Monitoring of Hazardous Scenarios using Multi-Sensor Devices and Sensor Data Fusion

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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 and sensor data fusion.**

Keywords- monitoring, multi-sensor, 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 [1]. 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-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.

A. Concept and Components

Objectives of the 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 [2] 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).

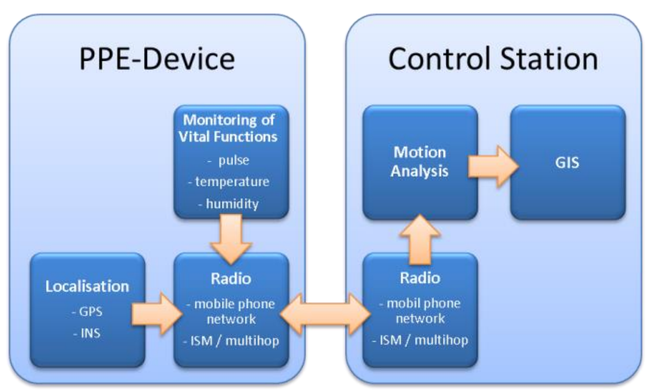

Figure 1. Scheme of the OMEGa units.

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 [2][3][4].

B. Results

Different motion sequences can be identified by analyzing the different sensor signals. In a series of experiments, persons were moving on a treadmill with different speed. The OMEGa device was placed at their central lower back in height of the hip. The type of movement (walking or running) and the speed lead to varying acceleration signals. Figure 3 displays the data for walking at speeds from 2 to 7 km/h and running at speeds from 8 to 12 km/h. The walking results show significant differences in length and time of single steps between putting down and lifting the feet. In contrast to walking, running results deliver similar step times, but the acceleration impulse differs for different speeds. This example shows how movement sequences can be characterized and identified by simple means of pattern recognition.

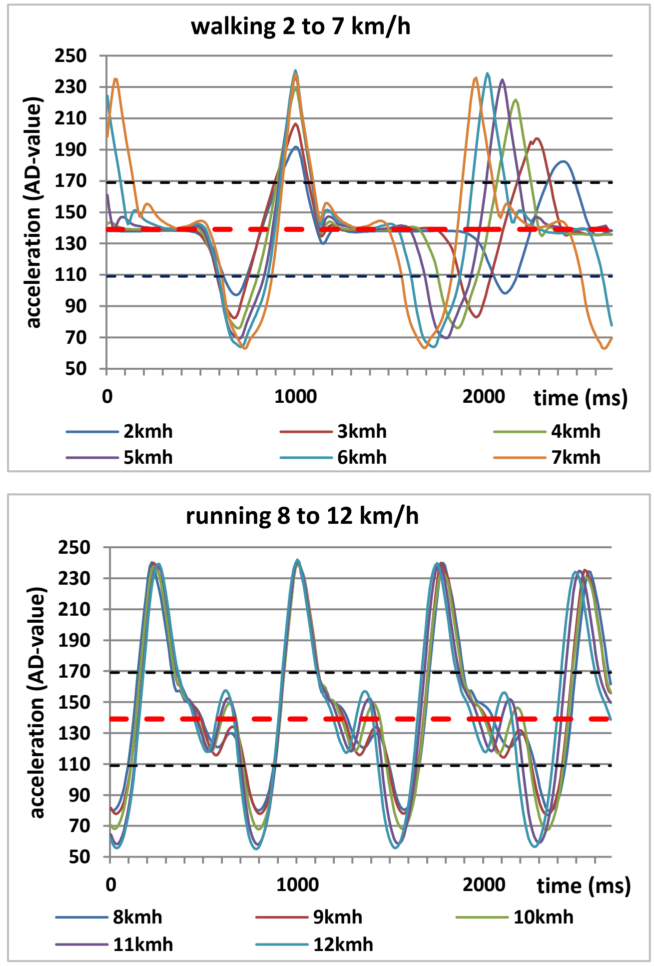

Figure 3. INS acceleration signals of different motion sequences.

The combination of these findings with the measurement of vital functions can be used to enable comprehensive monitoring of relief forces during operation. Further objectives are automated detection of critical situations and alarming.

Another result of the project was the implementation of a new calibration method for an INS. This principle is based on the free motion at the curved surface area of an ellipsoid, which allows free motion calibration of the sensor at any place or position [3][4]. In the same way, the algorithm can use the movement of the holder as input for a continuous recalibration during a normal operation. By moving the sensor system in a pseudo static motion, measurement data is generated and used to determine the ellipsoid. This geometrical figure describes the sensor idle state and amplitude at a known measurement value. An optimisation function was implemented in the algorithm to gain the ellipsoid out of noisy measurements. Furthermore, the advantage of this principle is that it is possible to calibrate a free motion of the sensor system at any place or position on a person. In other words, the sensor system is calibrated and adjusted during normal operation. Hence, there are no more movements after the activation of the system or during the working process necessary for the calibration [4].

