A Smart System for Monitoring the Building Infrastructure and Utility

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Abstract

Many commercial buildings embrace various utility services such as heating and ventilation, mechanical piping, electricity system, elevators, and smart control systems. Moreover, especially work centres and institutions houses important assets and data. Especially at night when the staff and the visitors were not inside the building any malfunctioning or a natural hazard caused failed utility may cause unexpected losses and damages. Smart control systems of the building may not always notice the root cause of the malfunctioning and this may even be able to make the side effects of malfunctioning cause adverse consequences. In this study, an autonomous rover vehicle is introduced in order to detect any event causes damage to the building is introduced. The vehicle can rover inside the building and precisely locate itself by detecting its position and orientation by sinus theorem based positioning algorithm. Dedicated sensor holders were produced from 3D printers and laser distance measurement sensors were mounted on the sensor holder. The motors are controlled by motor controllers with h-bridge and pulse width modulation. Arduino Mega 2560 microcontroller controls the motors of the vehicle and makes necessary calculations to detect vehicle position and orientation. The rover can detect any adverse event by its optic camera. The leakage from the heating system of the civil engineering building located inside İnönü University was detected by the system. This proposed system provides important opportunity for timely detection of malfunctioning of the utility systems of the buildings.

1. Introduction

The first encounter of the construction design and project industry with digital technologies can be defined as computer-aided design (CAD). While CAD application has many benefits which are impossible to count utilization of CAD has made the design process quite easy, cost-effective, and fast. Moreover, making changes to a project drawing and communicating these changes to project stakeholders were executed easily. The necessary investments for CAD application can be listed as a computer, CAD software, and a technical drawing technician to use this system, all of which are relatively inexpensive and easy to recruit. Consequently, the use of CAD software does not present significant difficulties. However, the most important disadvantage of using CAD is that drawings may not open correctly on computers with different CAD versions due to incompatibility issues that may exist between different versions of CAD software. The construction industry has been able to overcome these drawbacks. Therefore, the use of CAD is quite widespread in the construction sector.

Technological advancements in software and hardware have rendered the benefits provided by CAD alone insufficient, and the more complex but more beneficial Building Information Modeling (BIM) approach and software have been developed. BIM applications offer stakeholders five key features: visualization, coordination, simulation, optimization, and drawing capabilities. BIM implementations reduce planning errors, perform rapid calculations, measure costs, and show changes (Alaloul et al., 2018).

Modeling a building with BIM presents significant challenges compared to drawing it using CAD. Besides the system cost, BIM use also requires the employment of personnel with a significant level of theoretical knowledge. Furthermore, information exchange among stakeholders is necessary in the design process. Designers who could not meet the specified requirements preferred to continue their designs using CAD instead of BIM, thus foregoing the benefits that BIM would provide. Therefore, the use of BIM in the design process in the construction industry has been lower than the use of CAD.

Advances in sensor technologies have facilitated data collection and enabled the acquisition of more precise data more economically. The progress of statistical software and the widespread use of artificial intelligence have made it possible to process and analyze the collected data cloud, generating meaningful information. Following these improvements, sensors are installed in buildings to collect data for various purposes, and by collecting and analyzing this data, inferences are made about building health, predictive maintenance, and energy efficiency. Data collected from the building's physical environment is evaluated through computer-based analyses, while simulations are performed on a digital copy of the building. While Digital Twin applications have very different levels of detail, a digital copy of the existing physical structure is created with sufficient detail to allow for the analysis of the collected data. The obtained data constitutes the input parameters for the analysis as model parameters on the created digital copy. Based on the analyses performed using the collected data, inferences are made about the building, its utility services, and the structural health. The models created are defined as follows: a digital model if it consists only of a static structure, a digital shadow if there is a one-way data flow from the structure, and finally, a digital twin if there is a bidirectional interaction between the physical structure and the virtual model (Opoku et al., 2021).

