Advancing civil infrastructure assessment through robotic fleets

Kay Smarsly* and Kosmas Dragos

Hamburg University of Technology, Institute of Digital and Autonomous Construction,

Blohmstraße 15, 21079 Hamburg, Germany

Abstract

Modern civil engineering structures, instrumented with Internet-of-Things-enabled smart sensors and actuators, are considered cyber-physical systems that integrate physical processes with computational and communication elements. This short communication aims to portray a milestone in the field of monitoring and inspection of civil infrastructure, collaboratively conducted by autonomous, robotic devices orchestrated in robotic fleets. It is expected that robot-based civil infrastructure assessment will revolutionize structural maintenance of the deteriorating building stock, which is increasingly exacerbated by the effects of climate change and develops into a major societal challenge.

Introduction

Deteriorating and damaged civil infrastructure poses significant hazards to public safety and represents a major economic challenge of modern societies. Stress exerted on civil infrastructure under operational conditions, over extended periods of time, contributes to aging-induced structural degradation, which is an issue that is frequently overlooked when developing smart city concepts. The degradation of infrastructure is further exacerbated by population growth and urban overcrowding, surpassing the original design capacities of civil infrastructure, as well as by exposure to adverse weather phenomena, as a result of the effects of climate change, such as floods, storms, and heatwaves (1).

In light of potential hazards posed to public safety, the issue of deteriorating civil infrastructure has been raising increasing public concern, with attempts to mitigate its adverse effects being underway, usually in the context of predictive maintenance (2). In addition to public safety, modern societies seek to ensure the uninterrupted operation of civil infrastructure for economic purposes. For example, if structural damage is not promptly addressed by appropriate repair and rehabilitation measures, direct costs (repair) as well as indirect costs (loss of operability) may increase exponentially, thus highlighting the importance and urgency of appropriate monitoring strategies.

State-of-the-art monitoring strategies frequently make use of structural response data, collected by sensor networks (3). Nonetheless, requirements for sensors, cabling, data acquisition units and permanent installations thereof, are likely to conflict with budgetary and aesthetic constraints of civil infrastructure, hence rendering current monitoring strategies impractical for widespread application across large parts of the building stock.

Alternative monitoring strategies foster wireless technologies, mainly seeking to promote cost-effective, flexible sensor networks consisting of wireless sensor nodes, which are equipped with embedded models and algorithms for automated, decentralized on-site data analysis (4). While the elimination of cabling indeed results in significant cost reduction, as well as in enhanced network scalability, wireless sensor networks have yet to gain the wide trust of practitioners. Hindering factors against employing wireless technologies are the limited reliability of wireless communication and the finite power autonomy; both these factors being of utmost importance for permanent installations and continuous monitoring (5). As a result, innovative approaches that transcend conventional practices are required to enable monitoring of large parts of the building stock and, thus, address the societal challenge of deteriorating civil infrastructure (6).

Autonomous civil infrastructure assessment through robotic fleets

In recent years, autonomous robotic monitoring strategies have been proposed, following the advances in robotics, smart cities, and cyber-physical systems research (7, 8). The idea behind autonomous robotic monitoring is to employ robots, equipped with sensors, that are able to scan large areas of civil infrastructure and that act as mobile, IoT-enabled cyber-physical systems (9). The monitoring processes may be conducted on board the processors of the robots, using embedded algorithms for wirelessly communicating and for analyzing structural response data. In essence, autonomous robotic monitoring systems constitute "refined" versions of wireless sensor networks, substituting stationary sensor nodes by robotic fleets. At a first glance, the direct analogy between autonomous robotic monitoring and conventional wireless sensor networks arguably renders the autonomous robotic monitoring solution onerous, considering the unit price of robotic devices. Budgetary requirements, however, may be offset by the benefits of autonomous robotic monitoring systems, which are summarized below:

- Autonomous robotic monitoring systems are reusable, without requiring any installation/uninstallation efforts, and can, thus, be used to conduct monitoring across large parts of the building stock (10).
- The ability of robots to scan large areas on civil infrastructure results in rich information on the structural condition, as opposed to the relatively few points measured by stationary sensor nodes (11).

- The flexibility of robotic devices to autonomously navigate across civil infrastructure allows reducing the robotic fleet of an autonomous robotic monitoring system to a minimum (12).

