EWSHM 2024
11th European Workshop on Structural Health Monitoring

Implementation and validation of robot-enabled embedded sensors for structural health monitoring

Sergej Johann [1,2], Jan Stührenberg [2], Aditya Tandon [2], Kosmas Dragos [2], Matthias Bartholmai [1], Christoph Strangfeld [1], and Kay Smarsly [2]

[1] Federal Institute for Materials Research and Testing (BAM), Berlin, Germany,
+49 8104-1612, sergej.johann@bam.de

[2] Institute of Digital and Autonomous Construction (IDAC), Hamburg University of Technology, Hamburg, Germany, jan.stuehrenberg@tuhh.de

Abstract. In the past decades, structural health monitoring (SHM) has matured into a viable supplement to regular inspections, facilitating the execution of repair and maintenance work in the early stages of structural damage. With the advent of wireless technologies and advancements in information and communication technologies, civil infrastructure has been increasingly instrumented with wireless sensor nodes to record, analyze, and communicate data relevant to SHM. A promising method for SHM is to embed sensors directly into concrete for recording SHM data from inside structural elements. In this paper, a sensor system for embedment into concrete is proposed, able to assess SHM data recorded from concrete. Power is supplied to the sensors on-demand by quadruped robots, which also collect the SHM data via radio-frequency identification (RFID), providing an automated and efficient SHM process. In laboratory experiments, the capability of the sensor system of automatically collecting the SHM data using quadruped robots is validated. In summary, the integration of RFID technology and robot-based inspection presented in this study demonstrates a vital approach to evolve current SHM practices towards more digitalized and automated SHM.

Keywords: Structural health monitoring, RFID-based sensors, smart sensors, embedded sensors, legged robots, quadruped robots

1. Introduction

Structural health monitoring (SHM) is essential for cost-effective maintenance through timely damage detection. In recent years, wireless sensor nodes have gradually been incorporated into SHM to reduce installation efforts and enhance the flexibility and scalability compared to cable-based SHM systems [1]. In this direction, embedding sensors into concrete offers a promising method for wireless SHM, as degradation processes, such as corrosion in reinforced concrete [2], may be hardly visible on the surface of structural elements, where wireless sensor nodes are typically installed.

Challenges of approaches employing embedded wireless sensors are related to the power autonomy and to the retrieval of data. On the one hand, continuous power supply is hardly possible in embedded sensors, and, on the other hand, the retrieval of data may be cumbersome, especially in massive structures with large arrays of embedded sensors. Given

Media and Publishing Partner

the merits of obtaining data across the thickness of structural elements, approaches of wireless embedded sensors that can be efficiently powered and accessed would significantly enhance SHM.

A promising technology for supplying power wirelessly is radio-frequency identification (RFID), which has increasingly been adopted in the construction sector for identifying and monitoring objects wirelessly [3]. For example, in the construction phase, RFID tags embedded in building materials enable real-time tracking of components and ensure that the right materials are used at the right time and in the right location, minimizing errors and streamlining construction processes. Moreover, performing large-scale inspection on structures during construction has been facilitated by mobile robots, which have increasingly been used in construction sites. In conclusion, current SHM practice stands to benefit from both aforementioned technologies, RFID and mobile robots.

A review of studies integrating RFID technology with SHM can be found in [7]. In [8], Lay et al. have proposed an approach for sealing structures for underground disposal of nuclear or toxic waste. Furthermore, approaches employing mobile robots for SHM are reviewed in [5]. In recent approaches, Smarsly et al. have reported on legged robots for SHM, leveraging the advanced locomotion techniques providing enhanced maneuverability and adaptability to different environments [6]. However, integrating RFID with mobile robots for increasing the efficiency of SHM, e.g. for facilitating the deployment of embedded sensors, has received scarce attention.

In this paper, a methodology for embedding wireless sensors into concrete structures (hereinafter termed “concrete-embedded sensors”) is proposed. The concrete-embedded sensors record SHM data to assess the structural state. Quadruped robots are employed to supply power on demand to the concrete-embedded sensors via RFID and to navigate structures for collecting the SHM data from the concrete-embedded sensors wirelessly, thus rendering the concrete-embedded sensors “robot-enabled”. The automated collection of SHM data minimizes human interaction and increases efficiency.

