Miniaturized self-sufficient sensors and actuators for factory applications

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1 Introduction to the project

MIKOA stands for “Miniaturised self-sufficient components with reliable wireless communication for automation systems”. This is a composite project which forms part of the microsystems research program of the Federal German Ministry of Education and Research (BMBF).
Within this project, a consortium of institutes and companies has developed autonomously-operating components and systems for the factory and process automation of the future. Key topics are the miniaturization of function modules and the development of an interference-immune and reliable wireless communication system based on new or optimised transmission methods.

1.1 State of the art/motivation

The state of the art in automation is represented by a variety of functionalities which are used to create highly-complex installations and production plant. The variety of functions is increasingly continuously in line with increasing levels of automation. New official directives governing working safety and rising requirements with regard to quality and added value (e.g. plant availability), or in short the comprehensive controllability of production processes, to a increasing degree require continuous monitoring of all process parameters. This trend has led to a continuous increase in the demand for additional sensors and in certain cases redundant actuators for safety purposes.
The high level of plant complexity also means higher costs for planning and installation work and places correspondingly high demands on communications technology with regard to data volume and availability. **Fig. 1** shows an example of this.

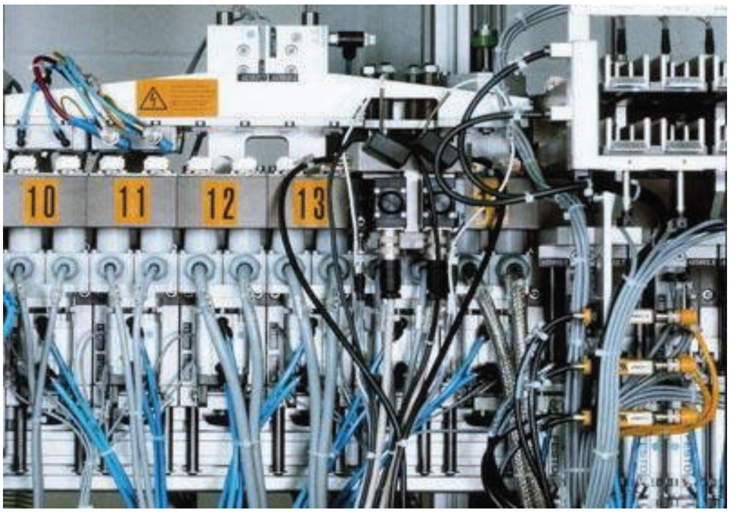

Fig. 1 Example of complex wiring in production plant (picture: Festo)

For moving, rotating or mobile installation components, contact and connector systems are required which are subject to wear and costly to operate, such as commutator rings or cable conduits. Furthermore, cables used under harsh environmental conditions involving, for example, extreme motions or temperature stresses represent a potential source of faults or else need to be installed in appropriately heavy-duty and costly variants. Servicing and maintenance costs may be considerable due to lack of accessibility and the static installation present. A final factor is that expansion or conversion of installations of this kind may be possible only to a limited extent or only at considerable cost in terms of money and planning time.

1.2 Vision

The installation topologies described in 1.1 have initiated a process of reflection which is driving forward the further development of production installations in order to meet future requirements with regard to automation technology.
The automated factory installations of the future will consist of independent cells which will operate largely autonomously and offer a high level of flexibility with regard to modifications such as conversion and expansion.

The efficiency and reliability of factory and process automation installations of this kind depends to a large extent on the amount and quality of data available. This is usually provided by wired sensors and is available only locally at the

end of the cable connection. This in turn means restrictions in terms of flexibility and application areas (mobile units and moving/rotating installation components).
These restrictions can be resolved by using wirelessly communicating components, systems and units, thus creating new possibilities for extensive system or installation diagnosis thanks to globally available and networkable information. This leads to improved understanding of overall processes and creates potential for the optimisation of costs and quality. In this context, the energy efficiency of a production installation is of particular importance.
The following factors are crucial for the establishment in the market of a competitive concept of this kind:

- Realisation of an interference-immune and real-time-capable wireless communication
- Development of miniaturised and maintenance-free sensor/actuator units which allow efficient operation with autonomous or mono-energy power supplies.

The development and optimisation of these basic technologies and components is the main aspect of the work of the consortium involved in the MIKOA project.