An important aspect for ensuring efficiency in robotic monitoring is the agility of the robotic devices. In this context, the focus of the discussion herein deviates from early practices on autonomous robotic monitoring of civil infrastructure, which are based on wheeled robots, and is shifted towards legged robots. Owing to the enhanced locomotion capabilities, legged robots are capable of autonomously traversing surfaces with impediments, which are frequently encountered in civil infrastructure. As such, autonomous robotic monitoring systems based on legged robots are capable of navigating large civil engineering structures.

In this context, we are proposing a methodology to advance civil infrastructure assessment through monitoring conducted by fleets of collaborating, legged robots, validated in detail in (13). As shown in Figure 1, first, the monitoring tasks are allocated to the legged robots involved in monitoring. For coordination, cooperation, and collaboration, the robots communicate and navigate to the measurement locations using lidar-based simultaneous localization and mapping. Next, the robots synchronize their internal clocks using the "precision time protocol", defined by the IEEE 1588-2008 standard (14); synchronization is verified also at the post-sampling stage based on the slope of the cross-spectral density phase angle (15). Then, the robots switch to the "measuring posture" to start recording data relevant to monitoring-based civil infrastructure assessment, such as images, acceleration measurements, and laser scans. Once data acquisition is complete, the robots analyze the data using embedded software. Frequently, data analysis when monitoring civil infrastructure entails detecting damage, either on a local level (such as identifying cracks in concrete through visual analysis based on images) or on a global level, e.g. by investigating the structural dynamic behavior via modal analysis, based on acceleration data recorded under operational conditions (16, 17). As for the latter, a minimum of two legged robots would be necessary, since estimating the structural dynamic behavior requires synchronized structural response data from at least two locations. Last, but not least, and particularly relevant to monitoring during the construction process of civil infrastructure, geometric analyses are conducted using laser scans. In either way, applying artificial intelligence techniques for data analysis is generally state of the art. Finally, through Internet-of-Things technologies, the analysis results, i.e. the information extracted from the data, is transferred to a centralized server that hosts a digital twin of the structure to be assessed, which typically consists of finite element models and building information models (18). The models are updated with the newly extracted information and used for decision support with respect to civil infrastructure assessment.