The Structure from Motion (SfM) Multi-View Stereo (MVS) algorithm holds a significant place in photogrammetry with its flexible and low-cost approach to reconstructing complex structures and areas. The SfM approach has made it possible to produce high-resolution data using collected images. This technique reconstructs a three-dimensional model of an object in focus by matching a series of two-dimensional images or photographs of the object, and therefore does not require expensive equipment for standard use (Yiğit and Uysal, 2023).

Although the implementation of digital twins has become cheaper, the high-cost sensor installation and continuous data collection process necessitate their application throughout the building's lifespan. Furthermore, highly qualified personnel are required to analyze and evaluate the collected data. Moreover, preventing unauthorized access to the data collected and generated about activities within the building is a significant challenge. For these reasons, digital twin applications remain relatively low compared to BIM. However, digital twin applications are common in factories, workshops, and workplaces where highly complex activities are carried out and have a widespread impact. Therefore, ensuring the successful implementation of digital twins is critically important. Consequently, significant literature studies have been conducted on the development of digital twin systems.

2. Literature Review

Digital Twin can serve as an Enabler for Intelligent Maintenance, Repair, and Operations (MRO). Product health status and remaining lifespan predictions can be used to perform proactive maintenance. In the event of a failure, ultra-high-resolution virtual models are used for diagnosis and analysis of the failures. Finally, the effectiveness and feasibility of MRO strategies are tested with virtual reality and augmented reality, contributing to product improvement (Qi and Tao, 2018).

The features that a digital twin system designed for a manufacturing plant should have are listed in five points by Kong et al. (2021). The listed properties are: Hierarchical Representation of Production Data, Characteristic Representation for Different Applications, Data Preprocessing for Raw Production Data, Customized Data Processing, and Storage and Retrieval Capability for Large-Scale Production Data. Sacks et al. (2020) have expanded the digital twin concept with "Digital Twin and Construction" (DTC), a data-centric planning and control mode for the construction industry. In this approach, digital representations of physical assets are continuously updated. DTC monitors both the geometry of a building and how it is constructed. Process information includes a wide range of data, from worker movements to materials used. This information is used to optimize both design and construction plans. Project Intent Information (PII) represents the goals in the design and construction phases, while the realized state Project Status Information (PSI) represents the actual construction process and results. DTC compares PII and PSI to support decision-making processes by transforming raw data collected from sensors into meaningful information.

Hasan et al. (2022) developed a Cyber-Physical System prototype compatible with BIM platforms. The developed prototype was tested at the laboratory level on small robotic analogues. This choice eliminated the need for expensive real-scale construction machinery. However, the developed system was designed to be applicable in real-world scenarios. A microcontroller sensor and actuator network was programmed to control the established physical model. In addition, the necessary software components for the Digital Physical Link were developed. On the developed Digital Physical Link (DPL) prototype, the physical model operation, Augmented Reality application, 3D digital model display, and sensor data accuracy were tested. As a result of the testing phase, the Augmented Reality controller delay was measured as approximately 0.25 seconds; Augmented Reality screen delay was measured as less than 0.1 seconds; and the delay of the digital twin due to Physical model movement and 3D model animation was measured between 0.5-1.0 seconds.

Digital twins have enabled projects to be completed more efficiently, safely, and sustainably thanks to features such as real-time monitoring, data analytics, and process optimization (Zhang et al., 2021). By implementing digital twin a 90% reduction in downtime in logistics processes was achieved. The main benefits that digital twin provided were reduced error rates in project planning, and more accurate results in design and assembly. Costs have been reduced and safety increased in the maintenance and management processes of structures. Su et al. (2023) proposed a 3+1 D model for the application of digital twin technology to the construction sector and identified the opportunities and challenges encountered in the proposed model. The first challenge is to model the physical structure accurately and with computational efficiency. The second difficulty is the emergence of communication problems due to different stakeholders in the project using incompatible software or data models. Accurately addressing real-world stressors in the simulation is also a significant challenge. The necessity of investing in simulation during design, robotics during construction, and monitoring technologies during the usage phase for an efficient digital twin application is described as the challenges of this technology. Digital model can also help reducing the environmental impact of the construction. Erzurum and Bettemir (2026) prepared a digital model of a faculty building inside the İnönü University campus and Khajavi (2019) created a Wireless Sensor Network (WSN) installed on the facade of an office building at Aalto University in Finland to collect data on ambient light, temperature, and relative humidity measurements in order to more deeply investigate the creation and benefits of digital twins. After analysing the performance of the system it was reported that Bluetooth signals were weakened due to the thick, double-layered glass. Furthermore, the Bluetooth and Wi-Fi conflict was resolved by using a USB Bluetooth dongle for the gateway. Data transmission issues arising from the use of numerous sensors were resolved by assigning the sensors to specific gateways and extending the data transmission intervals.

