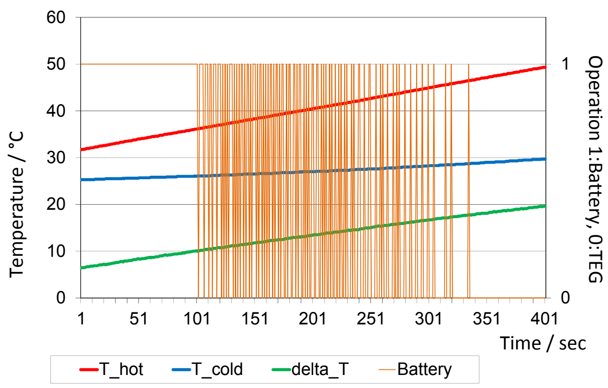

Figure 14 Operation test in startup sequence

At the beginning of this sequence the temperature difference is too low to power the sensor module. The supply comes from the battery. This corresponds with the orange curve of figure 14, this binary signal indicates battery operation when the signal is high (1) or TEG operation when the signal is low (0). With the increasing temperature difference at the TEG the sensor module achieves a transitional phase where the module is partly powered by the TEG. Due to current peaks caused by the RF transmitter the power management switches back to battery operation for a short bridging time. Only after exceeding a threshold in temperature difference – in the present prototype design of 17.5 °C – the module is completely powered by the TEG. This behavior was considered to optimize the power management and to obtain a robust startup operation. With the also measured temperature difference the transmission rate is automatically adapted and so unintentional resets are avoided.
Figure 15 shows the realized sensor module to be mounted at the coolant tube.

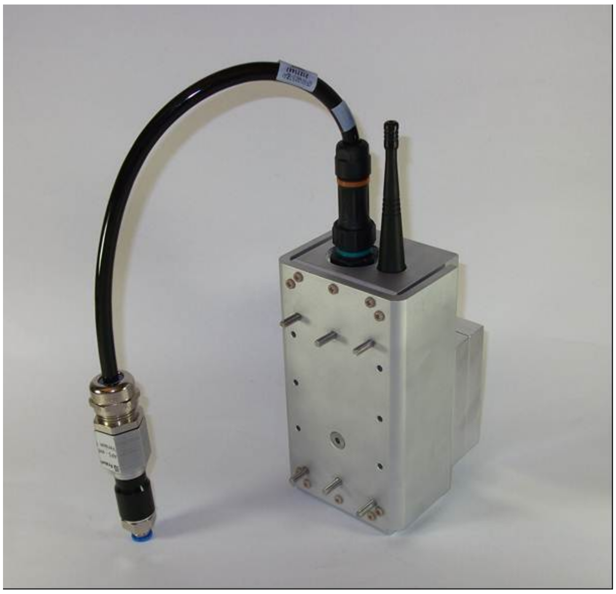

Figure 15 Realized sensor module with pressure and temperature sensor plug (Source: Fraunhofer IMS)

5 Outlook

Up to now the system was tested under laboratory conditions as well as in an industrial environment using a number of 20 modules. In this configuration the system fulfils the given requirements. After completion of field test, that is currently running for a period of three months, further modules will be manufactured and added to the test environment in subsequent steps.
For the development of the next system generation a smaller housing and a more efficient power management is planned.

6 References

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