Structural Health Monitoring with Robot and Augmented Reality Teams

ALIREZA FATH, YI LIU, SCOTT TANCH, NICK HANNA,
TIAN XIA and DRYVER HUSTON

ABSTRACT

Mobile robots can access regions and collect data in structural locations not easily reached by humans. This includes confined spaces, such as inside walls, and underground pipes; and remote spaces, such as the underside of bridge decks. Robot access provides the opportunity to sense in these difficult to access spaces with robot mounted sensors, i.e. cameras and lidars, and with the robot placing and servicing standalone sensors. Teams of robots, sensors and AR-equipped humans have the potential to provide rapid and more comprehensive structural assessments. This paper presents results of studies using small robots to explore and collect structural condition data from remote and confined spaces including in walls, culverts, and bridge deck undersides. The presentation also covers system and network architecture, methods for automating data processing with localized and edge-based processors, the use of augmented reality (AR) human interfaces and discusses key technical challenges and possible solutions.

INTRODUCTION

Robots are potentially very useful tools in structural health monitoring [1] [2]. Good use cases arise when: 1. There is an important sensing or monitoring need. 2. The location of interest is inaccessible, dangerous, or too tedious for humans. 3. There is a mobility solution with a robot that can access the location of interest. 4. There is a sensing solution that mounts on a robot or deploys from a robot. 5. There is a telemetry solution that sends data from the inaccessible location on the structure back to the operators of the monitoring effort.

Alireza Fath, Yi Liu, Scott Tanch, Dryver Huston, Mechanical Engineering, University of Vermont, Burlington, VT 05405, U.S.A.
Nick Hanna, Computer Science, University of Vermont, Burlington, VT, 05405, U.S.A.
Tian Xia, Electrical and Biomedical Engineering, University of Vermont, Burlington, VT 05405, U.S.A.

Successful use of a robot in structural health monitoring benefits from additional considerations. These include: 1. Planning and control of robot motions and paths, 2. Use of cognitive methods to process and interpret the data, 3. Presentation of data to humans in an easily understood format, 4. Use of multiple robots in teams of robots and humans. Localized machine intelligence, information processing methods through facile networks and augmented reality methods are useful tools in this regard. The following sections describe some of these techniques for using robots in structural health monitoring.

RELEVANT STRUCTURAL MONITORING CASES

Structural health monitoring is a complicated process that intertwines structural conditions, importance of the structure, sensing technologies and human interactions [3]. Conditions that favor the use of structural health monitoring are: 1. The structure is important. Failure poses large safety and economic consequences. 2. Structural measurements provide meaningful information about specific damage processes. 3. Information about structural conditions can be used to remedy or mitigate deleterious situations. 4. The monitoring system can take measurements in situations that are dangerous, too difficult, too expensive, or too tedious for humans. And 5. Data processing poses cognitive challenges for humans.

Two examples of possible good use cases for robotic structural health are culverts and bridge deck undersides. Culverts carry stormwater underneath roads [4] [5]. Small culverts, approximately less than 1 m diameter, are difficult for humans to access for inspection, yet quite common, Figure 1. Failure modes include corrosion, water leaks in and out, blockage by debris, and collapse. Failure can lead to cascading expensive roadway washout failures. Intervention with repairs can prevent such failures. The Vermont Agency of Transportation has 9,600 small culverts, each of which needs to be inspected once every five years. The underside of concrete bridge decks is another example. Damage due to corrosion of reinforcing bars and concrete degradation due to chloride and harsh environmental loadings can lead to spalling and delaminations, Figure 2. Falling debris poses a severe hazard to motorists and pedestrians passing underneath. Inspection with humans is difficult due to the remote location and hazards to traffic of inspection vehicles.

Figure 1 Small culvert with difficult access for humans: a. Exterior entrance, and b. Inside view with other entrance visible [5].

Figure 2 Highway overpass bridge with multiple delaminations of concrete on underside of the deck

MOBILITY SOLUTIONS

The use of robots in structural health monitoring requires robots that can move to the desired locations of interest. Multiple mobility solutions are available for mobile robots. The robots can roll on wheels, walk on legs – possibly with specialized gripping feet, fly, swim and float [2] [3]. These mobile robots are a mix of specialized robots for the structure under inspection and others are generalized mobile robots being adapted to the specialized inspection use cases. Figure 3.a shows the HIVE 2.0 mobile robot built on a hobby Sherman tank chassis to inspect culverts. It is an upgraded version of the HIVE 1.0, which used a four-wheel drive hobby automobile chassis [6]. Figure 3.b shows a mobile robot built on a commercial UAV platform. It is presently configured for water sampling from lakes and is being modified for bridge deck underside inspections.