Ergen and Bettemir (2026) prepared the digital model of a building and extracted the rebar scan data to the formed digital model. The scanned rebar referenced with respect to the building coordinate system and represented in 3D. The visualization of the rebar was overlapped with the corresponding columns and as-built rebar detailing is obtained in 3D.

Feng et al. (2021) examined articles published between 2016 and 2021 to investigate the applications and challenges of digital twins in improving their integration into construction. The manuscripts were obtained using the keywords "digital twin in construction", "semantic web", "artificial intelligence", "construction 4.0" and "BIM". The authors noted that significant benefits could be achieved through the information extracted from the analysis of data using a Knowledge Engine. Tao et al. (2018) analysed the current state of digital twins in

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the industry by reviewing 50 articles, 8 patents, and best practices from 6 leading companies. Digital twins were examined and theories were investigated from four perspectives: modelling, simulation, verification, validation, and accreditation (VV&A), data fusion; interaction and collaboration; and service. Digital twins have provided significant improvements in areas such as process monitoring, failure prediction, productivity enhancement, and maintenance optimization. In addition digital twin implementation increases operational efficiency and reliability. Hu et al. (2022) reviewed 182 academic studies to analyse the use and technological architecture of digital twins. Hu also systematically categorized the results. The analysis on the past studies revealed that digital twins improve project management in the construction industry by automating data collection, analysis, and decision support processes. However, high initial investment costs and complex data management requirements hinder widespread adoption of these technologies. Furthermore, the temporary equipment structure on construction sites necessitates the development of cost-effective digital twin systems.

Opoku et al. (2021) analysed studies on digital twin applications in the construction sector between 2010 and 2020. The analyses revealed that the United Kingdom, China, and the United States are forerunners in developing digital twin technology, but the investigation of the studies revealed the lack of a strong collaboration among institutions.

3. Motivation

Recent developments in the field of autonomous vehicles made autonomously execution of earthwork possible (Bettemir, 2026). This encouraged handling indoor activities and tasks in an autonomous manner. In this study, an autonomous vehicle with multi-sensor integration to monitor indoor environmental conditions in real time is developed. The proposed model aims to enable early detection and prevention of potential risks. Inside a building the orientation of the vehicle is lost if it is provided by an inertial measurement unit. In this study a new measurement system is proposed which uses laser distance measurement sensors with different angle constellation. The heading angle of the rover can be detected by forming triangles from the range measurements and then applying the sinus theorem. After detecting the orientation of the vehicle local position with respect to local coordinate system of the vehicle is computed by considering its heading and the distance measurements.

The vehicle can accommodate temperature and humidity sensors, as well as optical and thermal camera. The proposed system can collect data from the environment as the vehicle moves with the aim to create a digital twin of the building. This allows for the detection of changes in humidity levels, enabling the prevention of events such as flooding. Smart building systems and digital twin technologies are of great importance for building safety. Digital twins, powered by real-time data, enable critical functions such as real-time status monitoring, anomaly detection, early warning, and the development of preventive systems.

