32ND RESEARCH SYMPOSIUM ASNT | EVENTS.

Presented At: ASNT Research Symposium:
25 – 28 June 2024
Pittsburgh, Pennsylvania, USA

A multi-scale approach for scanning small cracks in concrete structures using an AI guided robotic arm

Ali Ghadimzadeh Alamdari [1], Arvin Ebrahimkhanlou [1, 2, *]

[1]Drexel University
Department of Mechanical Engineering and Mechanics, Drexel University
(575) 418-0624; email ag4328@drexel.edu

[2]Drexel University
Department of Architectural, Civil and Environmental Engineering, Drexel University
(215) 571-3786; email ae628@drexel.edu

ABSTRACT

In the realm of civil infrastructure, detecting and analyzing small-scale defects, such as cracks is often challenging due to the large scale of the structure. Even with the advancement of the AI algorithms and high resolution of vision systems, still some defects are either missed or falsely detected. This paper presents a novel robotic technique aimed at addressing this challenge by imitating human inspectors' approach for bridging the scale difference: getting closer to the potential cracks. In this way, the proposed multi-scale approach provides precise measurement of the dimensions, contours, and attributes of even hairline cracks in concrete structures across multiple scales. Our approach utilizes a convolutional neural network for the initial identification of potential surface cracks. Following detection, these small-scale cracks undergo a detailed examination using a high-definition laser scanning system, operated by a robotic arm. This laser scan data is then merged with extensive environmental scans conducted using LiDAR technology, applying 3D point cloud alignment techniques for comprehensive analysis. The effectiveness of this methodology is corroborated through robotic simulations and testing on a physical concrete specimen. This technique achieves a remarkable resolution in crack width measurement, down to 0.004 mm, and has been successfully applied to real-world cracks as narrow as 0.17 mm. Additionally, a comparative study with existing vision-based methods and conventional crack-width measuring tools highlights the enhanced accuracy and efficiency of our multi-scale robotic system. This system plays a critical role in gathering essential data for the evaluation and maintenance of civil infrastructures.

Keywords: robotic inspection, structural health monitoring, automated defect measurement, structural health monitoring

ITRODUCTION

Cracks in reinforced concrete structures are a common yet potentially serious issue, influenced by aging, environmental factors, and loading conditions. Identifying these cracks, especially smaller-scale ones like hairline fractures, is critical for ensuring structural assessment [1]. Traditional manual inspections, however, are subject to human error and variability [2]. Recent technological advancements, particularly in robotics, offer a more reliable solution. Automated systems, employing non-destructive testing methods, can consistently monitor large-scale infrastructures, detecting even the smallest defects with high-resolution accuracy [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Advancements in crack detection have shifted from manual methods to automated techniques, guided by extensive research [13, 14]. Early methods relied heavily on image processing for crack identification, but these were often limited by environmental factors and lighting conditions. The integration of computer vision and machine learning, especially convolutional neural networks (CNNs), has significantly improved reliability and accuracy in detecting cracks in various structures [15]. This paper presents a novel multi-scale approach that combines advanced sensing, robotics, and AI technologies. It includes a detailed analysis using a laser line scanner and a robotic arm, supplemented

[*] Corresponding author

by computer vision for initial crack detection. This system not only identifies but also accurately measures cracks, creating a precise digital twin of the structure. This digital twin incorporates a detailed multi-scale representation of the inspected area, overcoming the limitations of conventional methods. The approach results in a comprehensive 3D point cloud, significantly enhances infrastructure assessment [16]. The paper is structured to detail the methodology and results with future research directions.