1.1 Main aspects of work

On the basis of concrete market and customer requirements, concepts for miniaturized and wirelessly networked components for use in factory and process automation and diagnosis are designed, implemented and verified by means of appropriate prototypes. These components are energy-autonomous sensors or sensor/actuator modules used to control processes or carry out system diagnosis. Energy-autonomous in this context means having a decentral electrical power supply from ambient sources, for example kinetic process energy (impact, shock, vibration) or energy obtained from light by photovoltaic means. The potential power delivery of these sources will generally not adequately satisfy the requirements of the described sensor or sensor/actuator modules, with the result that use is also made of the pressure and flow energy of any fluidic process media present. Energy-autonomous therefore means the elimination of all wired electrical interfaces outside the system boundaries. In order to make this goal possible and at the same time achieve a balanced energy budget, it may be appropriate to combine different types of converters and energy storage devices. This requires the development of an energy management system which provides firstly conversion of the different voltages and secondly appropriate energy distribution in accordance with overarching priorities.
In order to allow wireless communication to be realised and to achieve the necessary market acceptance for wireless solutions in competition with wired systems, the wireless solutions must be comparable to wired systems in terms of reliability, size and ability to provide maintenance-free operation and also offer significant advantages regarding installation and suitability for mobile applications.
It is also necessary to further develop wireless technologies to meet the requirements of the automation sector, particularly with regard to defined real-time behaviour and energy efficiency.

It therefore follows that the priorities with regard to project work must be as follows:

- Miniaturisation of sensors and function modules for wireless communication, components for data processing and energy supply with the aid of microsystem methodology
- Development of suitable wireless modules which allow the implementation and operation of new data transmission methods with an appropriate level of reliability, real-time capability and energy efficiency.

2 Autonomous systems

As mentioned in Chapter 1.3 and shown schematically in **Fig. 2**, systems can be called autonomous if they have no wired energy or communications interface. It is thus possible, within the limits of a given component or system, to deviate from the usual standard specifications for factory or process automation, since units of this kind are intrinsically capable of being encapsulated or being produced as enclosed systems. In concrete terms, this means, for example, a free choice of internal system voltages in order to optimise the efficiency of the unit as much as possible and reduce losses caused by voltage conversion. This also favours use in environments with higher-level requirements, for example areas with extreme temperatures or with potentially explosive atmospheres.

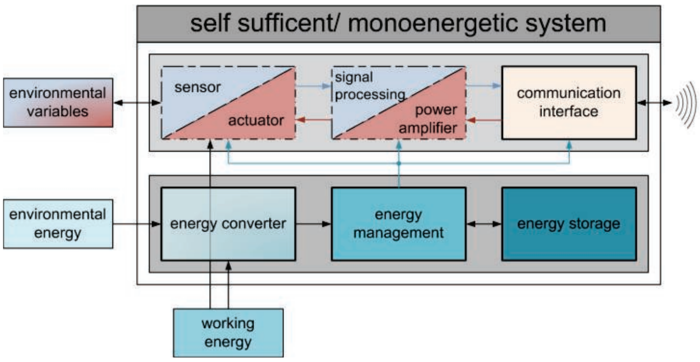

Fig. 2 Schematic representation of an autonomous system (source: Festo)

One major core technical problem is, however, to ensure a reliable power supply for sensors and sensor/actuator units when there is a strict definition with regard to the power consumption or functionality of the unit in question. A discrepancy arises here between the energy which can be accumulated within a certain time window and the power consumption of the unit.

In order to develop meaningful solutions to this problem, it is necessary to conduct analysis and solution development on a holistic basis. This means, for example, that first the provision of the necessary energy/power must be optimised. This can be achieved by improving the efficiency of the converters or by using several different energy sources (converter arrays). For example, it is possible through the use of buffering and several energy sources to bridge periods in which particular energy sources are not available.

It is also necessary to optimise the efficiency of sensors, actuators, function modules for wireless communication and data processing components. Finally, energy management offers ways of using efficient strategies to activate or deactivate targeted components or functions.

2.1 Examples of applications

Two application cases have been defined for the realization of autonomous units. These differ significantly in terms of their requirements for wireless communication and energy supply.

In the area of plant monitoring, it is of interest to be able to determine process variables such as system pressure or air consumption with the aid of a p-Q sensor unit, as shown in **Fig. 3**. These variables can be measured and transmitted at lengthy intervals or when triggered by state changes and are not relevant to the control system. The longer measuring-cycle intervals thus result in lower energy consumption. With regard to energy sources, the main focus here is on the pressure and flow energy of the medium of compressed air. This approach is highly suitable in view of the fact that the emphasis is on determining the process parameters of the medium, the pneumatic interfaces are therefore defined and the energy density of the compressed air offers sufficient potential for the decentral provision of electrical energy. However, to cover the case in which an adequate level of pneumatic energy is not available, for example due to system malfunctions, a solar cell is used to provide sufficient energy to permit low-power operation with limited communication capacity.