4. Methodology

The developed vehicle is equipped with laser range sensors mounted on plates placed on all four sides of the vehicle. These sensors enable the vehicle to navigate and determine direction, avoid obstacles and irregularities, and collect data to create a digital twin of its surroundings. The distance measurement sensors were mounted by making 15 degrees angle with respect to the centre point which constitutes the top of the triangle that will be formed by the sinus theorem. The sensor holders were manufactured by 3D printer as shown in Figure 1.

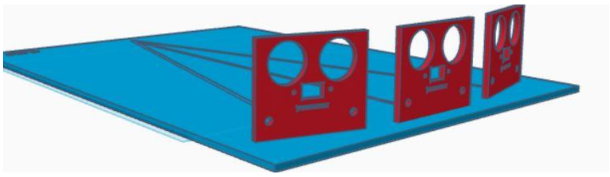

Figure 1. 3D drawing of the sensor holders.

The sensor holders were designed to hold many distance measurement sensor including sonar, laser and infrared. The printed sensor holder is shown in Figure 2.

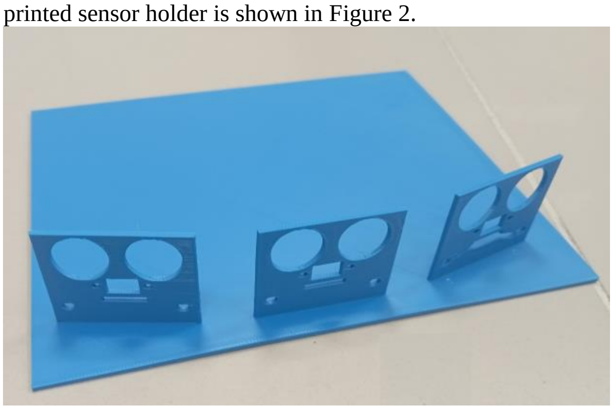

Figure 2. Printed version of the sensor holders.

Before the implementation of 3D printing technology the sensor holders were manufactured by manually measuring and marking the inclination angle and the positions of the sensor holders. The pre-supplied mass production sensor holders were assembled on the metal plates as shown in Figure 3.

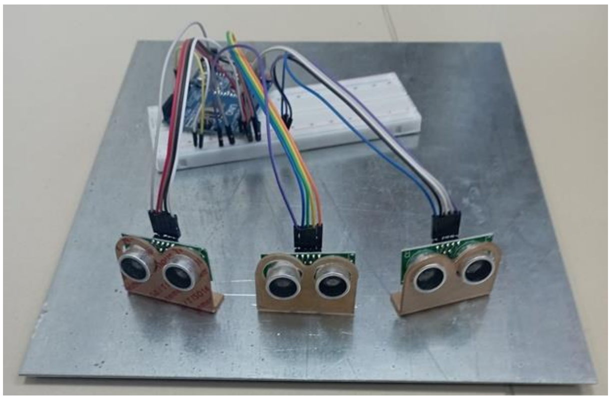

Figure 3. Manually prepared sensor holder.

In Figure 3 US-100 ultrasonic distance measurement sensors mounted on the sensor holder were seen. Even though the sensor positions and the sensor orientations were marked with the utmost care, the sensor positions and orientations deviate from the ideal position and orientation due to the mistakes in the manufacturing process. Even 1 mm of drilling misalignment of the screw holes can lead to 5 degrees of deviation in sensor alignment. Therefore, the orientation computed by the sensor holder shown in Figure 3 ended with more than 5 degree of standard deviation. Therefore 3D printed sensor holders were preferred as shown in Figure 4.

Figure 4. 3D printed sensor holder with TOF400C-400cm laser distance measurement unit

The vehicle performs wall tracking and scanning from the left side. For this reason, a temperature and humidity sensor, a thermal camera, and an optical camera are placed on the left-hand plate in addition to the ultrasonic sensors. The developed vehicle and plate placements are shown in Figure 5.

Previously, the distance measurement sensors are mounted on metal plates in order to fix their angle and relative positions fixed. The metal plates were intended to protect the sensors from any possible impacts and to reduce the installation time during assembling and disassembling (Kaya et al. 2026). However, using metal plates increases the possibility of short circuit. Therefore, they were replaced by 3D printed plates made from filament.