METHODOLOGY

Our methodology integrates camera-based detection, laser scanning, and LiDAR to construct a multi-scale digital twin of concrete structures, focusing on crack detection and analysis. The system employs an RGBD depth camera and a convolutional neural network (CNN) to identify and locate potential cracks (Regions of Interest, ROIs). These ROIs are initially detected in 2D and then mapped into 3D space using depth information. Simultaneously, a LiDAR sensor develops a global point cloud of the environment. Which, when combined with the detailed crack data, our approach forms a comprehensive digital twin representing both the macro and micro-scale elements of the structure. Upon detection, the system calculates the real-world coordinates of these defects using the depth camera and intrinsic camera parameters. If the defects are within the robotic arm's workspace, the arm guides a laser scanner to the location for a detailed scan. This process generates a dense point cloud of the crack, offering precise measurements and shape characterizations. In contrast, areas outside the robotic arm's reach continue under visual inspection. The depth camera, mounted on the robotic arm, captures high-definition images, which are then processed by a CNN U-Net model, trained specifically for semantic segmentation tasks in identifying cracks. Post detection, a script creates bounding rectangles around these flaws, translating them from 2D images to 3D coordinates. This step involves parameter restrictions to ensure the targeted cracks are within the operational range of the robotic arm. The laser scanner, attached to the arm's end effector, conducts detailed scans of these identified regions, providing high-resolution data and shape measurements. This results in an accurate and detailed point cloud representation of the cracks, enhancing our understanding of their dimensions and 3D shape. Figure 1 depicts the experimental and simulation setup used in the methodology of our study, showcasing the sensor fusion for structural defect analysis.
Central to the setup is a robotic arm positioned over a concrete specimen, equipped with a laser head designed for high-resolution scanning of surface cracks. Mounted on a stand above the robotic arm is a depth camera, which captures detailed images of the concrete's surface, and a LiDAR sensor that collects coarse-point cloud data of the surrounding environment. The depth camera processes images to detect and locate regions of interest (ROIs) - primarily the hairline cracks. These ROIs are then outlined by the robotic arm, utilizing the precise laser head to generate a dense point cloud of the specified area. This setup allows for a multi-scale representation of the structure, where the fine details captured by the laser scanner are merged with the broader environmental data from the LiDAR, resulting in a comprehensive digital twin of the concrete specimen that is instrumental for subsequent analysis and assessment.

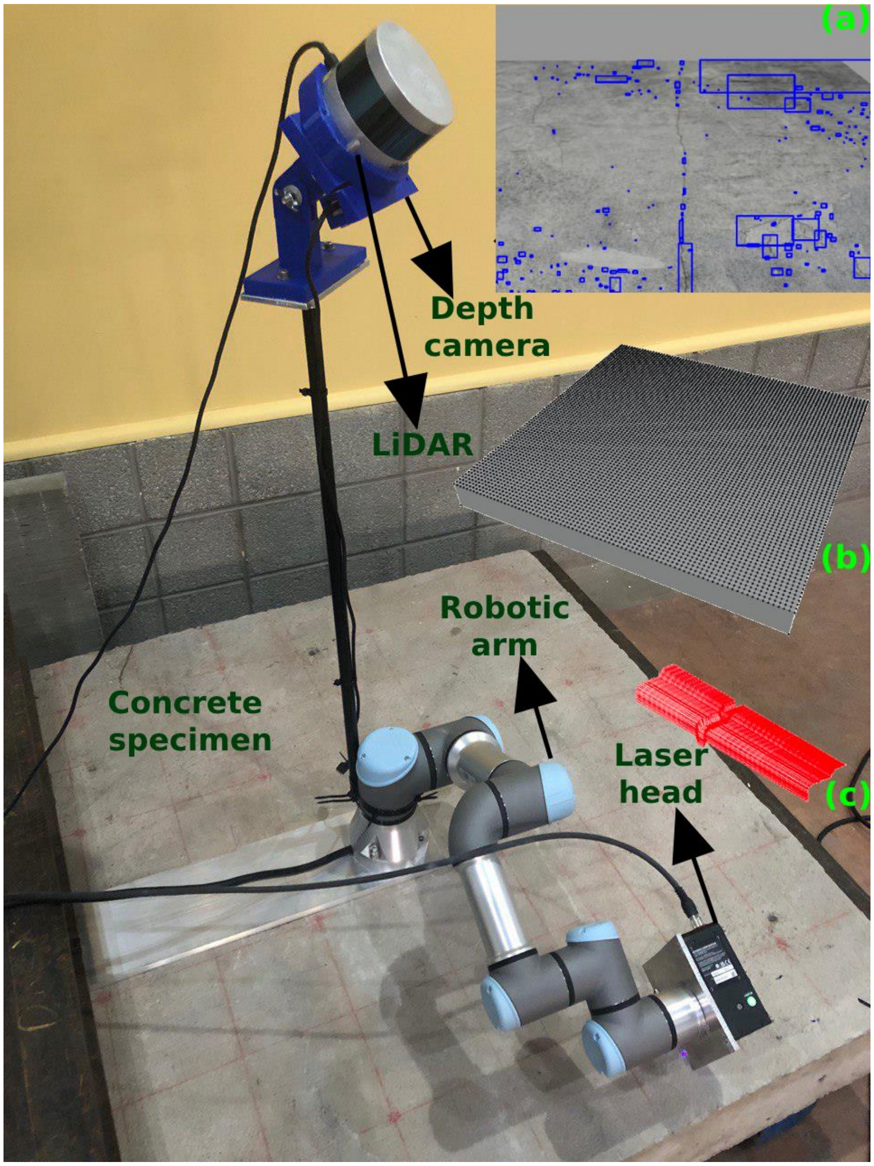
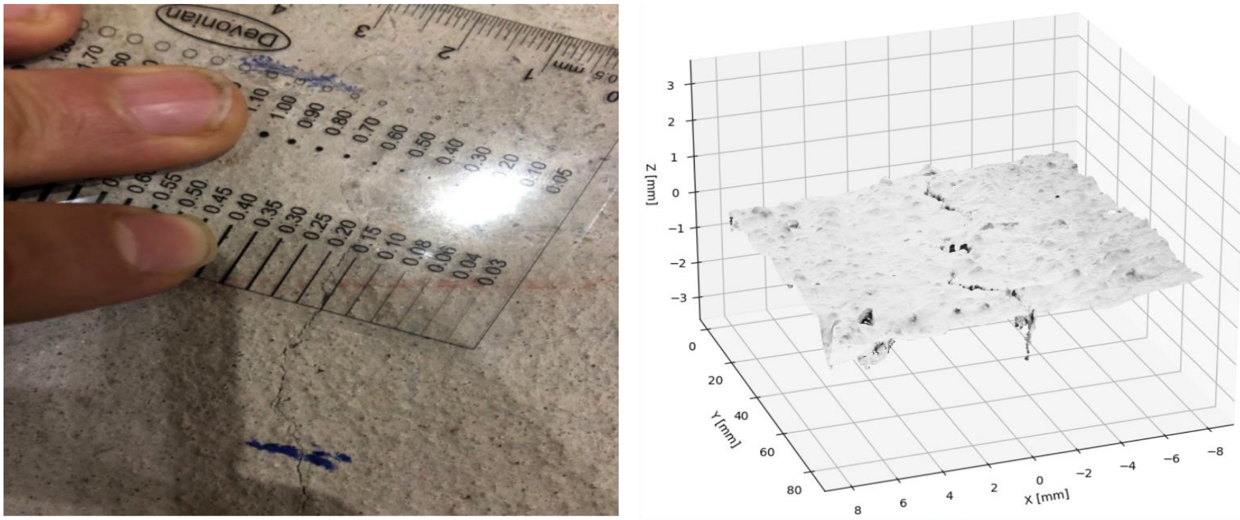