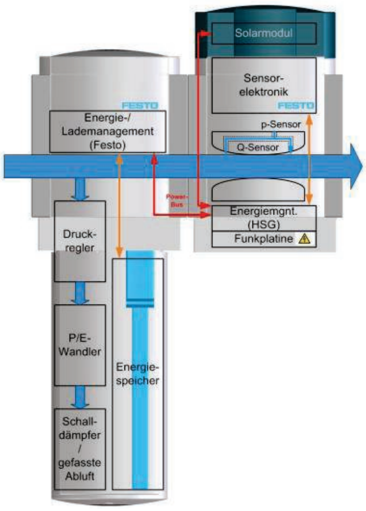

Fig. 3 p-Q sensor unit for plant monitoring

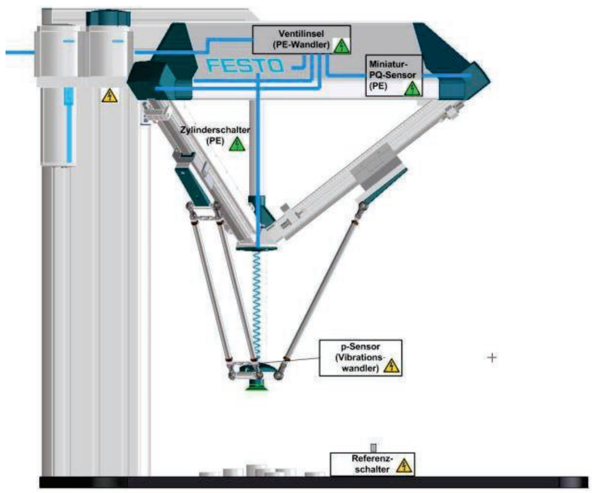

Fig. 4 Sensor units in a handling process (sources: Festo)

Applications involving high-speed handling systems, such as those commonly used in factory automation, are more complex in energy terms. **Fig. 4** shows a study as an example. The characteristic data which is determined, such as positions, pressures and flow rates, is mainly relevant to the control system and is measured and transmitted with a high sampling rate. This requires reliable transmission and wireless communication with deterministic and real-time capability.

These stringent time and reliability requirements in turn mean a relatively high power consumption which cannot normally be met by familiar energy-harvesting concepts such as thermal converters, vibration converters or solar cells. For this reason, the emphasis here is once again on the exploitation of energy from the medium in combination with a solar cell.

For this application case, too, a p-Q sensor unit has been developed which exploits the residual energy in the exhaust air of individual pneumatic drives. The emphasis here is not only on the energy requirements already described but also on the miniaturisation of the overall sensor unit, as shown in **Fig. 5**.

There is also a need in handling systems of this kind for diagnostic and monitoring functionality. It may therefore be appropriate to install sensor units in combination with, for example, kinetic converters. This is shown in **Fig. 7** through the example of a pressure sensor which monitors the vacuum of a suction cup. The kinetic energy of the handling unit in the form of impact or shock energy can be converted by inductive, capacitive or piezo-electric means and made available in the form of electrical energy.

Fig. 5 Miniaturised p-Q sensor units (source: Festo)

2.2 Hardware platform

In order to allow the creation of sensor and converter clusters, it is appropriate to define a uniform hardware platform, which can be used both as a sensor node for high-speed handling processes and for monitoring purposes. This is shown in **Fig. 6**. The platform includes a microprocessor unit, which organises wireless management, sensor signal processing and energy management. The platform can be combined with HF transmitters as appropriate to the radio protocols required, based on 868 MHz for monitoring and on 2.4GHz for high-speed handling processes. A uniform power and signal interface allows the connection of any desired converter and energy storage modules, which can be combined freely as desired.