The remainder of the paper is organized as follows. In Section 2, the methodology and implementation details for deploying the robot-enabled concrete-embedded sensors are described, with emphasis on the automated collection of the SHM data using quadruped robots. In Section 3, the validation tests are presented, conducted in an office environment to demonstrate the automated data collection capabilities of the robot-enabled concrete-embedded sensors. Section 4 summarizes and concludes the paper.

2. Radio-frequency identification for robot-enabled concrete-embedded sensors

The description of the methodology, presented in this section, starts with an overview of the RFID technology, including the components used to read out the SHM data from concrete-embedded sensors. Next, the attachment of the RFID components to quadruped robots and the process of automatically collecting SHM data from the concrete-embedded sensors using quadruped robots is illuminated.

2.1 RFID technology

The role of RFID technology in the proposed methodology is twofold, (i) providing power supply to the concrete-embedded sensors and (ii) enabling data transmission from the concrete-embedded sensors to “reader” devices. Figure 1 illustrates the RFID components required to conduct measurements in the context of SHM. Essential components include *RFID tags*, marking the objects to be identified, and *RFID readers*, which read the information and SHM data from the RFID tags and store the data for further processing. The RFID tags contain unique identifiers and can incorporate information pertinent to the application, such as product or location information. RFID readers emit electromagnetic waves to activate RFID tags and analyze the signals, containing SHM data, received from the RFID tags. *Loop antennas* enable wireless communication between the RFID tags and the RFID readers. Energy transmission occurs through electromagnetic fields, allowing the tags to operate without any energy storage. In addition, middleware and databases are integrated into the RFID readers to store, manage, and analyze SHM data. In terms of types of SHM data collected in this study, the RFID tags are designed to collect data from temperature, humidity, and pressure sensors [9].

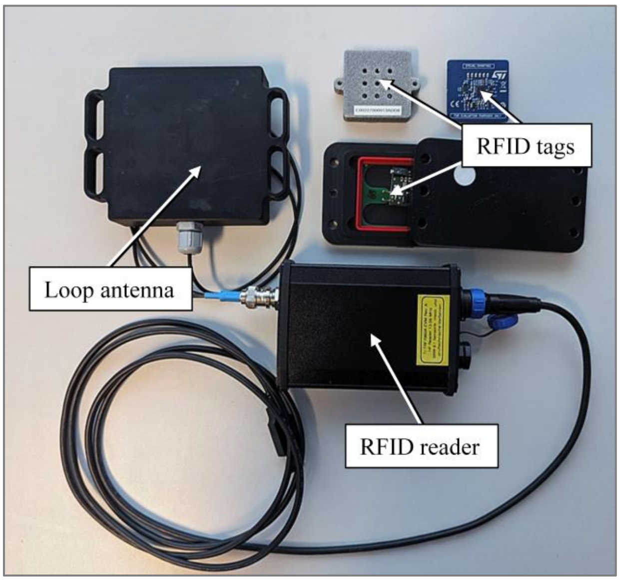


Fig. 1. Prototype RFID components for concrete-embedded sensors.

2.2 Automated collection of concrete-embedded sensor data using legged robots

To enable automated and efficient collection of SHM data from concrete-embedded sensors, the RFID components are installed on a quadruped robot, shown in Figure 2. The RFID reader is connected to the robot operating system via a universal asynchronous receiver/transmitter (UART) interface. The loop antenna is attached to the end effector of a robot arm mounted on the quadruped robot, allowing for flexibility in motion. The robot arm enables the antenna to move close to the RFID tags embedded in concrete.