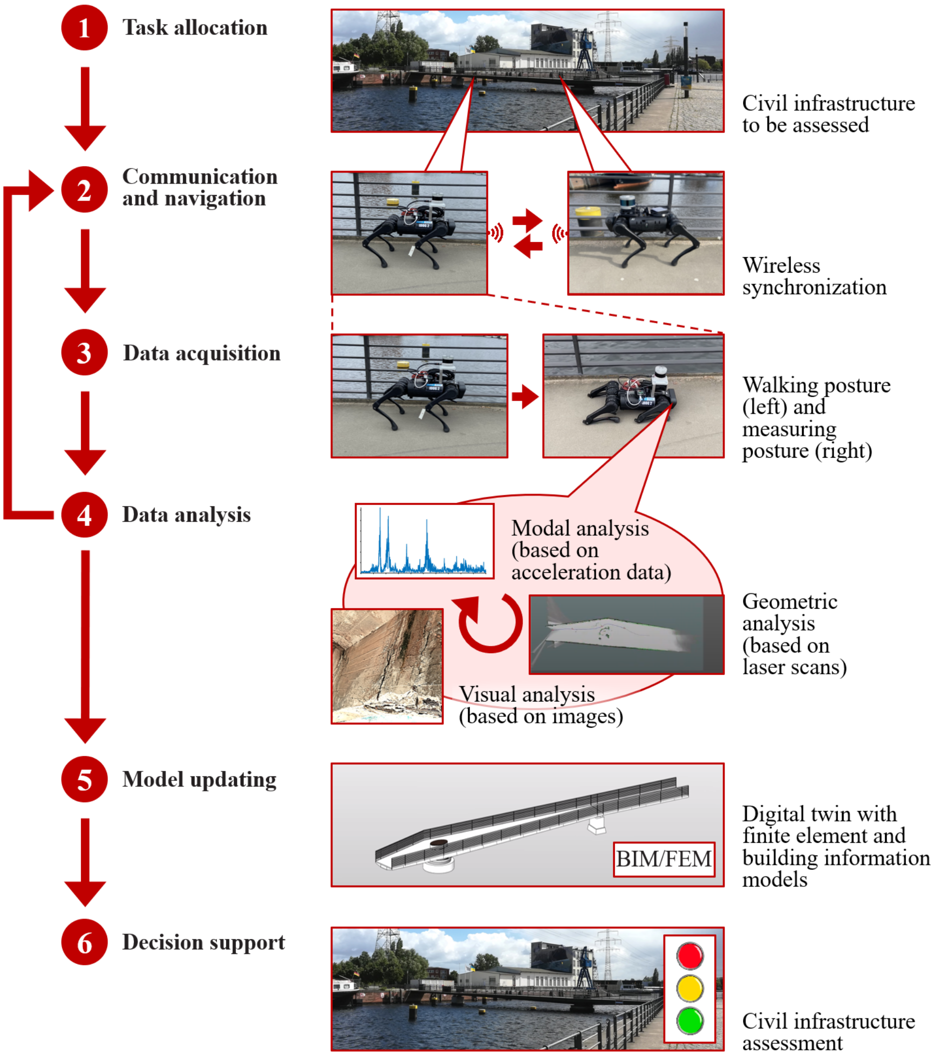

Figure 1. Civil infrastructure assessment using autonomous robotic monitoring systems.

For validating the proposed concept in field tests, a prototype autonomous robotic monitoring system is implemented, consisting of a fleet of legged robots. The hardware is centered on the robot model A1 of Unitree Robotics (19), and it is supplemented by further sensing components required for civil infrastructure assessment. Specifically, an inertial measurement unit, type LORD MicroStrain 3DM-GX5-AHRS (20), is attached to the robots for recording acceleration response data, using a built-in accelerometer that is capable of recording data at a maximum sampling rate of 1 kHz, within a range of ± 8 g, and with a resolution of 0.02 mg. In addition, a light-weight Lidar sensor, type Velodyne Lidar Puck LITE (21), is attached to the robots for simultaneous localization and mapping based on laser-scanned point clouds. The Lidar sensor has a range of 100 m and generates approximately 300,000 points/second from a 360° horizontal field of view. In the prototype system, wireless communication is accomplished within a local 5G WiFi network, which is also used to transfer the data to a server-side digital twin, implemented in terms of a building information model in compliance with the Industry Foundation Classes standard (22). In the field tests, conducted at a number of bridges in Germany, the autonomous robotic monitoring system has proven capable of scanning large areas on the bridge decks, while effectively navigating and localizing itself on measurement locations. Also, the autonomous robotic monitoring system has proven capable of yielding reliable information relevant to assessing civil infrastructure with accuracy comparable to a wireless sensor networks, comprising state-of-the-art stationary wireless sensor nodes. In particular, the autonomous robotic monitoring system has been tasked to progressively navigate measurement locations on the bridge deck, and collect structural response data in pairs with overlapping locations. Subsequently, the analysis of the structural response data has enabled identifying eigenfrequencies and estimating vibration mode shapes, by synthesizing the results from every pair of measurements.

Summary and conclusions

In summary, autonomous robotic monitoring shows the potential to address the challenges in monitoring of civil infrastructure. Deploying robotic fleets in lieu of stationary wireless sensor nodes may result in efficient, non-invasive monitoring that yields rich information on the structural condition. Furthermore, the transportability of the robotic monitoring system enables reusing the system across large parts of the building stock. The proposed methodology represents a first step in adopting legged robots for monitoring civil infrastructure. Questions including the autonomous navigation of legged robots, as well as the ability of the robots to reach hardly accessible locations, are still open. Furthermore, in light of digital cities and ageing infrastructure, it seems promising to couple land-based, water-based, and aerial robots, to achieve a broader picture of the infrastructure to be assessed. Such coupling requires a joint understanding of the robotic fleets regarding the communication and the models (or the digital twins) to be updated. Nevertheless, in the future, the ubiquity of robotic devices is expected to further expedite the transition of the proposed methodology to practice, effectively addressing the escalating challenges posed by deteriorating and damaged civil infrastructure, thus mitigating the hazards posed to public safety and economy.

