Cyber-Physical Systems for Digital Twin in Home Maintenance

Data acquisition methods and framework for human building interaction

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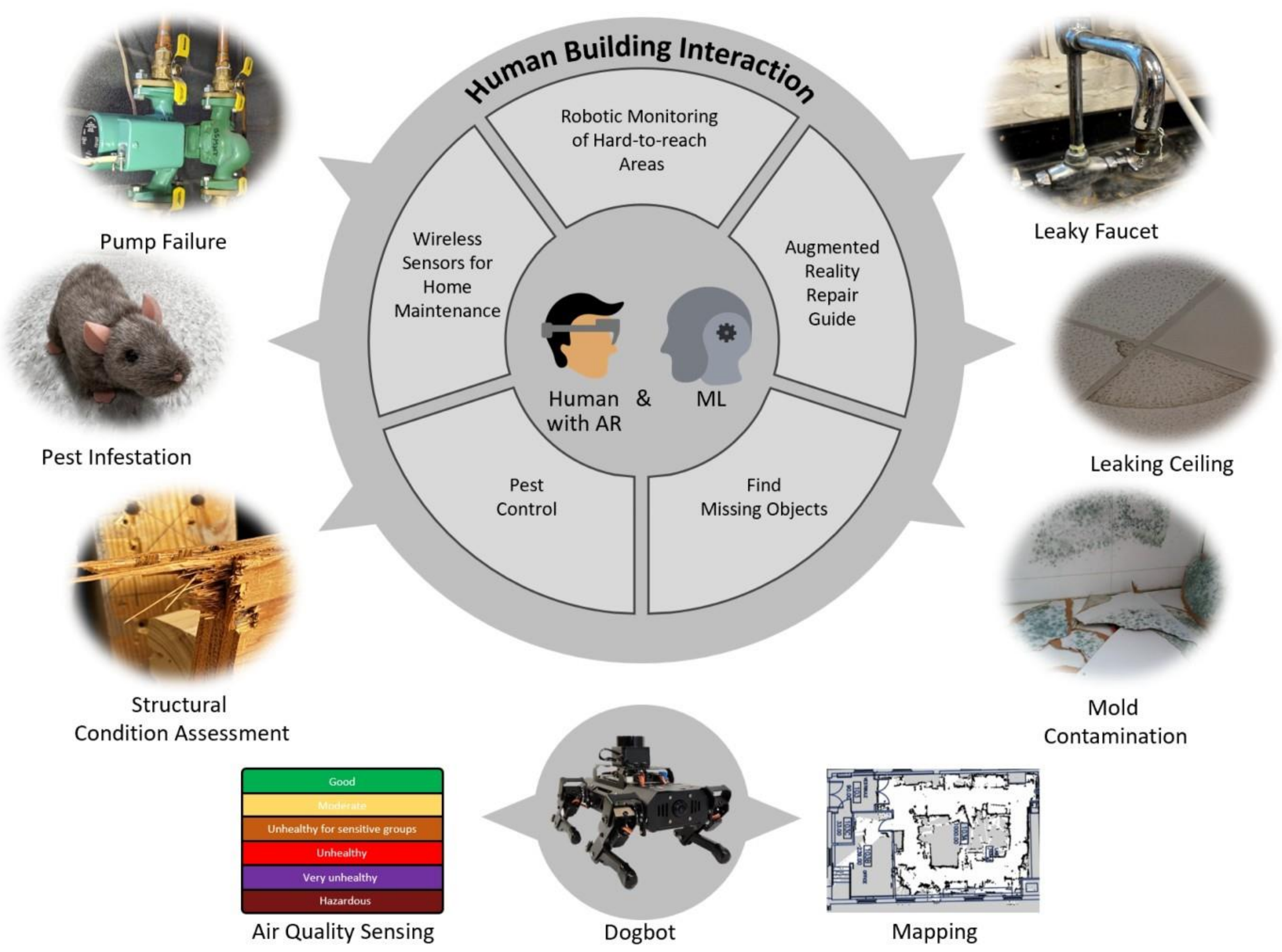
Introduction & Summary

The homeowner's ability to effectively maintain a house depends on timely and accurate information, based on which they can promptly implement repairs and upkeep. Aging populations, rising material costs, and reduced availability of the maintenance workforce place additional pressure on homeowners to seek help through modern technology.