Figure 1: Experimental and simulation setup for sensor fusion in multi-scale inspection of the concrete with hairline cracks. (a) crack detection results. (b) point cloud generation by LiDAR. (c) hairline crack point cloud.

RESULTS

This section summarizes the outcomes of the integrated multi-scale sensor fusion framework developed for automated crack detection and measurement in concrete structures. The system combines a CNN for image-based crack identification, a laser line scanner for detailed profile measurements, and high-resolution 3D point cloud generation. The results, demonstrated through both experimental and simulated data, reveal the system's effectiveness in capturing the physical characteristics of cracks. For instance, experimental scans across a 6 cm crack on a concrete specimen achieved a remarkable resolution of 0.004 mm per scan slice, highlighting the precision. Figure 2 depicts the results obtained from scanning a crack. Figure 2(a) presents the manual measurement of the crack's width while Figure 2(b) represents the same cracks dimensions in 3D. Crack width measurements ranged from 0.02 mm to 0.5 mm across various crack locations, showcasing the system's ability to handle varying crack sizes. The system demonstrated a higher resolution and precision in crack detection and measurement compared to existing methods. These results not only illustrate the system's advanced capabilities in detailed structural defect detection but also underscore its potential to enhance existing inspection methodologies for civil infrastructure.



(a) **(b)**

Figure 2: (a) corresponding photo of the real-world crack that was scanned with a scale representing crack width. (b) experimental 3D point cloud data demonstrating the real-world crack scan.

REFERENCES

[1] Chang, P.K, Peng, Y.N and Hwang, C.L. "A design consideration for durability of high-performance concrete." Cement and Concrete Composites Vol. 23 No. 4 (2001): pp. 375–380. DOI https://doi.org/10.1016/S0958-9465(00)00089-5.

[2] Laofor, Chollada and Peansupap, Vachara. "Defect detection and quantification system to support subjective visual quality inspection via a digital image processing: A tiling work case study." Automation in Construction Vol. 24 (2012): pp. 160–174. DOI https://doi.org/10.1016/j.autcon.2012.02.012.

[3] Alamdari, Ali Ghadimzadeh and Ebrahimkhanlou, Arvin. "A robotic approach for crack detection through the integration of cameras and LiDARs." Su, Zhongqing, Glisic, Branko and Limongelli, Maria Pina (eds.). Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023, Vol. 12486: p. 1248606. 2023. International Society for Optics and Photonics, SPIE. DOI 10.1117/12.2658110.