References

1. Buhl, M. and Markolf, M., 2023. A review of emerging strategies for incorporating climate change considerations into infrastructure planning, design, and decision making. *Sustainable and Resilient Infrastructure*, **8**(S1), 157–169.
2. Zonta, T., Da Costa, C.A., Righi, R., De Lima, M.J., Da Trindade, E.S., and Li, G.P., 2020. Predictive maintenance in the Industry 4.0: A systematic literature review. *Computers and Industrial Engineering*, **150**, 106889.
3. Farrar, C.R. and Worden, K., 2006. An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A*, **365**(1851), 303–315.
4. Lynch, J.P. and Loh, K., 2006. A summary review of wireless sensors and sensor networks for structural health monitoring. *Shock and Vibration Digest*, **38**(2), 91–128.

5. Nagayama, T., Sim, S.H., Miyamori, Y., and Spencer Jr., B.F., 2007. Issues in structural health monitoring employing smart sensors. *Smart Structures and Systems*, **3**(3), 299–320.
6. Kot, P., Muradov, M., Gkantou, M., Kamaris, G.S., Hashim, K., and Yeboah, D., 2021. Recent Advancements in non-destructive testing techniques for structural health monitoring. *Applied Sciences*, **11**(6), 2750.
7. Zhu, D., Yi, X., Wang, Y., Lee, K.-M., and Guo, J., 2010. A mobile sensing system for structural health monitoring: Design and validation. *Smart Materials and Structures*, **19**(5), 55011–55021.
8. Ashraf, S., 2021. A proactive role of IoT devices in building smart cities. *Internet of Things and Cyber-Physical Systems*, **1**(2021), 8–13.
9. Scuro, C., Lamonaca, F., Porzio, S., Milani, G., and Olivito, R.S., 2021. Internet of Things (IoT) for masonry structural health monitoring (SHM): Overview and examples of innovative systems. *Construction and Building Materials*, **290**(2021), 123092.
10. Tian, Y., Chen, C., Sagoe-Crentsil, K., Zhang, J., and Duan, W., 2022. Intelligent robotic systems for structural health monitoring: Applications and future trends. *Automation in Construction*, **139**(2022), 104273.
11. Halder, S. and Afsari, K., 2023. Robots in inspection and monitoring of buildings and infrastructure: A systematic review. *Applied Sciences*, **13**(4), 2304.
12. Junho Lee, A., Song, W., Yu, B., Choi, D., Tirtawardhana, C., and Myung, H., 2023. Survey of robotics technologies for civil infrastructure inspection. *Journal of Infrastructure Intelligence and Resilience*, **2**(1), 100018.
13. Smarsly, K., Dragos, K., Stührenberg, J., and Worm, M., 2023. Mobile structural health monitoring based on legged robots. *Infrastructures*, **8**(9), 136.
14. The Institute of Electrical and Electronics Engineers, 2008. *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems (1588-2008)*. IEEE: New York, NY, USA, 2008.
15. Dragos, K., Magalhães, F., Manolis, G.D., and Smarsly, K., 2024. Frequency-domain synchronization of structural health monitoring data. *Journal of Sound and Vibration*, **571**(2024), 118017.
16. Fritzen, C.-P., 2005. Vibration-based structural health monitoring – Concepts and applications. *Key Engineering Materials*, **293–294**, 3–20.
17. Milani, G. and Clementi, F., 2019. Advanced seismic assessment of four masonry bell towers in Italy after operational modal analysis (OMA) identification. *International Journal of Architectural Heritage*, **15**(1), 157–186.
18. Pierdicca, A., Clementi, F., Fortunati, A., and Lenci, S., 2019. Tracking modal parameters evolution of a school building during retrofitting works. *Bulletin of Earthquake Engineering*, **17**(2019): 1029–1052.
19. Unitree Robotics, 2023. A1 robot, https://www.unitree.com/products/a1/ (accessed on: 10/05/2023).

20. Microstrain Sensing, 2020. *MicroStrain Sensing Product Datasheet: 3DM-GX5-AHRS*. Parker Hannifin Corp: Williston, VT, USA, 2020.
21. Velodyne Lidar, 2023. Puck LITE, https://velodynelidar.com/products/puck-lite/ (accessed on: 10/06/2023).
22. International Organization for Standardization (ISO), 2018. *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*. ISO 16739:2018.

Funding: Supported by the German Research Foundation (DFG) under grant DFG SM 281/20-1.