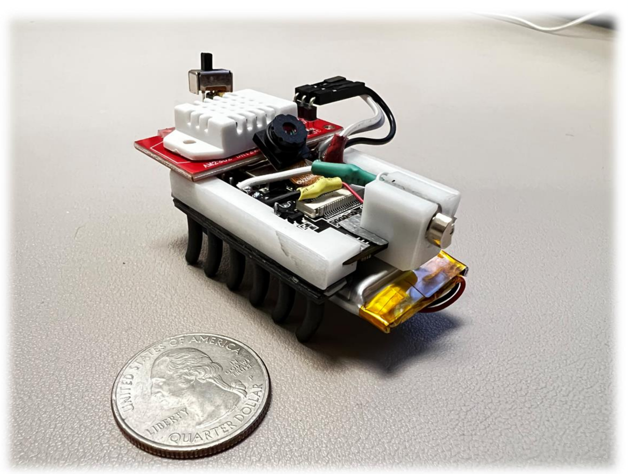
The proposed Home Maintenance 4.0 Digital Twin framework [1] follows the rise of technology for home-based maintenance using novel robots, microrobots, machine learning, and augmented reality headsets for human interaction.

Digital Twin for Home Maintenance



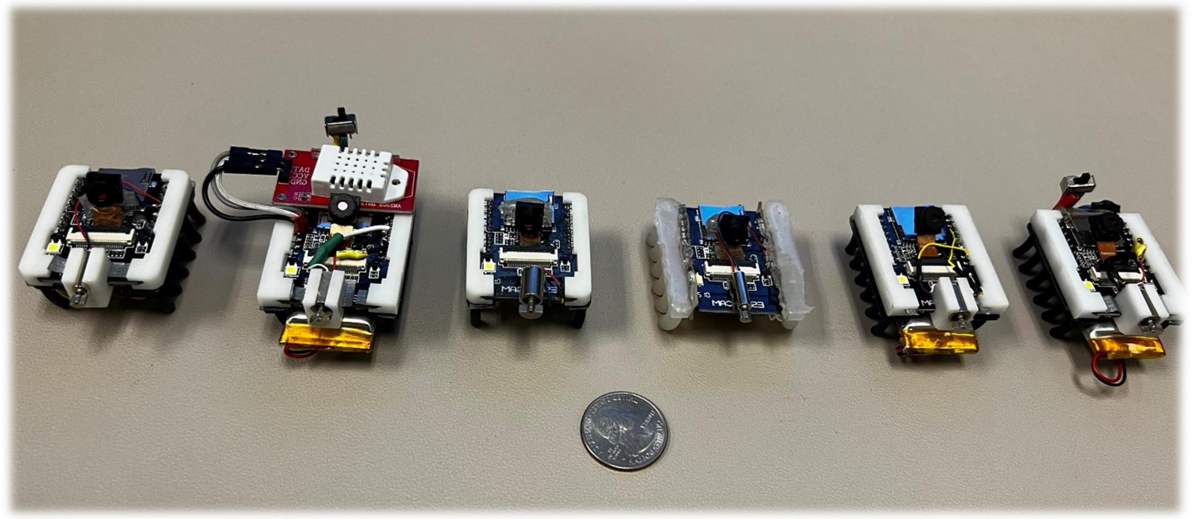
Methods

For extensive availability of technologies to each home-owner, the systems use low-cost and novel methodologies that integrate into the current home networks.



