Monitoring of Hazardous Scenarios using Multi-Sensor Devices

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Abstract— **The combination of different types of sensors to multi-sensor devices offers excellent potential for monitoring applications. This should be demonstrated by means of four different examples of actual developments carried out by Federal Institute for Materials Research and Testing (BAM): monitoring and indoor localization of relief forces, a micro-drone for gas measurement in hazardous scenarios, sensor-enabled radio-frequency identification (RFID) tags for safeguard of dangerous goods, and a multifunctional sensor for spatially resolved under-surface monitoring of gas storage areas. Objective of the presented projects is to increase the personal and technical safety in hazardous scenarios. These examples should point to application specific challenges for the applied components and infrastructure, and it should emphasize the potential of multi-sensor systems.**

Keywords-monitoring; multi-sensor device; hazardous scenarios; data-fusion

I. INTRODUCTION

The safe operation in hazardous scenarios (conflagrations, chemical incidents, etc.) and handling of dangerous substances (toxic, explosive, harmful for human and/or the environment) often requires the usage of sensor systems, e.g., to measure the status of a process, to enable early warning in case of an accident, or to evaluate the situation after an accident happened. In many cases not only one measuring variable is sufficient for a comprehensive evaluation of such scenarios, demanding for technical solutions with integration of multiple types of sensors. Technical enhancements like miniaturization, data processing, and wireless communication are the basis for application specific multi-sensor solutions. Data-fusion offers sophisticated possibilities to analyze and clarify the hazard potential of relevant situations – in many cases quasi in real-time.

The following examples present multi-sensor concepts applied to different scenarios of condition monitoring and safety management. Often similar issues and requirements must be taken into account, regardless of whether the monitoring object is a firefighter, a cask for radioactive material or a subsurface storage area.

The paper is structured in 6 sections. The sections II till V describe the above mentioned examples on basis of the physical principle, functionality and application. Section VI gives a short summary and the most relevant conclusions.

II. MONITORING AND INDOOR LOCALIZATION OF RELIEF FORCES

Rescue forces often operate in dangerous scenarios and situations in which their localization can be crucial for safe operation and return. Fire, landslip-, or flood scenarios pose hazards like suffocation, burn, or undercooling. The localization and quick recovery raise the survival chance clearly. The use of Global Positioning system (GPS) technology allows the exact localization of persons or objects everywhere a sufficient satellite reception is possible. However, in many hazardous scenarios no or only insufficient GPS reception is available. This may be the case in underground, indoor, or fire scenarios, making GPS localization complicated or impossible.

Objectives of the ongoing project “Localization and monitoring of relief forces in hazardous scenarios” with acronym OMEGa are the development and validation of a monitoring system, which complements GPS localization with indoor navigation [1] and in addition measures the most important vital functions. The overall system consists of two units, which operate spatially separated and communicate via radio with each other. The first unit are portable multi-sensor devices, which serve as personal protective equipment (PPE-Device) of the rescue force and should be implemented, e.g., by integration in the clothes. The second unit consists of the components of the control station for data processing and display (Figure 1).

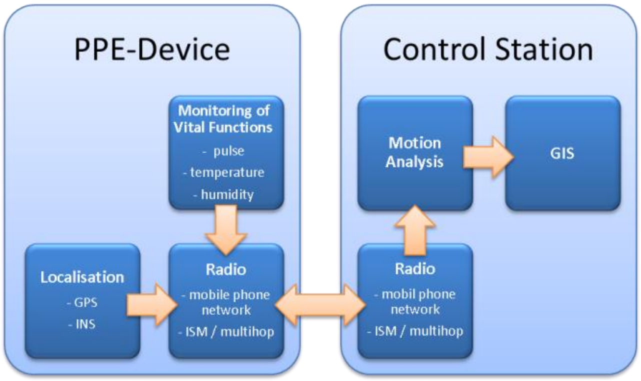

Figure 1: Scheme of the OMEGa units.

The multi-sensor device (Figure 2) should consist of an outdoor localization system (GPS), an inertial navigation system (INS) for indoor localization, and sensors for monitoring of vital functions like pulse, temperature and humidity at the body surface. The communication between both units should be implemented through a redundant solution of two radio modes, based on mobile phone network and ISM band, the latter with multihop routing. Principal elements of the control station are analysis tools for calculating motion sequences from the sensor data and a geographical information system (GIS) to track and monitor the equipped persons in map-based software.

Figure 2: Prototype of the OMEGa multi-sensor device.