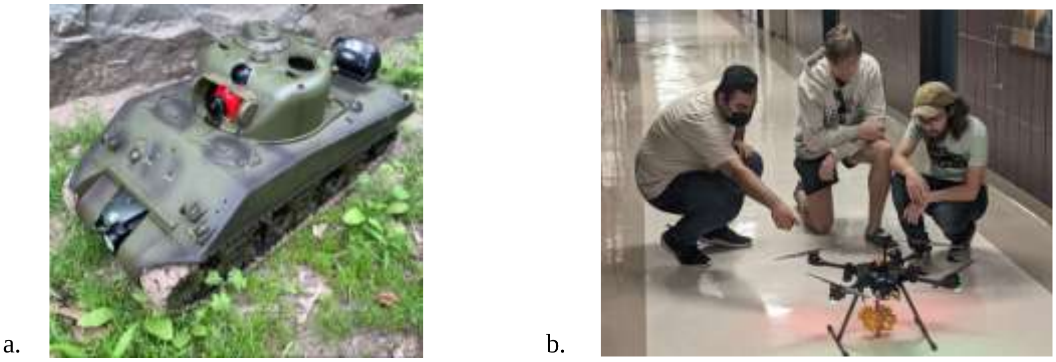

Figure 3 Mobile inspection robots: a. HIVE 2.0 culvert inspection robot [5], and b. Water sampling UAV robot under development for modification to inspect the underside of bridge decks.

Quadruped Robot Dogs (QRDs) are an emerging class of mobile robots that are excellent at climbing through difficult terrain, up and down stairs, and confined spaces. Advantages of QRDs are that they carry sophisticated native sensors, e.g. lidar, and onboard computation, e.g. Simultaneous Localization and Mapping (SLAM). Figure 4.a shows a QRD with onboard lidar and supplemental sensor module for confined space inspection. Figure 4.b shows a heterogeneous robot inspection team with a QRD and two microrobots. The microrobots use vibratory locomotion and carry small First Person View (FPV) cameras with wireless (WiFi) telemetry.

SENSING SOLUTIONS

Mobile robots need lightweight onboard sensors that can gather relevant data from the structures under inspection. The FPV camera continues to shrink in size and cost, while improving in performance. Figure 5.a shows an image from an FPV camera on a mobile HIVE 2.0 robot taken inside a culvert and transmitted in real time to an operator through wireless telemetry. Figure 5.b shows a mechanical tapper mechanism with digital microphone undergoing laboratory testing. The tapper is being developed for mounting on a UAV and used to test the underside of a concrete bridge deck for delaminations.

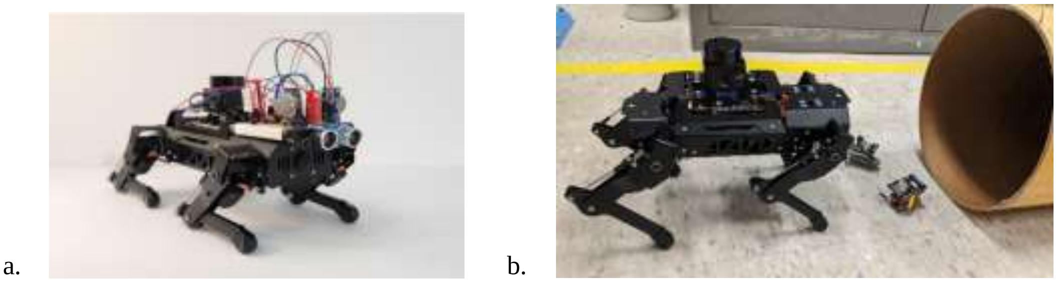

Figure 4 QRDs set up for structural inspection in confined spaces: a. Modified with multi-sensor module, and b. Teamed with microrobots that use vibratory locomotion and FPV cameras.