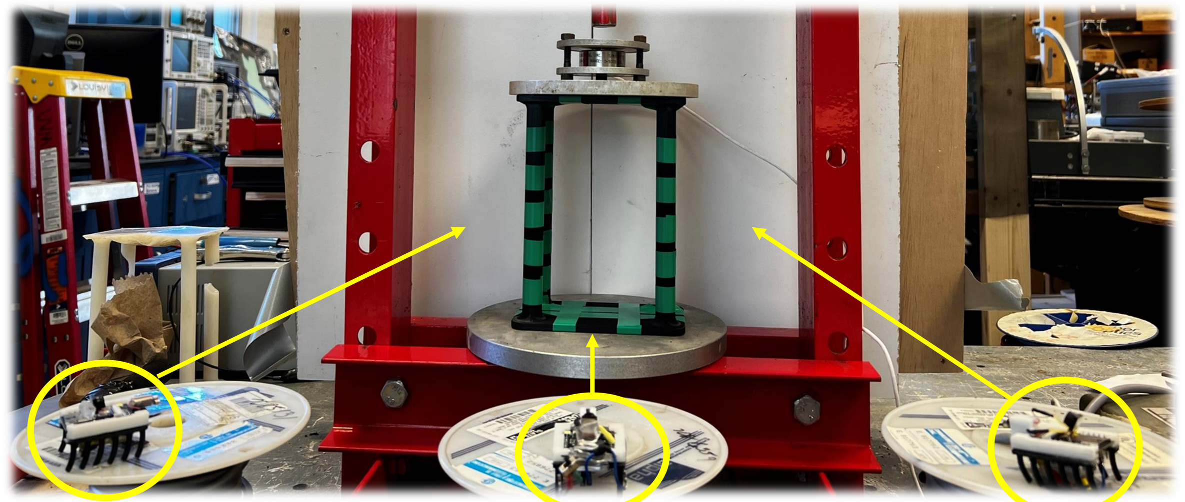
Camera-based bristle-bots called MARSBot [2] combine sensors with a novel inertial steering capability. The camera's visual data wirelessly transmits to the user inspecting confined spaces.

Fabricating a heterogenous swarm of microrobots with specific application-based features assists in autonomous inspection. The collected data can be processed using computer vision and machine learning to assist users in everyday home maintenance issues.

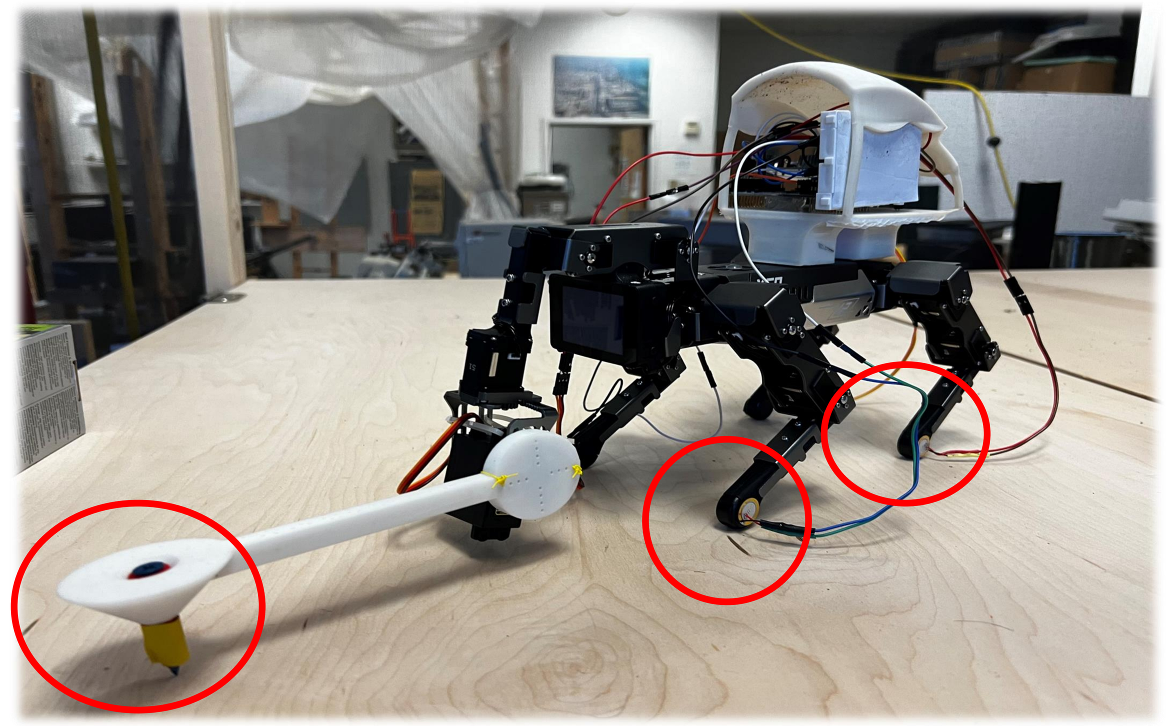


Possible applications of the swarm of microrobots are monitoring for structural changes, locating maintenance tools, alerting to pest infestations, finding obstructive objects in passages, and locating defects, such as cracks in the structures.