For automatically collecting SHM data from multiple concrete-embedded sensors, distributed on a structure being monitored, the quadruped robot is equipped with reliable autonomous motion planning and control. Motion planning and control relies on real-time perception of the surrounding environment for creating detailed maps, for accurately localizing within the maps, and for identifying obstacles. In this study, the quadruped robot utilizes the widely-used combination of a 3D light detection and ranging (LiDAR) sensor and an inertial measurement unit (IMU) for perception, as shown in Figure 2. Given that motion planning and control with complete 3D representations in real time on embedded platforms, such as quadruped robots, poses significant computational challenges [10], the 3D LiDAR data is projected onto the 2D horizontal plane to ensure manageable data processing. Motion planning is conducted by representing the quadruped robot as a holonomic robot in the horizontal 2D plane with a rectangular footprint, corresponding to the physical space occupied by the quadruped robot. The motion planning builds upon the Robot Operating System (ROS) architecture [11].

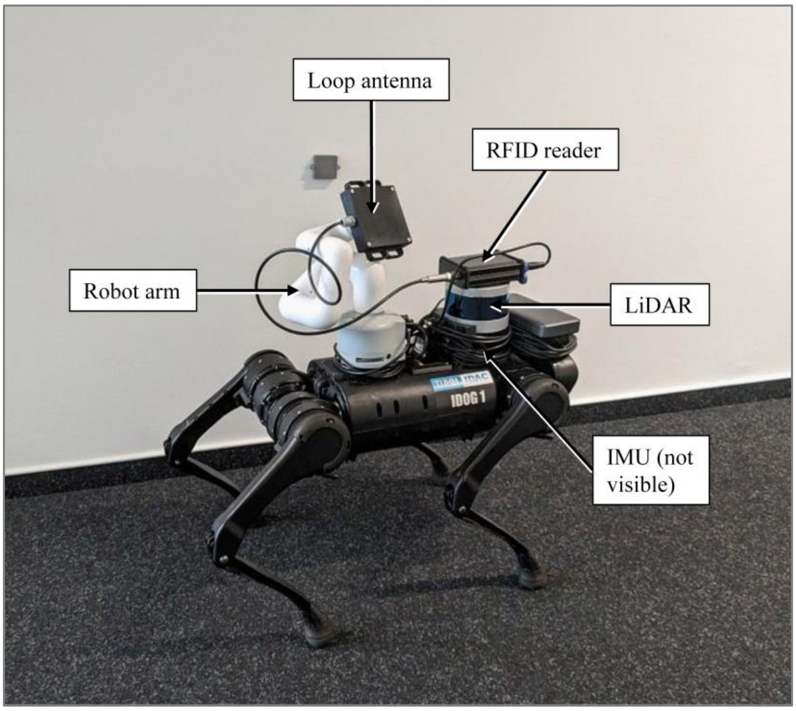


Fig. 2. RFID components attached to the quadruped robot.

The process of automatically collecting SHM data from concrete-embedded sensors consists of:

- Creating a map of the surrounding environment,
- Planning inspection tasks by providing "goal poses" in the map next to the RFID tags, marking the positions of concrete-embedded sensors,
- Planning and following trajectories to the goal poses, and
- Fulfilling the inspection tasks by moving the loop antenna with the robot arm to the RFID tags to read out SHM data.

The map of the surrounding environment is generated using a simultaneous localization and mapping (SLAM) system, specifically, the SLAM system "Cartographer" [12]. The Cartographer system uses the projected LiDAR data (i.e. projected onto the 2D horizontal plane) and the IMU measurements for creating a 2D static map of the environment, encoded as an occupancy grid map, which represents the surrounding environment as a uniformly spaced grid with each grid cell indicating the presence or absence of obstacles.

Planning inspection missions, such as collecting SHM data from the concrete-embedded sensors from multiple RFID tags, is achieved via an inspection mission planning framework based on hierarchical finite-state machines. Inspection missions consist of goal poses and inspection tasks, both modeled as individual states. Transitions between the states are defined based on the execution status of each state. The state machine is implemented using the SMACH library [13] in the ROS architecture. To plan inspection tasks intuitively, a planning panel in the ROS visualization tool RViz is developed, which allows marking goal poses on maps generated by robots and adding inspection tasks to the goal poses.