[4] Ghadimzadeh Alamdari, Ali and Ebrahimkhanlou, Arvin. "A multi-scale robotic approach for precise crack measurement in concrete structures." Automation in Construction Vol. 158 (2024): p. 105215. DOI https://doi.org/10.1016/j.autcon.2023.105215

[5] Shim, Seungbo, Lee, Seong-Won, Cho, Gye-Chun, Kim, Jin and Kang, Sung-Mo. "Remote robotic system for 3D measurement of concrete damage in tunnel with ground vehicle and manipulator." Computer-Aided Civil and Infrastructure Engineering Vol. 38 No. 15 (2023): pp. 2180–2201. DOI https://doi.org/10.1111/mice.12982.

[6] Yang, Liang, Li, Bing, Feng, Jinglun, Yang, Guoyong, Chang, Yong, Jiang, Biao and Xiao, Jizhong. "Automated wall-climbing robot for concrete construction inspection." Journal of Field Robotics Vol. 40 No. 1 (2023): pp. 110–129. DOI https://doi.org/10.1002/rob.22119.

[7] Meng, Qingling, Yang, Jiabing, Zhang, Yun, Yang, Yilin, Song, Jinbo and Wang, Jing. "A Robot System for Rapid and Intelligent Bridge Damage Inspection Based on Deep-Learning Algorithms." Journal of Performance of Constructed Facilities Vol. 37 No. 6 (2023): p. 04023052. DOI 10.1061/JPCFEV.CFENG-4433.

[8] Asjodi, Amir Hossein, Dolatshahi, Kiarash M. and Ebrahimkhanlou, Arvin. "Spatial analysis of damage evolution in cyclic-loaded reinforced concrete shear walls." Journal of Building Engineering Vol. 49 (2022): p. 104032. DOI https://doi.org/10.1016/j.jobe.2022.104032.

[9] Momeni, Hamed and Ebrahimkhanlou, Arvin. "High-dimensional data analytics in structural health monitoring and non-destructive evaluation: a review paper." Smart Materials and Structures Vol. 31 No. 4 (2022): p. 043001. DOI 10.1088/1361-665X/ac50f4. URL https://dx.doi.org/10.1088/1361-665X/ac50f4.

[10] Yeum, Chul Min, Dyke, Shirley J. and Ramirez, Julio. "Visual data classification in post-event building reconnaissance." Engineering Structures Vol. 155 (2018): pp. 16–24. DOI https://doi.org/10.1016/j.engstruct.2017.10.057.

[11] Spencer, Billie F., Hoskere, Vedhus and Narazaki, Yasutaka. "Advances in Computer Vision-Based Civil Infrastructure Inspection and Monitoring." Engineering Vol. 5 No. 2 (2019): pp. 199–222. DOI https://doi.org/10.1016/j.eng.2018.11.030.

[12] Hamidia, Mohammadjavad, Mansourdehghan, Sina, Asjodi, Amir Hossein and Dolatshahi, Kiarash M. "Machine learning-based seismic damage assessment of non-ductile RC beam-column joints using visual damage indices of surface crack patterns." Structures Vol. 45 (2022): pp. 2038–2050. DOI https://doi.org/10.1016/j.istruc.2022.09.010.

[13] Pan, Yue, Zhang, Gaowei and Zhang, Limao. "A spatial-channel hierarchical deep learning network for pixel-level automated crack detection." Automation in Construction Vol. 119 (2020): p. 103357. DOI https://doi.org/10.1016/j.autcon.2020.103357.

[14] Mazzia, Vittorio, Daneshgaran, Fred and Mondin, Marina. Use of Deep Learning for Automatic Detection of Cracks in Tunnels. Springer Singapore, Singapore (2021): pp. 91–101. DOI 10.1007/978-981-15-5093-5_9.

[15] Chen, Fu-Chen and Jahanshahi, Mohammad R. "NB-CNN: Deep Learning-Based Crack Detection Using Convolutional Neural Network and Naïve Bayes Data Fusion." IEEE Transactions on Industrial Electronics Vol. 65 No. 5 (2018): pp. 4392–4400. DOI 10.1109/TIE.2017.2764844.

[16] Bazrafshan, Pedram, On, Thinh, Basereh, Sina, Okumus, Pinar and Ebrahimkhanlou, Arvin. "A graph-based method for quantifying crack patterns on reinforced concrete shear walls." Computer-Aided Civil and Infrastructure Engineering Vol. 39 No. 4 (2024): pp. 498–517. DOI https://doi.org/10.1111/mice.13009.