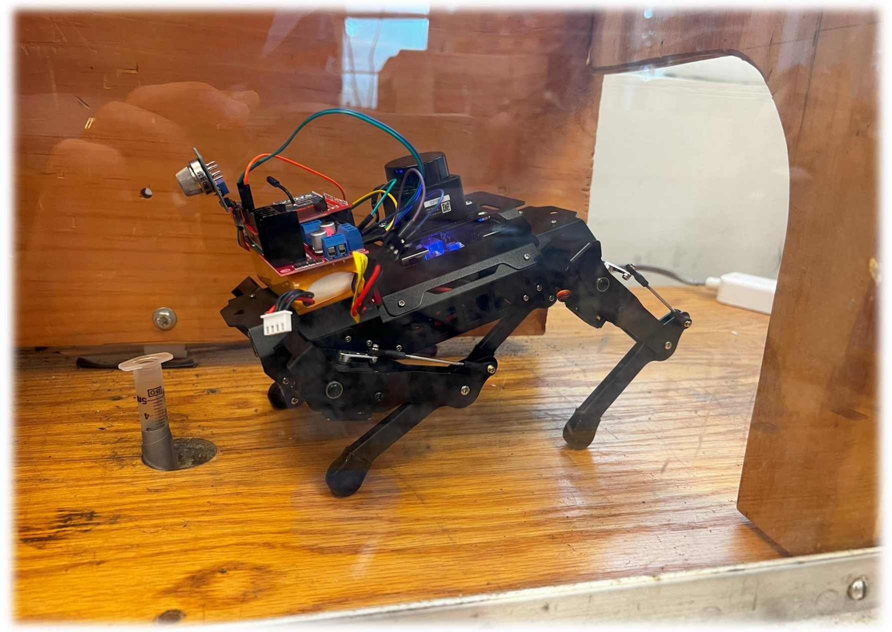
For monitoring the structural changes, the microrobots capture images from different angles of the structure with fixed time intervals. The resulting visual data can be analyzed by applying Canny edge detection and calculating statistical parameters.



Quadruped robot dogs (QRD) are a versatile way to scout the house, update digital twins and look for maintenance issues. To map materials surface properties and condition, an innovative elastodynamic sensing system uses the QRD's feet to detect the passage, direction and speed of surface waves. This technique attaches piezoelectric sensors to the sides of the feet, receives data with high-speed data acquisition on top, and uses a 3D printed arm to tap on the material's surface. The received data are registered for position, analyzed to determine material properties and subsurface conditions, and then sent to update the digital twin.

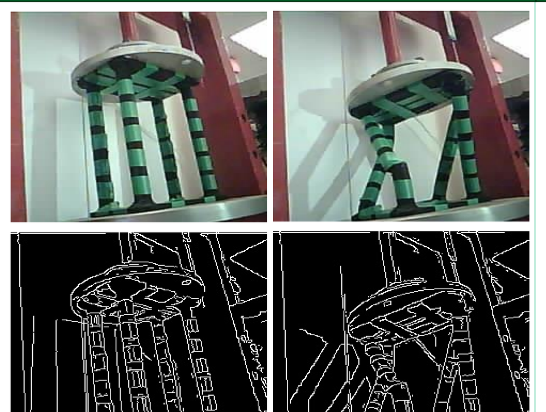


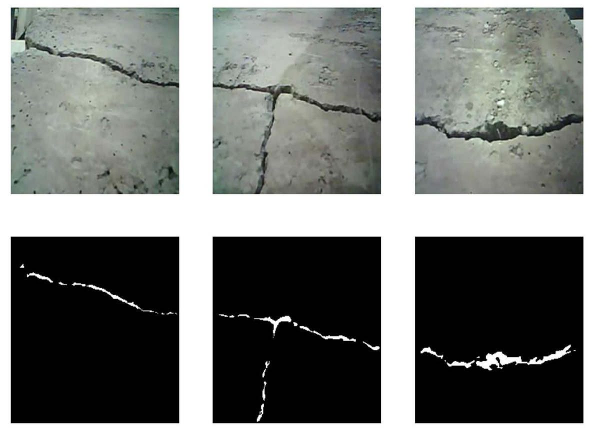
The QRD movement mechanism allows for maneuvering into confined spaces. This enables the robot with integrated wireless sensors to check for hazardous. The low-cost air quality sensors can detect depleted levels of oxygen and elevated values of CO_2 and other noxious gases to alert homeowners before they enter the affected area.