To automatically execute inspection missions, the quadruped robot (i) localizes itself in the map of the surrounding environment, (ii) plans paths to the goal poses of inspection missions, (iii) follows the path plans while avoiding dynamic obstacles, and (iv) executes the inspection tasks at the respective goal poses. To localize itself in the map, the quadruped robot uses the localization mode of the Cartographer system. In the localization mode, projected LiDAR data is matched against maps, allowing the quadruped robot to find its initially unknown pose in the map and to keep track of its pose while moving. The A* path-planning algorithm is used to plan coarse global paths, also referred to as "global plans", from the current poses of robots to goal poses in static maps of the surrounding environment.

To compensate for dynamic obstacles or static obstacles (untracked during mapping) and to ensure collision-free navigation, a local planner is utilized. The local planner leverages LiDAR data to construct local cost maps around the robots. The local cost maps track dynamic and static obstacles, and associate higher travel costs to grid cells around obstacles to ensure minimum distances between the quadruped robot and the obstacles. The local planner adapts coarse global plans for a short time window in the vicinity of the quadruped robot at high frequencies and supplies movement control commands to the robot. The timed elastic bands (TEB) approach is employed for the local planner [14]. The TEB planner generates time-optimal trajectories while complying with kinodynamic constraints of the holonomic quadruped robot.

Upon navigating to a goal pose next to an RFID tag, the robot arm moves the loop antenna attached to the end effector towards the RFID tag. After measuring for a predefined period of time, the robot arm is retracted and the quadruped robot moves to the next goal pose.

3. Validation and results

Validation tests are conducted to showcase the applicability of the proposed methodology in inspection missions, devised to automatically collect SHM data using a quadruped robot. The tests are conducted in an indoor office environment with two RFID tags encapsulated in 3D-printed cases attached to a wall. The quadruped robot deployed in the validation tests is of type "intelligent documentation gadget" (IDOG). The IDOG builds upon the Unitree A1 robot of Unitree Robotics, and it is equipped with the Velodyne Puck LITE LiDAR and a LORD MicroStrain 3DM-GX5-25 IMU for localization, mapping, and navigation purposes. Furthermore, the myCobot 280 robot arm by Elephant Robotics is mounted on the IDOG. The end effector of the robot arm holds the loop antenna. For further information on the IDOG, the interested reader is referred to [15].

The inspection missions devised for validation are performed as follows. The IDOG is remotely controlled throughout the indoor office environment, while generating a map using the Cartographer system. The inspection mission is planned by providing goal poses in the map next to RFID tags and adding inspection tasks using the planning panel introduced above. Upon saving the mission, the mission is repeated five times. During mission repetition, the IDOG automatically walks to the goal poses and collects SHM data from the embedded sensors. The data, the map as well as the planned and actual trajectory of the IDOG are displayed in RViz.

The generated map of the indoor office environment including the two goal poses provided is illustrated in Figure 3. Furthermore, Figure 4 and Figure 5 show snapshots of the automatic collection of the SHM data from the concrete-embedded sensors in the mission repetitions. In Figure 4, the planned and actual trajectory of the IDOG is shown. The actual trajectory is re-planned and diverges from the trajectory plan to avoid obstacles, in this case, a passer-by.