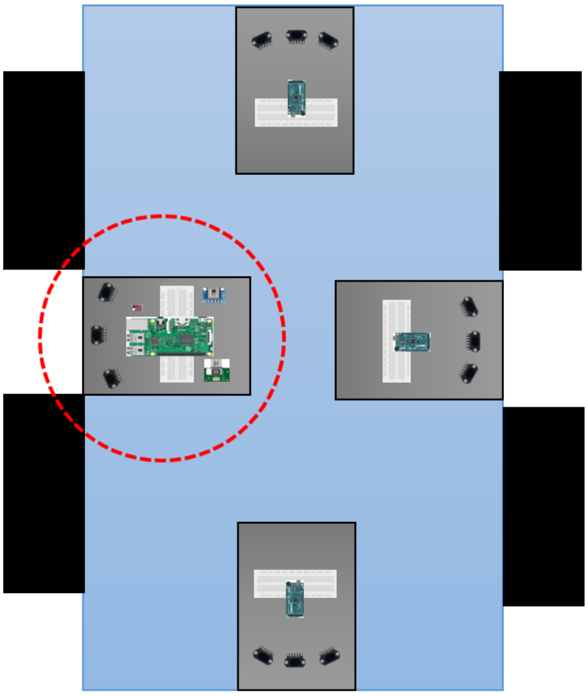

Figure 5. Schematic view of the autonomous vehicle assembled with distance measurement, humidity, temperature sensors as well as optic camera.

US100 wall sensors are more precise than HC-SR04 sensors their capabilities are not adequate. Therefore, US100 sensors were replaced by TOF400C-400cm laser distance measurement sensors. The utilized sensor is a cheap but accurate measurement unit. However, during the measurement the sensor produces noise due to the sensor heat and disturbing effects. The tests on the sensor revealed that making continues measurements of the same distance produces important errors. Therefore, a distance is measured 70 times the maximum and the minimum of the measurements were eliminated and the average of the remaining 68 distance measurements was computed. This approach provided more stable results. Then by using the law of sine based orientation computation approach the orientation of the vehicle is computed. The obtained orientation angles are given in Table 1.

S1(mm)	S2(mm)	S3(mm)	Alpha1	Alpha2	Alpha3
247.1	246.5	262.6	6.47	5.99	6.97
247.7	246.7	262.8	6.32	6.03	6.63
247.5	246.7	263.1	6.49	6.2	6.8
247.4	246.8	263.2	6.58	6.21	6.99
246.8	247	262.9	6.7	5.85	7.6
247.1	246.8	262.9	6.59	6.01	7.19
247.4	246.8	263.1	6.54	6.11	6.99
247.4	246.8	263	6.52	6.07	7
247.4	246.9	263.2	6.57	6.13	7.03
247.7	247.1	262.8	6.31	5.74	6.92
247.3	246.8	263.1	6.61	6.17	7.09
247.6	246.8	263	6.42	6.06	6.8
246.9	246.9	263	6.7	5.98	7.47
246.8	246.6	263.2	6.82	6.41	7.26
247.6	246.8	263	6.41	6.07	6.77
247.5	246.9	263.4	6.65	6.27	7.05
247.7	246.8	262.9	6.36	6.06	6.68
247.1	247	262.9	6.59	5.8	7.43
247	246.7	263.2	6.75	6.27	7.26
247.1	246.6	262.9	6.61	6.17	7.08
247.5	246.9	263.1	6.51	6.06	6.98
247.5	247	263.3	6.56	6.13	7.01
247.8	247	263.3	6.44	6.16	6.75
247.2	246.8	263.2	6.7	6.28	7.15
247	246.8	263.1	6.75	6.15	7.4
247.7	246.8	263.3	6.5	6.35	6.67
247.5	246.9	263.2	6.57	6.21	6.94
247.1	246.8	263.2	6.72	6.24	7.22
247.8	246.9	263.1	6.36	6.04	6.7
247.5	247.1	263.2	6.57	5.99	7.19
247	246.9	263.1	6.73	6.08	7.42
247.5	246.8	263.3	6.59	6.29	6.91
247	247.2	263.4	6.83	6.1	7.59
247.9	246.9	263.2	6.38	6.11	6.67
247.7	246.9	263.3	6.54	6.29	6.8
247.2	246.7	263.3	6.71	6.37	7.07
248.1	246.8	263.3	6.32	6.27	6.38
247.6	247	263.1	6.45	5.95	6.97
247.3	247.2	263.4	6.74	6.11	7.4
246.7	246.9	263.1	6.82	6.06	7.63
248.1	247	263.4	6.39	6.25	6.54