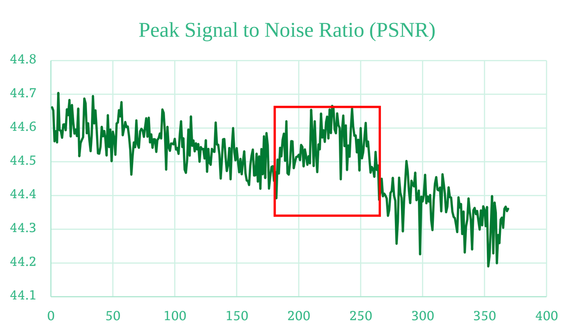


Results

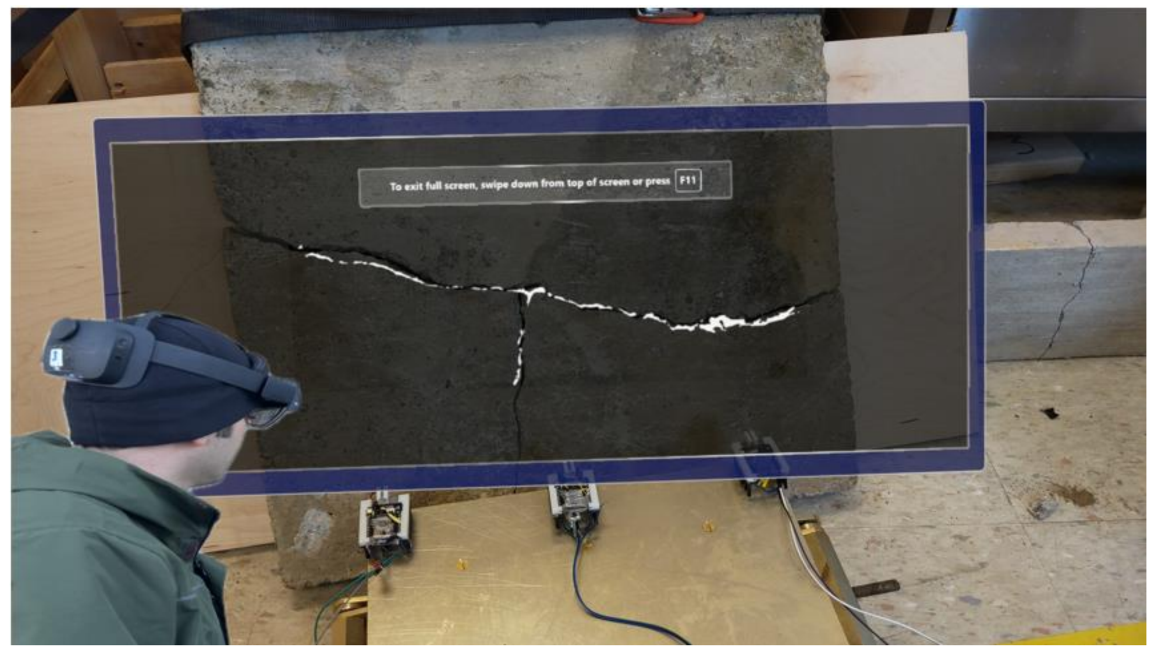
Calculating the parameters on the edge detected images, such as Normalized Absolute Error and Peak Signal to Noise Ratio, shows anomaly before failure by comparing the data from multiple microrobots and the data in terms of time. Integrating this analysis with models in a digital twin can alert the user about the failure ahead of time.