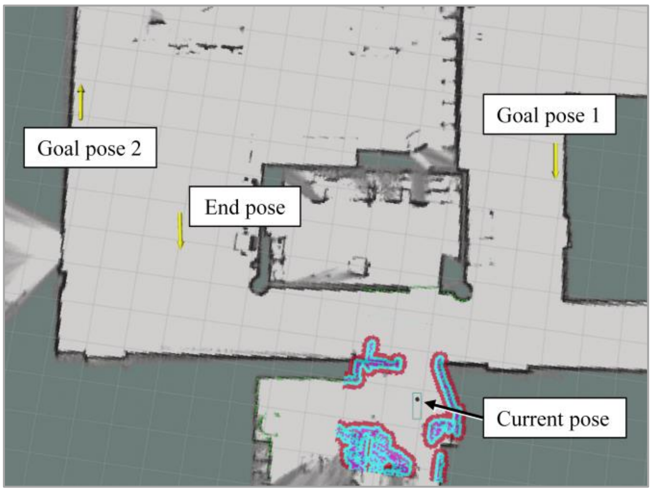
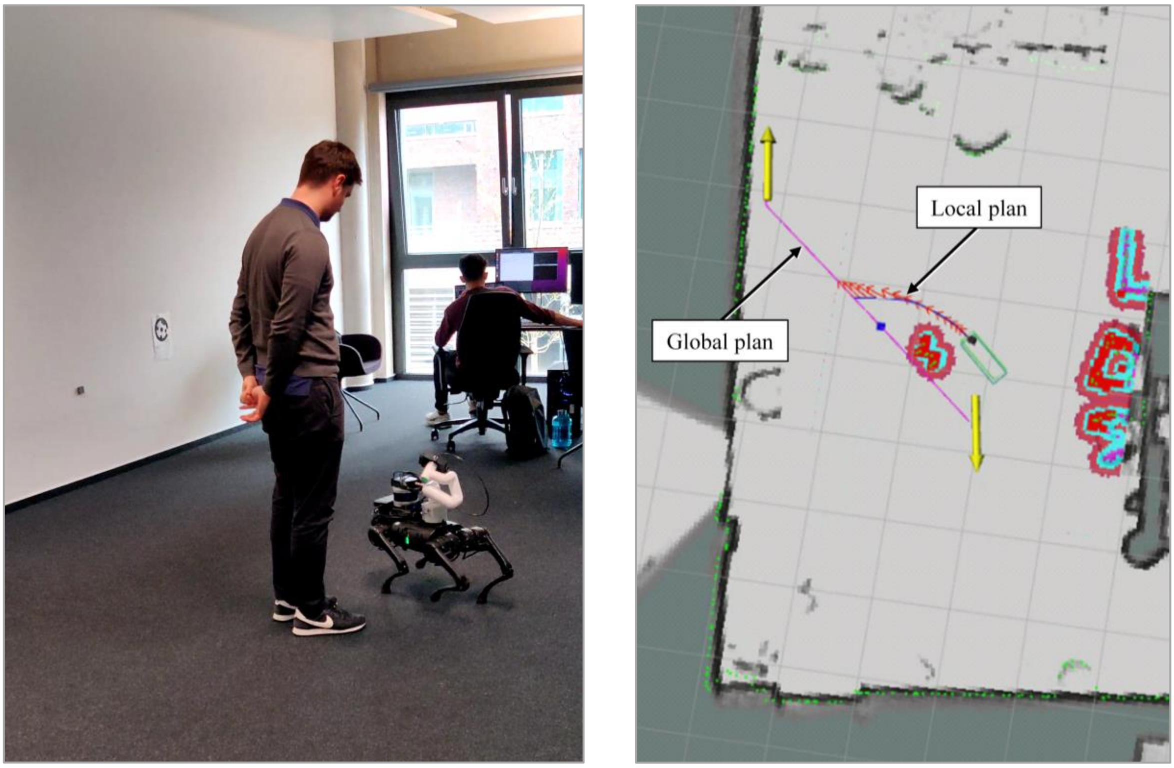