Indoor localization on basis of an INS is the most sophisticated challenge in the OMEGa project. The INS itself is a multi-sensor microelectromechanical systems (MEMS) device consisting of 3-axes accelerometers, gyroscopes, magnetic field, and barometric pressure sensors, partly redundant. The calculation of motion sequences from the combined sensor data is performed by data-fusion algorithms, which are currently under development [1, 2].

III. MICRO-DRONE FOR GAS MEASUREMENT IN HAZARDOUS SCENARIOS

A research project was carried out at BAM with the objective to develop a flying remote-controlled measuring system. The system is capable of operating in a variety of scenarios of gas emission, e.g., exhaust gas from a chimney, flue gas in case of a fire, gas emission in case of an accident of chemical or hazardous goods [3]. Another addressed field of application is spatially resolved emission control of geodynamic active regions, waste disposals, stockpiles, landfills, CO_2 storage areas (carbon capture and storage, CCS), industrial sites and pollution critical areas. Due to its mobility the system can measure the gas concentration in the immediate vicinity of the object, which causes the emission. A further stage of extension is the enhancement of the system for identification of gas source locations, and gas distribution modeling/mapping (GDM). The latter applications are implemented based on the combined analysis of position dependent gas concentrations and wind vector data.

Figure 3: Micro-drone with multi-sensor equippment in flight.

Gas concentration measurement from an air-borne platform (AR 100-B, Airrobot, Germany, Figure 3) is demanding in terms of weight, dimensions, energy consumption, influence of the rotors, and speed of the sensing device. A gas-sensing payload was developed on basis of a commercially available gas detector (X-am 5600, Draeger, Germany), which was originally designed as personal safety equipment. The device features low weight and compact design. The modular concept allows the ad hoc exchange of four sensors in the gas detector, which enables users to customize it for their specific application.

Due to the weight restrictions imposed by the platform (max. payload 200 g), the micro-drone does not carry any wind sensing modalities. Instead, wind measurements are estimated by fusing the different on-board sensors of its inertial measurement unit to compute the parameters of the wind triangle [4].

The wind triangle is commonly used in navigation and describes the relationships between the flight vector, the ground vector, and the wind vector. The micro-drone can be operated manually or in GPS mode, e.g., by autonomous waypoint following.

Both, gas distribution modeling and plume-tracking were enabled using data-fusion algorithms. For plume tracking three promising algorithms were implemented and adapted accordingly to meet the system characteristics of the micro-drone: the surge-cast algorithm (a variant of the silkworm moth algorithm), the zigzag/dung beetle algorithm, and a newly developed algorithm called “pseudo gradient-based algorithm”. First successful tests were performed in real-world experiments [5].

To build a predictive gas distribution model, the Kernel DM+V/W algorithm introduced by Reggente and Lilienthal [6] was used. The input to this algorithm is a set $D = \{(x_i,r_i,v_i)\}1\leq i\leq n$ of gas sensor measurements r_i and wind measurements v_i collected at locations x_i. The output is a grid model that computes a confidence estimate, as well as the distribution mean and variance for each cell k of the gridmap (Figure 4).

Additional sensors for temperature and humidity are integrated into the gas-sensing payload but so far not taken into account. It is conceivable to use these data for sensor compensation algorithms or to correlate the environmental conditions, e.g., in the case of fire. Integration of optical or IR data is another viable aspect.