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 [5]. 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, plume tracking, 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 4. Micro-drone with multi-sensor equippment in flight.

Gas concentration measurement from an air-borne platform (AR 100-B, Airrobot, Germany; see Figure 4) 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 [6]. 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.

A. Plume Tracking Algorithms

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 [7][8].

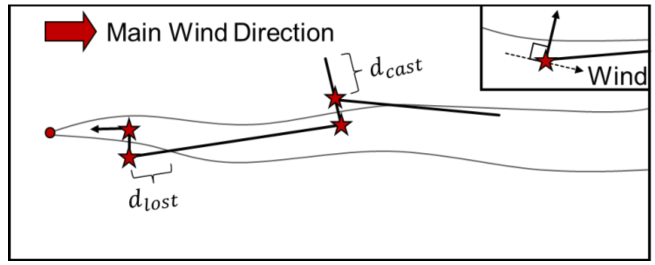

Figure 5. Surge-cast algorithm.

Lochmatter presented in [9] the surge-cast algorithm. It is a combination of plume tracking strategies used by the silkworm moth and works as follows (Figure 5): The robot moves straight upwind until it loses the contact with the plume for a certain distance d_{lost}. Then, it tries to reacquire the plume by searching crosswind for a defined distance d_{cast} on both sides. The chance of reacquiring the plume in the first crosswind movement is maximized by measuring the wind direction to estimate the side, from which the robot has left the plume. Every time the robot switches its behavior from upwind surge to casting and vice versa, the wind direction is re-measured. In comparison to the original algorithm, the plume is declared lost in the surge-cast algorithm used here, when the micro-drone measures an average gas concentration below the threshold after one step. To reacquire the plume, casting with increasing step size in crosswind direction is performed. These changes were necessary to address the constraints of the micro-drone in GPS-mode. Furthermore, the wind is re-measured every iteration of the algorithm to adapt faster to changing wind conditions. If casting fails to reacquire the plume (after a defined number of steps) the micro-drone returns to the sweeping strategy.

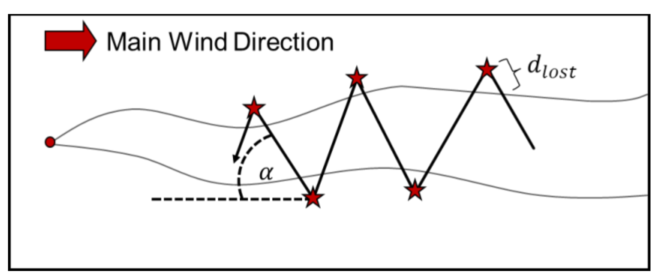

Figure 6. Zigzag or dung beetle algorithm.

The zigzag or dung beetle algorithm was first reported by Ishida et al. [10]. The basic algorithm works as follows (Figure 6): The robot moves upwind with an angle α (e.g., α = 60◦) across the plume constantly sensing gas concentrations. If the gas sensor measures a concentration below a given threshold, the robot is assumed to have reached the edge of the plume. It re-measures the wind direction and continues moving upwind with an angle -α with respect to the upwind direction. This procedure is repeated causing the robot to move in a zigzag fashion within the plume. The robot is stopped, when it has reached the source. In comparison to the original algorithm, the micro-drone does only collect gas and wind measurements at the waypoints where it stops.

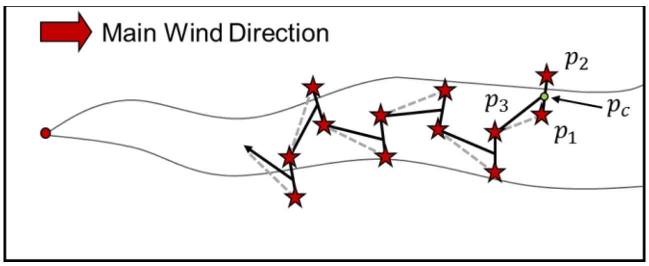

Figure 7. Pseudo gradient-based algorithm.

The idea for the first gradient-based algorithms for plume tracking goes back to Braitenberg [11]. The chemical gradient is measured by a pair of bilateral gas sensors mounted on each side of a robot, each directly controlling the speed of a wheel. Each sensor is connected to the motor on the same side, the motor on the opposite side (cross coupling), or both motors. Although it was a purely chemotactic approach, a Braitenberg-style robot is able to track a plume towards a gas source by following the concentration gradient [12]. As the first gradient-based algorithms do not consider wind information, the robot does not know whether it is following a plume towards or away from its source. Turning the robot in proportion to the concentration gradient in dependence of the upwind direction solves this problem [13]. As the rotors of the micro-drone introduce strong disturbances, measuring a local concentration gradient with spatially separated sensors is not feasible. Instead a new measuring strategy was developed, which basically splits up one measuring position into two spatially separated ones. In order to respect the minimum step size of the micro-drone of 1 m and to progress faster to the source, the step size in upwind direction was set to 1.5 × step size (Figure 7).