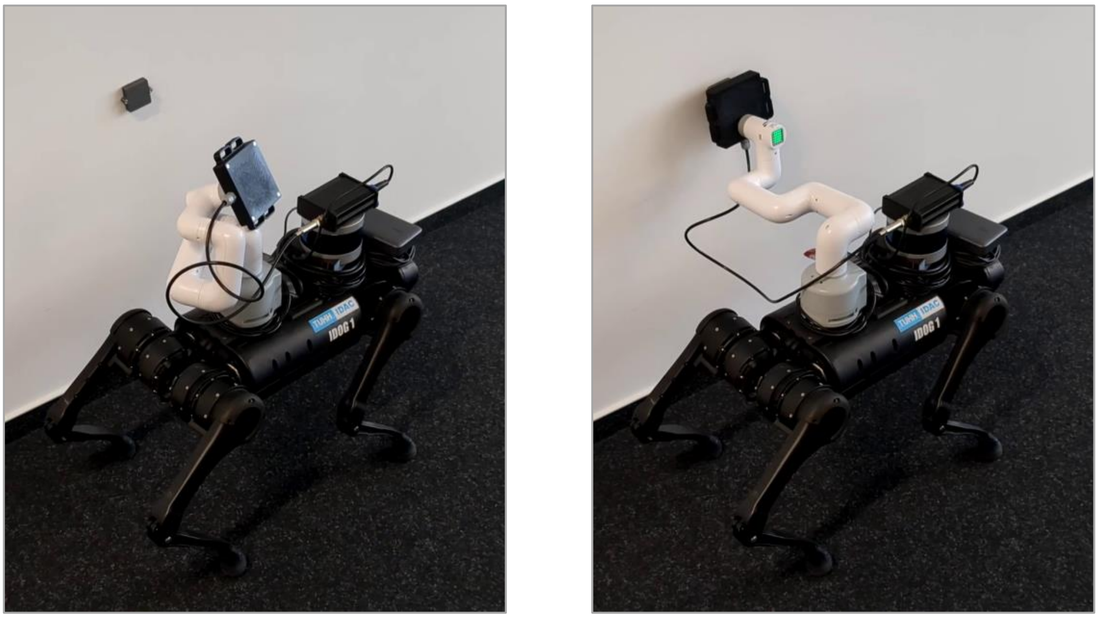
Fig. 3. Generated map of the environment with goal poses of the inspection mission.



(a) Re-planning around a passer-by **(b)** Divergence between global and local plan

Fig. 4. IDOG re-planning around a passer-by during execution of the inspection mission.

Figure 5 displays the collection of SHM data from the concrete-embedded sensors. Upon reaching a goal pose (Figure 5a), the IDOG moves the robot arm equipped with the loop antenna towards the RFID tag (Figure 5b) and collects SHM data. After measuring for 10 s, the IDOG retracts the robot arm and moves to the next goal pose. The data collected by the IDOG is given in Table 1 and comprises humidity, pressure, and temperature for two goal poses, i.e. for two sensors. SHM data is visualized in RViz using a custom sensor data display panel. In all five mission repetitions, the IDOG is able to successfully complete the inspection mission by navigating to all goal poses.



(a) IDOG upon reaching a goal pose **(b)** Collection of SHM data

Fig. 5. SHM data automatically collected by the IDOG at a goal pose of the inspection mission.

During the validation tests, SHM data has failed to be collected at inspection goal pose 1 during mission repetition number 2 and number 4 due to inaccuracies in localizing the RFID tags and in positioning the loop antenna. To improve the overall performance and increase fault tolerance during inspection missions for SHM, further accuracy of RFID tag localization and loop antenna positioning is required to prevent failure during SHM data collection.

Table. 2. SHM data collected by the IDOG at various poses in the inspection mission.

Test Nr.	**RFID tag 1**			**RFID tag 2**		
	Temperature [°C]	Humidity [%]	Pressure [hPa]	Temperature [°C]	Humidity [%]	Pressure [hPa]
1	24	55	1210	25	47	1001
2	-	-	-	25	47	1001
3	24	56	1210	24	56	1004.5
4	-	-	-	24	56	1004.5
5	24	56	1210	24	56	1004.5

4. Summary and conclusions

SHM has become an essential supplement to regular inspections. Robot-enabled concrete-embedded sensors for SHM represent a promising means to advance SHM, aiming to automate the information processing tasks within SHM, while being able to record sensor data from inside structural elements. This paper has presented a methodology proposed to implement robot-enabled concrete-embedded sensors for SHM. The methodology has been implemented on a quadruped robot using tailor-made RFID sensors proposed for embedment into concrete. Validation tests have been conducted in an indoor office environment to showcase the applicability of the proposed methodology, using the quadruped robot to automatically collect SHM data. The quadruped robot, prototypically equipped with an RFID reader and a loop antenna, has successfully collected the SHM data automatically from the sensors distributed in the office environment, while avoiding obstacles. In summary, the combination of RFID technology and robot-based inspection has proven a promising approach to advance current SHM practices, towards more automated and digitalized processes. Although the validation tests have been successful, room for improvement has been identified regarding the accuracy of the robot-based, automated localization of the RFID tags. In addition, it could be observed that the loop antenna requires accurate positioning to prevent failure during SHM data collection, representing a potential future research direction. Furthermore, an integration with building information modeling (BIM) is envisioned, as BIM models may provide robots with civil infrastructure maps, while SHM data collected through the RFID tags may be linked to objects in BIM models.