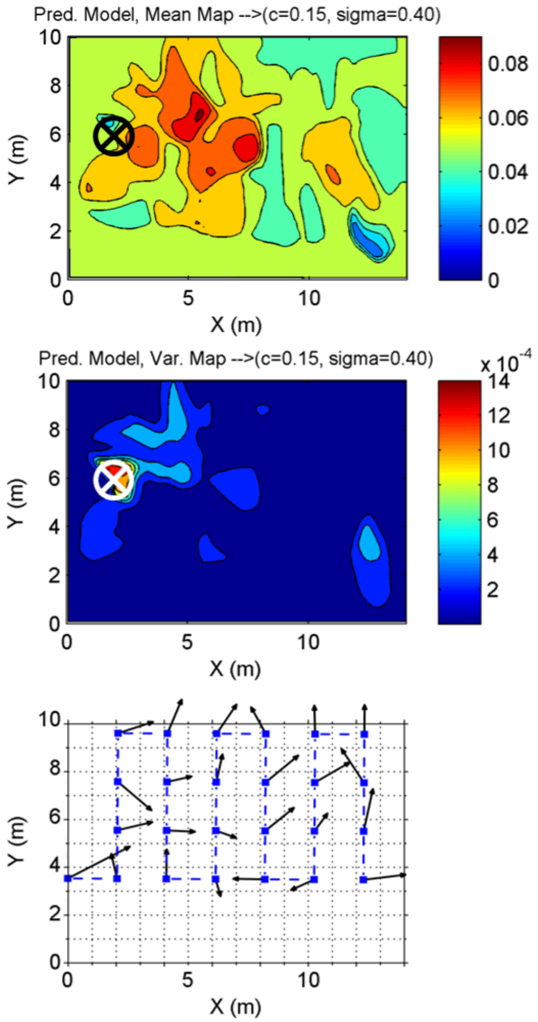

Figure 4: GDM Experiment: Predictive mean (top) and variance map (middle) of the gas distribution and the corresponding mean airflow map (bottom) and the path of the micro-drone created using Kernel DM+V/W. The gas source was located approx. at position (2, 6) m and is denoted by the cross. The concentration value of CO2 is given in % by volume.

IV. SENSOR-ENABLED RFID TAGS FOR SAFEGUARD OF DANGEROUS GOODS

The project “Sensor-enabled RFID tags for safeguard of dangerous goods” with acronym SIGRID investigates and assesses possibilities to improve safety and security of dangerous goods transports through the use of the latest RFID technology [7]. This technology can be used to greatly enhance the transparency of the supply chain and aid logistics companies in complying with regulations. In the context of SIGRID custom RFID sensor tags (Figure 5) were developed to monitor dangerous goods during transport and help to prevent hazards by allowing timely countermeasures. This requires the combination of communication technology and sensor functionality with low power consumption and small design.

To achieve long battery-life, the use of very energy efficient sensors is mandatory. Other desirable properties of the sensors include high accuracy, long lifetime, and short response time. For gas sensors a high selectivity is also very important. Currently four types of sensors are integrated in the RFID tag, which are a combined humidity and temperature sensor, gas sensors for carbon monoxide (CO) and oxygen (O_2), and a tilt sensor. Other interesting sensor options that might be tested in future include sensors for detecting the filling level and sensors for monitoring the operation of equipment that is built into the container like a stirring unit.

Figure 5: Prototype of the sensor enabled RFID tag

The integrated sensors enable the system for recognizing and evaluating of different scenarios. Adequate gas sensors indicate an emission from the containments via measured concentrations. If a possible gas release from the transported substance cannot be detected because of lacking the proper sensor, the O_2-sensor can indicate a leakage through decreasing oxygen values. For numerous dangerous goods a maximal transport temperature is defined to prevent any chemical reaction. Temperatures can be measured and compared periodically to substance specific values. If that value or a tolerance is exceeded an alarm or countermeasure can be activated. The tilt sensor can be triggered on heavy vibrations or tilting of the containment. In case of a dangerous good accident the available information about the type, amount, and condition of the dangerous goods can be used to accurately inform the relief forces. Unavailable or inaccurate information represents a significant problem. This often leads to a delay of the rescue operation, because relief forces must be aware of the involved substances and their condition to effectively protect themselves against them.

Sensor-Tags, data communication, and software are combined to an interactive solution, which can tackle various scenarios during dangerous goods transports. The underlying information is provided by a data base with expert knowledge, in this case the BAM dangerous goods database "GEFAHRGUT" [8]. Possible extensions of the system take into account vehicle data or GPS information in terms of route planning and geo-fencing.

V. MULTIFUNCTIONAL SENSOR FOR SPATIALLY RESOLVED UNDER-SURFACE MONITORING OF GAS STORAGE AREAS

One of the main unsolved issues of under-ground storages for, e.g., carbon dioxide, hydrogen, and natural gas (primarily methane) is the comprehensive surveillance of these areas with reasonable effort and costs. Conventional sensors, such as soil air probes or borehole probes, can only be used for punctual or locally limited measurements. Further they require invasive application, which causes structural influences.

Figure 6: Prototype of the sensor enabled RFID tag.

BAM in cooperation with the company MeGaSen UG carries out a research project to enhance and validate an innovative approach for distributed subsurface monitoring of gas storage areas. The concept combines different measurement technologies to one multifunctional sensor: membrane-based gas measurement technology for in-situ monitoring of gases in soil [9] and fiber optical sensing of temperature and strain as a measure for structural change [10].