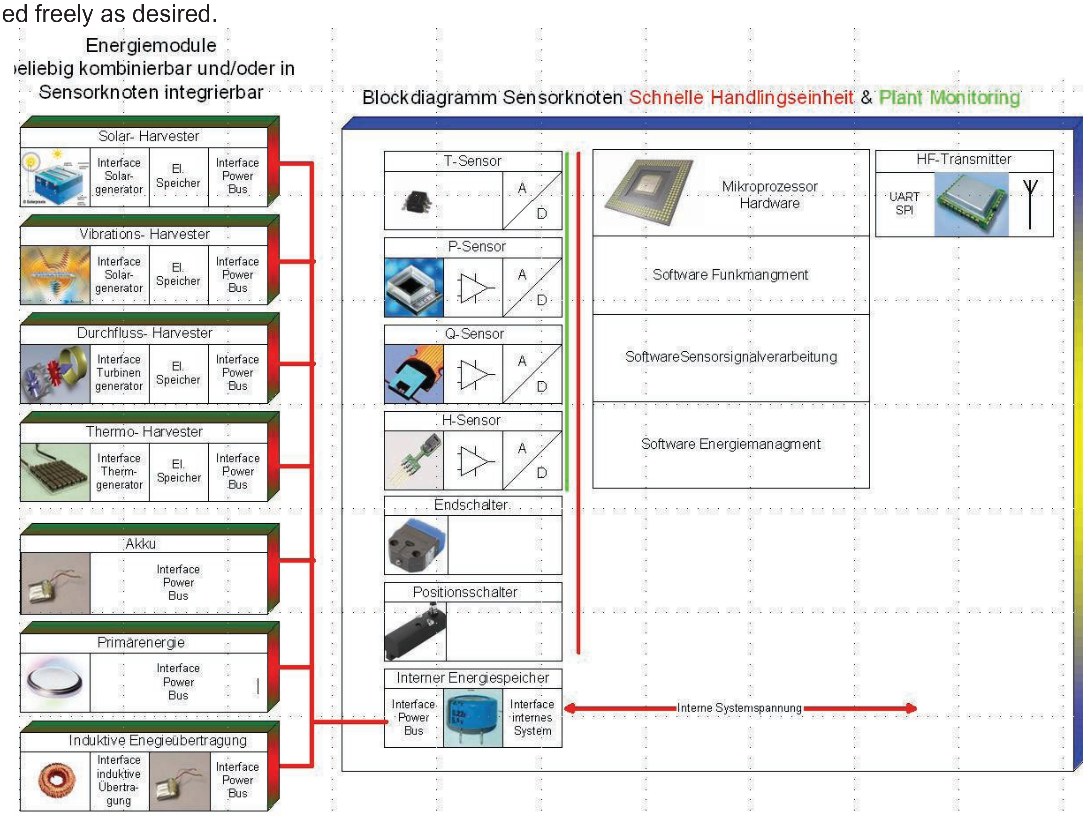

Fig. 6 Block diagram of sensor node (source: HSG IMIT)

2.3 Energy supply

Various conversion principles with different power ratings are used to meet the energy requirements of different application scenarios. These include, for example, electrodynamic converters which can, for example, be fitted via adapters to the front end of a handling unit in order to exploit acceleration energy and provide a local electrical energy supply. A selection of proposed converters is shown in **Fig. 7**.

Fig. 7 Examples of dynamic converters (source: HSG IMIT)

Kinetic converters of this kind can generally be excited by impact or shock energy, individually or in pulsed form or by vibration and can be of harmonic or discontinuous design. The power levels which can be achieved vary between a few µW and several 100 mW and depend heavily on the conversion principle used and the moving vibration mass. Inductive, capacitive or piezoelectric conversion methods can be used. In selecting a method, regard must be had to the achievable output voltages and their suitability for use. In general, kinetic generators need to be matched to specific application cases. An ideal generator can be selected for a given application with the aid of simulation tools on the basis of known dynamic excitation profiles.

Amorphous solar cells and so-called P/E converters are also used in order to provide a continuous electrical power supply in low-power operation. Their advantage is their relatively large bandwidth in terms of the meaningful exploitation of usable light energy, which is important particularly with indoor applications and artificial light. **Fig. 11** shows a study with an autonomous pressure sensor with wireless communication which is powered with the aid of solar cells. A further major feature of the project is the development of a solar cell energy management system which allows, among other things, maximum power point tracking, which involves adjustment for the optimum working point as a function of radiation intensity and temperature.

Fig. 8 Design study for a pressure sensor with an autonomous solar energy supply (source: Festo)

The most important conversion principle in terms of power output makes use of the fluidic pressure and flow energy from the compressed air supply system or the residual energy from the exhaust air of pneumatic systems. This energy is converted in pneumatic lamellar motors or turbines **(Fig. 9)** into rotary motion energy, which is then converted by generators into electrical energy using the inductive principle.