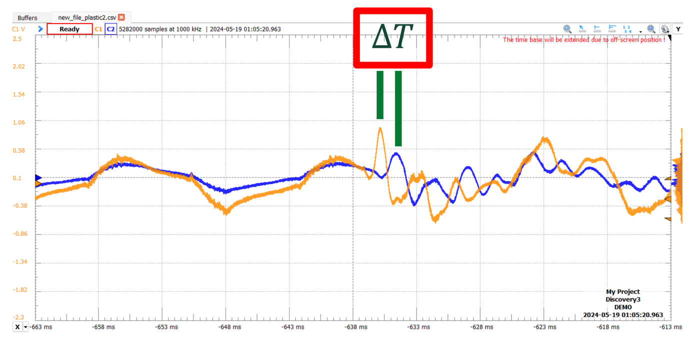


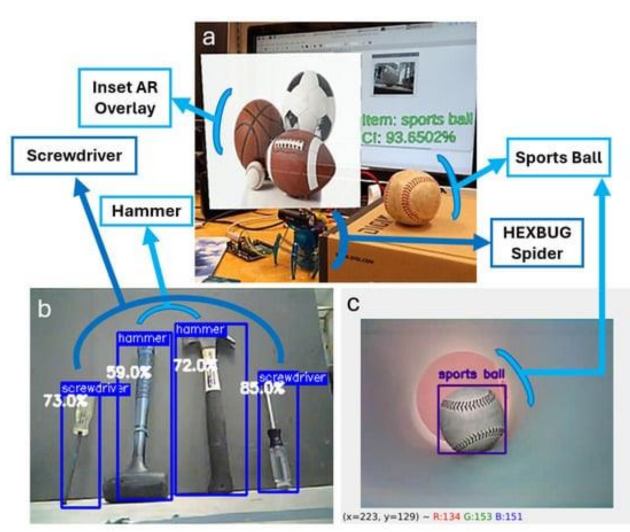


The captured images of the individual microrobots and their corresponding semantic segmentation are demonstrated. The process enables the user to track a long crack in confined spaces using swarm robots while transmitting the data-efficient mask to the user and updating the status in a digital twin. The operator views the hologram of the whole crack using an augmented reality headset.



Analyzing the 1 MHz data from the piezoelectric sensors attached to the feet of the QRD shows the time difference between the peaks. The Time shift between the peaks of the surface waves discerns surface material properties for building and updating a digital twin.



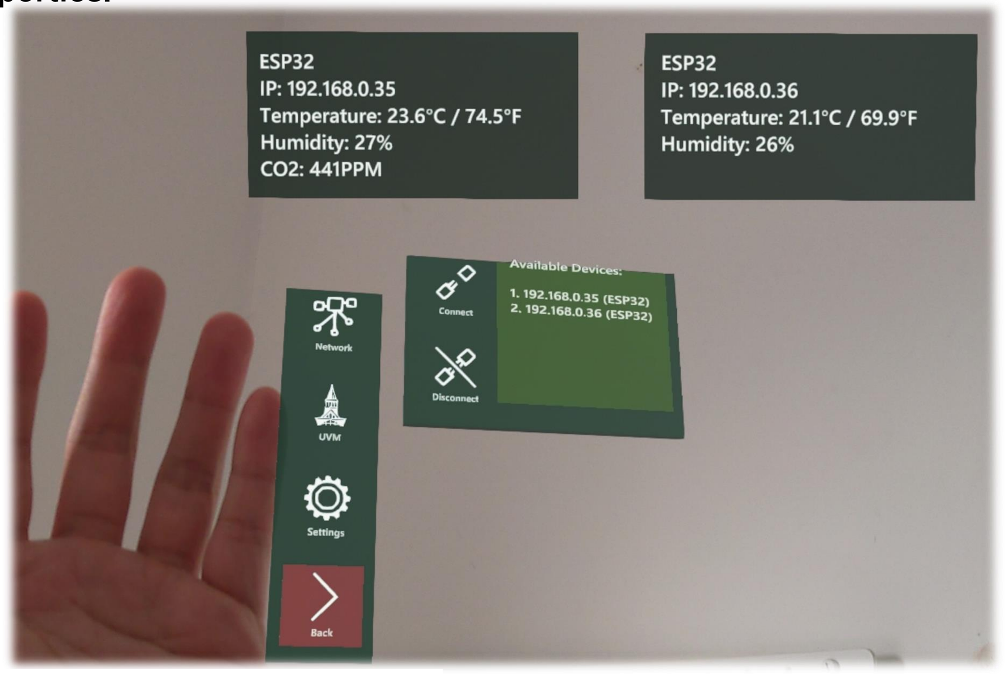


The swarm of microrobots through data collection and digital twin updating help the homeowner detect items obstructing passages, classify and send alerts regarding, pest infestation, and finding missing tools required for maintenance. This information is then broadcast as a token to the user, showing the visual hologram of the objects in AR.

Conclusions & Vision

Several technologies supporting data acquisition and human building interaction in a digital twin framework for home and structural maintenance are proposed. To provide a safe and sustainable place for people to live, structural health needs to be constantly monitored and maintained. Developing a digital twin for the house and incorporating the data into the BIM will make them accessible to the homeowner, assisting in the preservation of the properties.