The gas sensor (Figure 6) is based on the principle of selective permeation of gases through a membrane. The measuring method combines the gas specific diffusion rates through a membrane with Dalton's law of partial pressures. It enables the calculation of gas concentrations with the ideal gas law using measurements of pressure, time, and temperature. The sensor is implemented in form of a flexible tube. The synthetic material allows a variable subsurface installation, e.g., in meander or network form (Figure 7). So far the gas concentration measurement is implemented for carbon dioxide and oxygen, further gases should follow, e.g., methane and hydrogen sulfide.

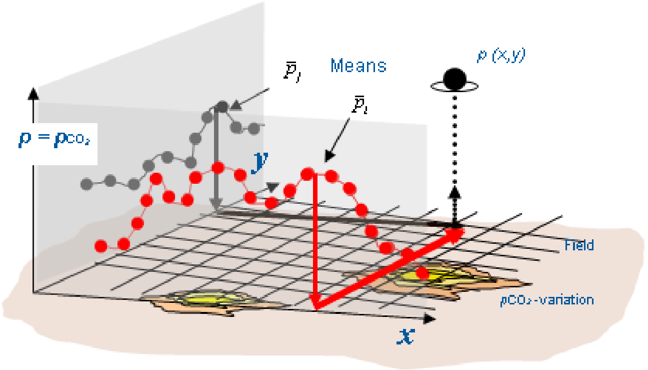

Figure 7: Spatially distributed gas monitoring built up of several membrane sensors. The brown and yellow areas indicate CO2 hotspots underground. The red and grey curves display the averaged measurements of the partial CO2 pressure over x and y.

Glass fiber optical sensors use the effects of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) for spatially resolved measuring of temperature and strain. Distributed strain measurements can also be performed with polymer optical fibers using optical time-domain reflectometry (OTDR). BAM develops, validates and uses such sensor systems in different areas of application, such as geotechnics, structural engineering, and physical protection.

Combining these two sensor types (membrane sensor and fiber sensor) to a multifunctional sensor offers an innovative and promising approach for spatially resolved monitoring of large-scale areas. Both technologies offer advantageous specifications, which support and encourage their combination:

- Distributed, area-wide applicable measuring system with spatially resolution of all variables
- Scalable and adaptable form of application, depending on monitoring object and problem
- Non-invasive system (no influence on the monitoring object, due to permanent presence of the sensor in the ground)
- No sensitivity against electro-magnetic fields (e.g., lightning and high-voltage lines)
- Applicable in explosive surroundings (no electrical components at the measuring locations)
- High thermal and chemical robustness
- Comparatively reasonable components

The structural combination is accomplished by linkage of the sensitive elements membrane sensor and optical fiber. For this purpose, geogrid materials (Figure 8) act as a carrier material.

Combined data analysis should be investigated and further developed to attain synergy effects, increase the sensitivity and informational value, and address new fields of application. Using sensor data fusion allows in-depth analysis of soil processes and early detection of relevant changes. For instance, the combined analysis of gas concentration, temperature, and strain can enable an indication of very small crack formation and gas emission, with significant higher reliability compared to sole gas measurements.

Figure 8: Geogrid with integrated fiber optical sensors.

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Two immediate fields of application are addressed: Landfills produce greenhouse gas and warmth. The combination of both measurement methods should allow a potent landfill monitoring by containment of chemical active areas and leakages.

Underground storage of CO_2 as part of CCS as well as extraction and production of gases from geological areas can lead to mechanical changes of the deck rock (lowering / elevation), with which a regional tension field is build up. Thus gas-leading gaps can be induced, which cause local ground structure changes. The simultaneous measurement of spatially resolved gas concentrations and strain allows the development of an efficient early warning system.

The validation, optimization, and practical demonstration of the overall system are carried out on the BAM Test Site Technical Safety (BAM TTS) [11]. For this purpose, a test field in application relevant scale of 20 x 20 m² is under construction.

VI. CONCLUSION

Safety related monitoring often is necessary in complex scenarios. It requires distinct information to evaluate the situation and to determine the further operation. The combination of several measurands can improve the informative value of a monitoring system in terms of measuring diversity and accuracy.

To present the great potential of such systems, four examples for monitoring in safety relevant scenarios are presented in this paper, which combine multiple application specific sensor techniques. An important result considering each of the examples and multi-sensor systems in general is that data processing and display of the results with focus of the relevant information is crucial. The experiences gained from these projects show that the focus should lay on the final application and end-users should be involved already in the conception of multi-sensor systems. Data-fusion offers broad possibilities, but conditions and objectives should be well defined and expediently applied.

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