Table 1. Orientation detection computed without averaging the orientation

In Table 1 three distance measurements were reported since a sensor holder accommodates 3 distance measurement units. The first 3 columns of the Table 1 illustrate the averaged distances obtained from the distance measurement units. One row in the table contains the measurements conducted in one epoch. The vehicle stood still during the measurement so that the same distances were measured. The standard deviations of the distance measurement were computed as 0.278656095, 0.123091491, 0.417412556 mm. The obtained precision is acceptable for a low price unit. The alpha1 to 3 columns present the orientation angle of the vehicle computed by the law of sine. It was expected that all of the alpha angles be equal to each other but it is seen that the angles deviate. The averages of the conducted orientation measurements were computed as 5.736060606, 5.474545455, and 6.011818182 degrees. The standard deviations were computed as 0.227595327, 0.346480931, and 0.244793723 for the orientation. The obtained orientation precision is moderate. The obtained orientation precision is moderate.

In order to improve the standard deviation of the orientation angle the computation process is repeated 5 times and orientation angles are reported after averaging the 5 measurements. The results were presented in Table 2.

S1(mm)	S2(mm)	S3(mm)	Alpha1	Alpha2	Alpha3
246,4	244,6	260,1	5,76	5,59	5,93
246,2	244,8	259,9	5,76	5,35	6,2
246,2	244,8	260,1	5,86	5,48	6,27
246,5	244,6	260	5,71	5,56	5,87
245,9	244,7	260,4	6,11	5,75	6,49
246,1	244,8	260	5,84	5,38	6,32
246	244,6	260,4	6,03	5,85	6,21
246,6	244,8	260,4	5,78	5,68	5,88
246,6	244,7	260,3	5,75	5,7	5,81
246,3	244,7	260,5	5,96	5,81	6,13
246,4	244,8	260,3	5,85	5,58	6,14
246,5	244,9	260,4	5,81	5,63	6
246,7	244,8	260,3	5,71	5,61	5,81
246,2	244,7	259,8	5,73	5,29	6,19
246,5	245	260	5,7	5,24	6,19
246,6	244,8	260,2	5,71	5,53	5,9
246,8	244,9	260,1	5,57	5,36	5,8
246,9	244,9	260,3	5,62	5,51	5,74
247	244,8	260,1	5,48	5,49	5,47
246,3	244,8	260	5,73	5,35	6,14
246,6	244,8	260,1	5,69	5,52	5,87
246,4	244,9	260	5,72	5,27	6,19
246,7	244,9	260,3	5,72	5,56	5,88
247	244,9	260,1	5,53	5,4	5,67
246,7	245	260,2	5,69	5,33	6,06
246,4	244,8	260,3	5,85	5,58	6,13
246,4	245,1	260,4	5,89	5,44	6,36
246,3	244,8	260,2	5,81	5,51	6,14
246,8	244,5	260,3	5,69	5,86	5,52
246,4	244,7	260,6	5,96	5,91	6,01
246,2	244,8	260,2	5,87	5,5	6,25
247	244,8	258	4,68	3,79	5,6
246,4	244,9	260	5,72	5,25	6,22

Table 2. Orientation detection computed with averaging the orientation

The standard deviations of the distance measurement were computed as 0.34327048, 0.147958545, and 0.183170569 mm. The obtained precisions were similar to the previous measurement cycle but the precision of the first and the third measurements were lower than the others. The averages of the conducted measurements were computed as 6.565609756, 6.124146341, 7.034146341 degrees and the standard deviations were computed as 0.145904225, 0.144963841, 0.298761473 for the orientation. The measurements demonstrate that significant improvement is obtained in the precision of the orientation.