Augmented reality-based interfaces present the data to the user without any advanced knowledge. This data can be in the form of a decision tree that the human user with the robots and AI use to collaborate to find a possible repair.



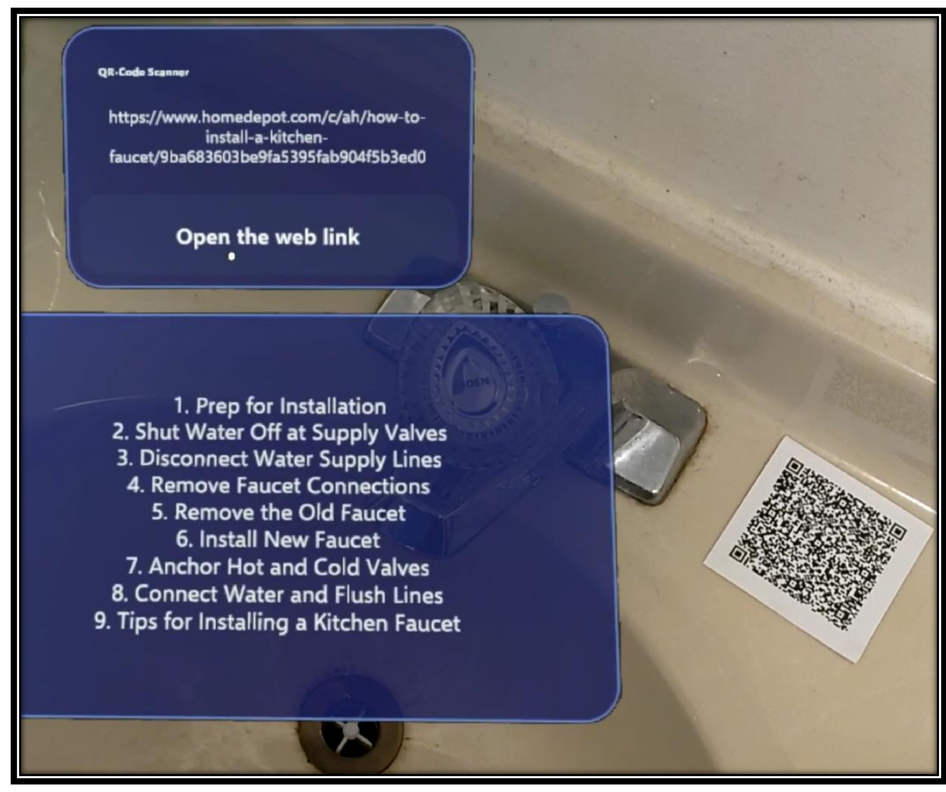
Home maintenance Decision Tree

Type of Maintenance Issue

- Pump Failure
- Leaking Ceiling
- Crack Development
- Pest Infestation
- Structural Change
- Leaky Faucet
- Mold Contamination

Similar to the use of decision trees for bridge damage analysis [3], home maintenance decision trees can be developed using AI to classify the common problems in the homes and provide the necessary steps for a homeowner to follow to fix the issue.

The repair options are presented to the home-owner in digital format and can be forwarded to professional contractors for evaluation or can link to guides for the homeowner to execute the repair. Parts suppliers are identified and materials ordered. An augmented reality (AR) headset provides information on repair steps via holograms while leaving both hands free to perform tasks.



References

[1]. Fath, A.; Hanna, N.; Liu, Y.; Tanch, S.; Xia, T.; Huston, D. Indoor Infrastructure Maintenance Framework Using Networked Sensors, Robots, and Augmented Reality Human Interface. Future Internet 2024, 16, 170. https://doi.org/10.3390/fi16050170.

[2]. Fath, A.; Liu, Y.; Xia, T.; Huston, D. MARSBot: A Bristle-Bot Microrobot with Augmented Reality Steering Control for Wireless Structural Health Monitoring. Micromachines 2024, 15, 202. https://doi.org/10.3390/mi15020202.

[3]. Huston, Dryver, "Cost-Effective and Rapid Concrete Repair Techniques" (2016). University of Vermont Transportation Research Center. 27. https://scholarworks.uvm.edu/trc/27.

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