B. *Gas Distribution Modeling/Mapping (GDM)*

Gas distribution mapping can be used in a number of relevant application areas where a better understanding of the gas dispersion is needed, such as environmental monitoring and safety and security related fields.

To build a predictive gas distribution model, the Kernel DM+V/W algorithm introduced by Reggente and Lilienthal [14] 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 8).

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.

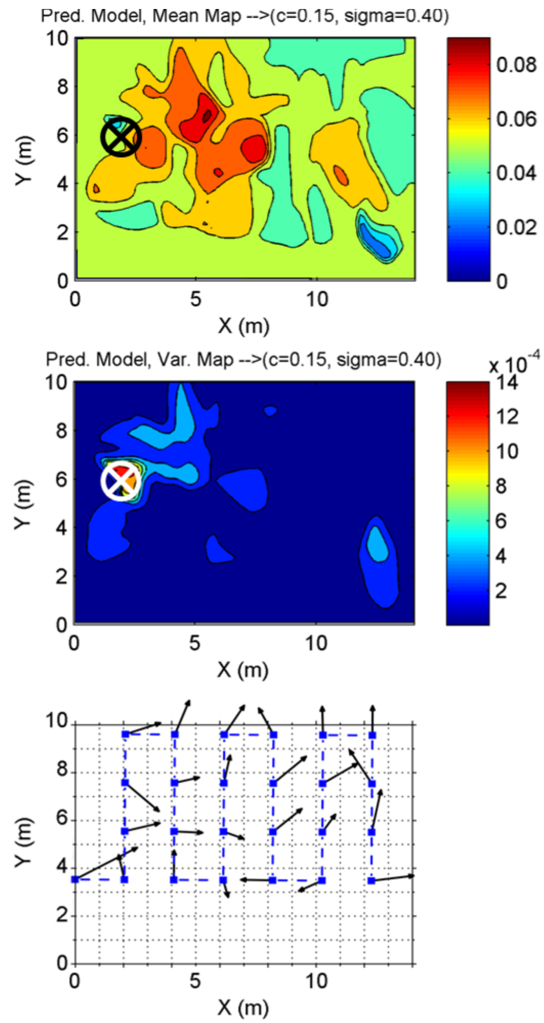

Figure 8. GDM Experiment: Predictive mean (top) and variance map (middle) of the gas distribution and the corresponding mean airflow map (bottom) and the path of the micro-drone created using Kernel DM+V/W. The gas source was located approx. at position (2, 6) m and is denoted by the cross. The concentration value of CO_2 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 [15]. 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 9) 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.

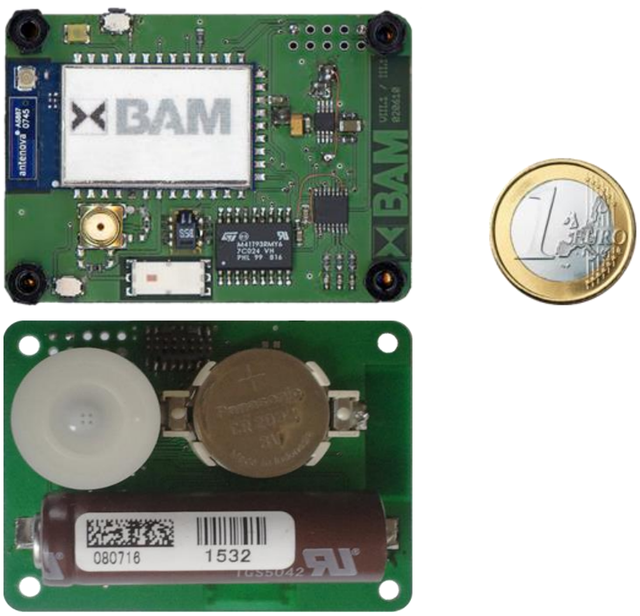

Figure 9. Prototype of the sensor enabled RFID tag

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 goods 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.

Within the scope of the project, an RFID tag was developed, that allows connecting with different types of sensors. This RFID tag combines the advantages of semi active (only sensors are battery supplied) and active tags (sensors and radio communication are battery supplied). On one side, this tag is compatible to the ISO 18000, respectively EPC-Gen2 standards; on the other side, this tag has also the ability to communicate via the widely adopted wireless LAN standard Wi-Fi. Because the tag is woken up the same way as battery-less passive tags and for that reason does not need to power-up a receiver-module, battery-lifetimes of more than half a year are possible - just as with semi active tags. After the tag is woken up, the WLAN module is activated and allows very fast data transmission, that otherwise would only be achievable with active tags. This greater transmission speed makes the tag suitable as storage device for much larger amounts of data, than the ones that are normally possible with RFID tags. The possibility to store great amounts of data in combination with a very long battery lifetime makes this tag ideal for use as a data logger. Logging intervals can be configured individually for every sensor. The tag has also an open interface, which allows an easy integration of different kinds of sensors.