The temperature and humidity sensors as well as the microcontroller are located on the plate highlighted within the red circle are shown in detail in Figure 5. The microprocessor-based Raspberry Pi was chosen for processing data from the sensors and analysing images obtained from optical and thermal cameras. Wiring diagram of the sensors were given in Figure 6. The obtained temperature and humidity data were assessed and interpreted real time. On the other hand, optic visible band images and thermal images are analysed and assessed after the rover completes its tour inside the building.

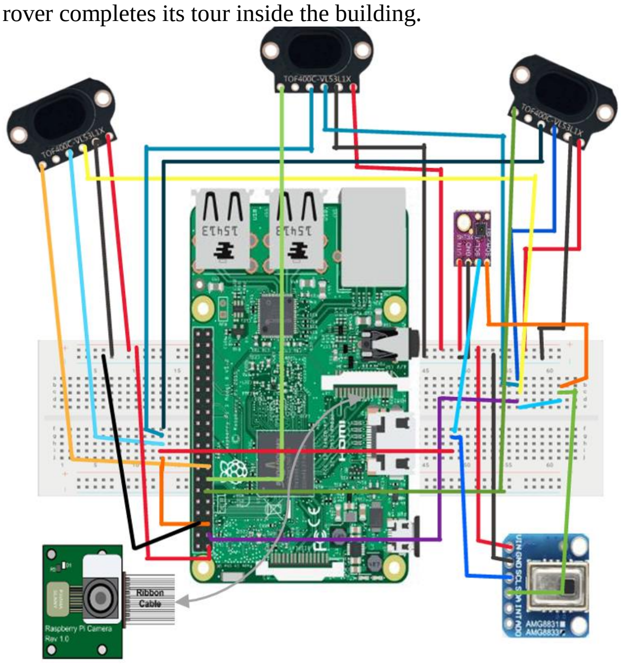

Figure 6. Wiring schema of the sensors utilized on the rover

Data from the humidity sensor is used to detect changes in ambient humidity. This data has vital importance on the detection of leakages from utility facilities such as radiators and water pipes. Leakages may also affect the temperature of the medium as vaporizing water may cool the medium unless the water is hot. Temperature sensor can also be a complementary sensor for detecting such anomalies. However, an open window or a tea kettle left on intentionally in a room can also affect the room temperature and humidity levels. For this reason, supplementary data is required to ensure robust fault detection. The developed model is enhanced a thermal camera that senses temperature differences in scanned areas. Besides the thermal camera an optical camera is used to identify phenomena such as colour changes caused by dampness on the wall surface.

5. Case Study

On April 8th a utility failure happened in the building of Civil Engineering Department of İnönü University (Malatya, Türkiye). At night one of the hot water pipes of the heating system began leaking when noone was inside the building. The leakage was at the third floor of the building. The leakage had arrived to the ground floor in the morning. Figure 7 shows dampness and moisture on the wall due to a malfunction in the heating pipe.

The humidity readings inside the room and outside the room were completely different. Only the humidity readings can be enough to detect there was an abnormal phenomena. However, solely the humidity sensors cannot be adequte to detect the problem related with the heating system of the building. This is because the increase in humidity can be caused by the leakage from the roof, watering the plants, or cleaning the floor with a wet mob.

The room at where the contradicrious humidity values were also scanned by optical and thermal images. In both images the leakages were manually detected. The mnual inspection can be cınducted after receving extraordinary sensor readings which do not cause immense workload.