Acknowledgements

The authors would like to express their sincere gratitude for the generous support received from the German Research Foundation (DFG) under grant SM 281/20-1. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of DFG.

References

[1] Dragos, K. & Smarsly, K., 2015. A comparative review of wireless sensor nodes for structural health monitoring. In: Proceedings of the 7th International Conference on Structural Health Monitoring of Intelligent Infrastructure, Turin, Italy, July 1, 2015.

[2] Strangfeld, C., Johann, S., & Bartholmai, M., 2019. Smart RFID sensors embedded in building structures for early damage detection and long-term monitoring. Sensors, 19(24), 5514.

[3] Adão, F. J. S. F., Helmerich, R., Voigt, G., Moldenhauer, L., & Neumann, P. P., 2017. Humidity monitoring in concrete using Bluetooth low energy sensors. In: Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, Zurich, Switzerland, September 13, 2017.

[4] Johann, S., Strangfeld, C., Müller, M., Mieller, B., & Bartholmai, M., 2017. RFID sensor systems embedded in concrete - requirements for long-term operation. Materials Today: Proceedings, 4(5), pp. 5827-5832.

[5] Tian, Y., Chen, C., Sagoe-Crentsil, K., Zhang, J., & Duan, W., 2022. Intelligent robotic systems for structural health monitoring: Applications and future trends. Automation in Construction, 139, 104273.

[6] Smarsly, K., & Dragos, K., 2024. Advancing civil infrastructure assessment through robotic fleets. Internet of Things and Cyber-Physical Systems, 4(2024), pp. 138-140.

[7] Zhang, J., Tian, G. Y., Marindra, A. M., Sunny, A. I., & Zhao, A. B, 2017. A review of passive RFID tag antenna-based sensors and systems for structural health monitoring applications. Sensors, 17(2), 265.

[8] Lay, V., Baensch, F., Johann, S., Sturm, P., Mielentz, F., Prabhakara, P., Hofmann, D., Niederleithinger, E., & Kühne H., 2021. SealWasteSafe: Materials technology, monitoring techniques, and quality assurance for safe sealing structures in underground repositories. Safety of Nuclear Waste Disposal, 1(2021), pp.127-128.

[9] Strangfeld, C., Johann, S., Müller, M., & Bartholmai, M., 2016. Moisture measurements with RFID based sensors in screed and concrete. In: 8th European Workshop in Structural Health Monitoring, Bilbao, Spain, July 5, 2016.

[10] Wellhausen, L. & Hutter, M., 2023. Artplanner: Robust legged robot navigation in the field. Field Robotics, 3(1), pp. 413-434.

[11] Quigley, M., Gerkey, B., Conley, K., Faust, J., Footey, T., Leibs, J., Berger, E., Wheeler, R., & Ng, A., 2009. ROS: An open-source robot operating system. In: Proceedings of the International Conference on Robotics and Automation, Kobe, Japan, May 12, 2009.

[12] Hess, W., Kohler, D., Rapp, H., & Andor, D., 2016. Real-time loop closure in 2D LIDAR SLAM. In: Proceedings of the International Conference on Robotics and Automation, Stockholm, Sweden, May 16, 2016.

[13] Bohren, J. & Cousins, S., 2010. The smach high-level executive. IEEE Robotics & Automation Magazine, 17(4), pp. 18-20.

[14] Rösmann, C., Feiten, W., Wösch, T., Hoffmann, F., & Bertram, T., 2012. Trajectory modification considering dynamic constraints of autonomous robots. In: Proceedings of ROBOTIK 2012; 7th German Conference on Robotics. Munich, Germany, March 21, 2012.

[15] Smarsly, K., Dragos, K., Stührenberg, J., & Worm, M., 2023. Mobile structural health monitoring based on legged robots. Infrastructures, 8(9), 136.