The general physical difference between pneumatic lamellar motors and turbines is that, with the former, drive torque is generated by the presence of a differential pressure, which is to say a force acting on different areas, while in the case of turbines it is generated by the impact of flowing medium on an impeller wheel. Levels of power output and efficiency comparable to pneumatic lamellar motors are achieved by turbines only at considerably higher rotary speeds, due to the differences in physical operating principles, which places special demands on the generator. On the other hand, the fact that the differential pressure required for starting is relatively low means that turbines can be operated with the exhaust air of pneumatic systems, allowing exploitation of unused residual energy without significant reactive effects on the system.

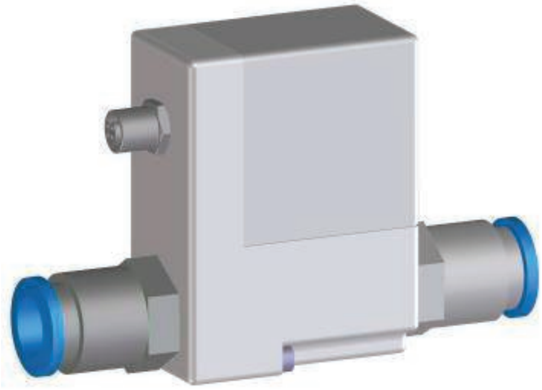

Fig. 9 Design study for turbine generator unit (source: Festo)

The power output possible with the lamellar motor generator unit which has been developed lies in the double-digit wattage range. Operation is chiefly intermittent. This means that the unit, when fed from the compressed air supply network for a certain time, delivers considerably more power than the application requires. This excess power is buffered in an energy reservoir which the application can access whenever the conversion process is not operating. Once a defined quantity of energy has been drawn from the energy reservoir, the conversion process is re-started.
The turbine generator unit behaves differently. Depending on its geometrical design, this delivers power in the low double-digit wattage range. As this type of converter unit is generally installed in the exhaust air of pneumatic systems, the level of flow energy which is applied to it may vary widely, a fact for which allowance should be made in the dimensioning of the system.

2.4 Communication

The parameters of the addressed automation areas make wireless communication one of the greatest challenges of the project. Two different wireless protocols are used to accommodate varying needs. For fast deterministic and reliable communication such as is required in handling processes, use is made of a proprietary protocol in the 2.4 GHz band which has specially developed and optimised for applications of this kind. This protocol is useful for local field communication in production cells. It provides narrow-band frequency-agile data transmission. In simple terms, it is able by using the frequency-hopping method to avoid conflicts with other wireless systems and thus co-exist with these without collisions. At the same time, it imposes only a very slight burden on the medium “wireless channel”. The typical latency period for a sampling of over 100 wireless devices is less than 10 ms, making it possible to conform to the real-time criteria customary in the automation sector. Thanks to the implemented safety mechanisms, the typical packet loss rate in data transmission is 1e-9, an order of magnitude which is comparable to a wired connection. This characteristic variable is the ratio of lost data packets to transmitted data packets. In order to illustrate the ability of this protocol to co-exist with WLAN, **Fig. 10** shows its narrow-band transmission in the bandwidth gaps between the WLAN frequency bands.

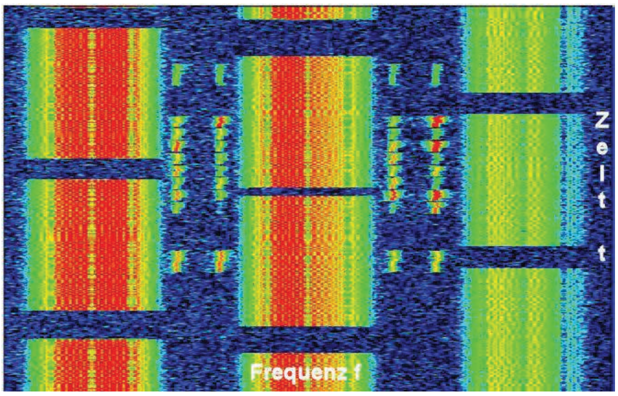

Fig. 10 Frequency/time graph (source: HSU/ Festo)

For non-time-critical monitoring functions in complete production installations, a protocol based

3 Summary

In view of their increased complexity and the large volumes of data involved, the factory installations of the future will require new groundbreaking concepts which allow better management of production and handling processes. The composite project MIKOA, which has the aim of developing miniaturised autonomously-operating sensor and actuator systems which communicate wirelessly, will make a major contribution to these concepts. The main work within this project will be the miniaturisation of all the necessary function modules and the development of suitable wireless modules for the implementation of reliable and energy-optimised transmission methods.