Thanks to the tool developed in this study, a digital twin of the building can be created, allowing for the early detection and prevention of risks such as water leaks within the building. The developed system will be able to identify abnormal conditions at the initial stage by analyzing sensor data. In this way, it can prevent the malfunctions caused by the heating system as shown in Figure 7. The aforementioned mulfunctioning may damage the electric circuits of the building and cause short circuit if the leakage progressed and reached any electric utility.

Figure 7. The observed leakage on the wall

6. Conclusion

Early detection of any malfunctioning of the utility services inside the building has vital importance. In the given case study example thousands of litres of hot water leaked outside the pipes and caused waste of important energy. Moreover, some of the leaked water propagated inside the building via walls as shown in Figure 7. This also deteriorated the walls, ceiling covering, plastering and paint of the building. Early detection could probably prevent the immense leakage and reduce the waste and damage of the malfunctioning. Smart infrastructure monitoring systems provides important benefits on the building management.

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References

Alaloul. W. S., Liew. M. S., Zawawi. N. A. W. A., Mohammed, B. S. (2018), Industry Revolution IR 4.0: Future Opportunities and Challenges in Construction Industry, *MATEC Web of Conferences 203*, 02010.

Bettemir, Ö. H. (2026). Autonomous Grading Maneuver Determination Algorithm for Electric Dozers. *Journal of Field Robotics*, 43(4), 2785-2804.

Doğan, N., Şengül, A. N., Uzunkaya, A., Kaya, M., & Bettemir, Ö. H. (2026). Development of a Land Vehicle and Data Acquisition System for Building Audit. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 111-118.

Ergen, F., & Bettemir, Ö. H. (2026). BIM-integrated digital twin framework for data collection and assessment of existing RC buildings. Expert Systems with Applications, 133555.

Erzurum, T., & Bettemir, Ö. H. (2026). Development of a comprehensive multi-criteria decision support system for assessing the environmental and cost impacts of buildings. Sustainable Cities and Society, 107521.

Feng, H., Chen, Q., & de Soto, B. G. (2021). Application of digital twin technologies in construction: an overview of opportunities and challenges. *In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 38, pp. 979-986). IAARC Publications.

Hasan, S. M., Lee, K., Moon, D., Kwon, S., Jinwoo, S., & Lee, S. (2022). Augmented reality and digital twin system for interaction with construction machinery. Journal of Asian Architecture and Building Engineering, 21(2), 564-574.

Hu, W., Lim, K. Y. H., & Cai, Y. (2022). Digital twin and industry 4.0 enablers in building and construction: a survey. *Buildings*, 12(11), 2004.

Kaya, M., Doğan, N., Bettemir, Ö. H. (2026). Law of Sines Based Approach for the Accurate Orientation Determination. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 187-193.

Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmström, J. (2019). Digital twin: vision, benefits, boundaries, and creation for buildings. *IEEE access*, 7, 147406-147419.

Kong, T., Hu, T., Zhou, T., & Ye, Y. (2021). Data construction method for the applications of workshop digital twin system. *Journal of Manufacturing Systems*, 58, 323-328.

Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, 40, 102726.

Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. IEEE Access, 6, 3585-3593.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, 1, e14.

Su, S., Zhong, R. Y., Jiang, Y., Song, J., Fu, Y., & Cao, H. (2023). Digital twin and its potential applications in construction industry: State-of-art review and a conceptual framework. Advanced Engineering Informatics, 57, 102030.

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. (2018). Digital twin in industry: State-of-the-art. *IEEE Transactions on industrial informatics*, 15(4), 2405-2415.

Yiğit, A. Y., & Uysal, M. (2023). Dijital ikizlerin geliştirilmesinde fotogrametrinin kullanımı ve artırılmış gerçeklik ile görselleştirilmesi. *Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi*, 12(4), 1372-1384.

Zhang, H., Zhou, Y., Zhu, H., Sumarac, D., & Cao, M. (2021). Digital twin-driven intelligent construction: features and trends. *Structural Durability & Health Monitoring*, 15(3), 183.