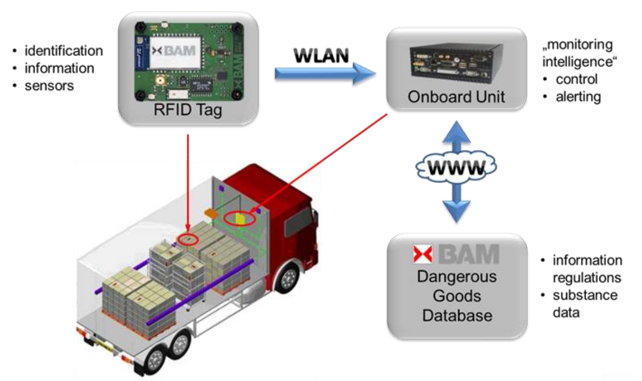

Figure 10. Interaction between the main system components during transport

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" [16]. Figure 10 displays the interaction between the main system components during transport. The focal point of the vehicle equipment is the onboard unit (OBU), which consists of a ruggedized industry PC that is specially designed for use in a truck. The main functions of the OBU include acquisition of position data via GPS, routing, generation of transport documents, data communication via the mobile phone network, monitoring of the load with sensors and surveillance cameras as well as WLAN connectivity. It is either possible to read the sensors of the semi-active transponders or sensors that are permanently installed in the loading area. The OBU constantly monitors the measurements to ensure, that they are in the allowable range. If that is not the case, an alarm is automatically triggered. Current status messages are transmitted to the centralized database, that has also the cargo manifest stored. In case of need, the OBU should supply the relief forces with all required information via WLAN. But if the OBU gets destroyed during an accident, all information is still available through the centralized database. 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 11. Membrane based gas sensor.

A. *Sensing principles*

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 [17] and fiber optical sensing of temperature and strain as a measure for structural change [18].

The gas sensor (Figure 11) 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 12). So far the gas concentration measurement is implemented for carbon dioxide and oxygen, further gases should follow, e.g., methane and hydrogen sulfide.

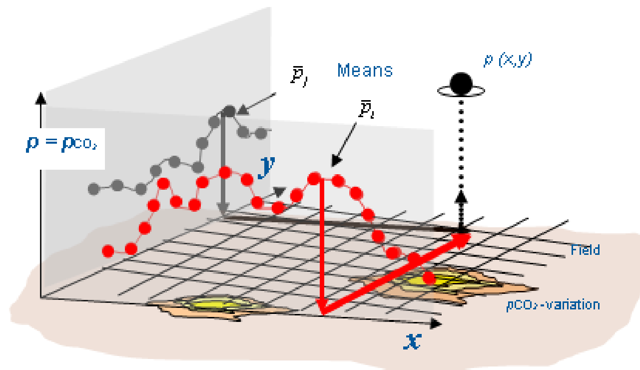

Figure 12. Spatially distributed gas monitoring built up of several membrane sensors. The brown and yellow areas indicate CO_2 hotspots underground. The red and grey curves display the averaged measurements of the partial CO_2 pressure over x and y.

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 [19]. 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 13) 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 13. Geogrid with integrated fiber optical sensors.

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.

B. Experimental Validation

The validation, optimization, and practical demonstration of the overall system are carried out on the BAM Test Site Technical Safety (BAM TTS) [20][21]. For this purpose, a test field in application relevant scale of 20 x 20 m² was built up (Figure 14). Additionally, a corresponding laboratory setup was constructed. Both setups use the same sensors and measuring procedures as well as the same soil, which acts as ambient medium. The laboratory setup (Figure 15) was designed as a cooperative tool to prepare the test site build up and operation.

Comparable investigations can be performed in small-size and short-term to estimate the efforts and benefits of full-size experiments. Gas emission processes can be simulated as well as temperature and mechanical impact to validate and enhance the proposed multifunctional sensor. First, CO_2 leakage experiments demonstrate the applicability of the technology for rapid leak detection, and thus qualify the sensor particularly for safety application in Carbon Capture and Storage (CCS) areas [22].

Figure 14. Built-up of the test site. Top: level with 4 linear sensors. Bottom: level with 40 linear sensors. Each sensor line combines membrane gas sensing and fibre optical sensing of temperature and strain.

Figure 15. Laboratory setup with corresponding design to the test site and size of 2.5 x 1.5 x 0.1 m^3.

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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