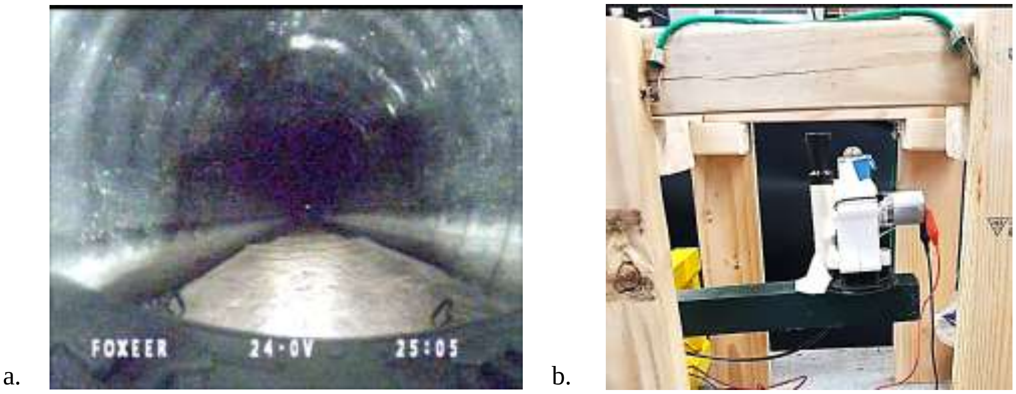

Figure 5 Example sensing options: a. FPV camera view from inside culvert [5], and b. Mechanical tapper with digital microphone for bridge deck sensing undergoing laboratory tests.

TELEMETRY SOLUTIONS

Mobile robots need to communicate with centralized operators to send data and to receive control commands. The centralized operator has traditionally been a human, but artificial intelligence approaches that hand off more of the detailed data processing and control commands to computers is becoming increasingly viable. The telemetry can pass through a tethered wire, which may also supply power. Wireless telemetry approaches with onboard power are presently more common configurations. Successful wireless telemetry requires consideration of the operating environment. Culverts are particularly challenging. The culvert walls tend to be electromagnetically lossy and do not act as conventional electromagnetic waveguides [5]. A combination of the proper frequency band (5.8 GHz works well) along with line-of-sight telemetry can achieve video transmit distances of 100 m or more inside small culverts, Figure 6.

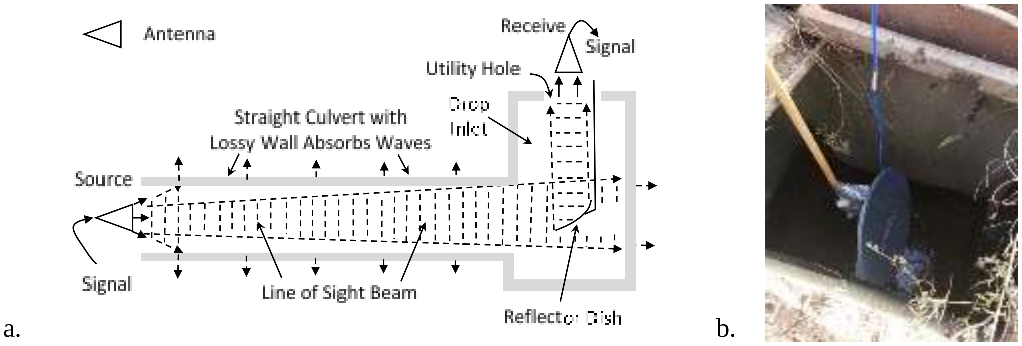

Figure 6. Line of sight wireless telemetry inside of small culvert with challenging drop inlet geometry: a. Geometry, and b. Use of reflector dish antenna in drop inlet, Figure 6.

COGNITION AND HUMAN INTERFACE

The raw data is often voluminous and in forms difficult to interpret without additional processing. Humans are the traditional cognitive interpreters, but increasingly machine learning methods are capable of distilling the data into abstractions beyond numerical data, i.e. the presence and assessment of damage levels. Networked and edge computing is an effective method of managing the tradeoff between data telemetry volumes, localized data processing and information latency. In addition to processing the data. the data needs to be converted into formats the make it easy for humans to interpret and act upon. Augmented reality is one possibility for presenting visual date to humans in a facile manner. Figure 7 shows the architecture of system that uses mobile robots to inspect confined spaces. The robots collect data, send it by a wireless link to an edge computer (Raspberry Pi 4), which uses convolutional neural networks to process, abstract and spatially register image data for passage to an augmented reality interface. This gives the human a real-time first-person view of conditions inside the confined space, Figure 8.

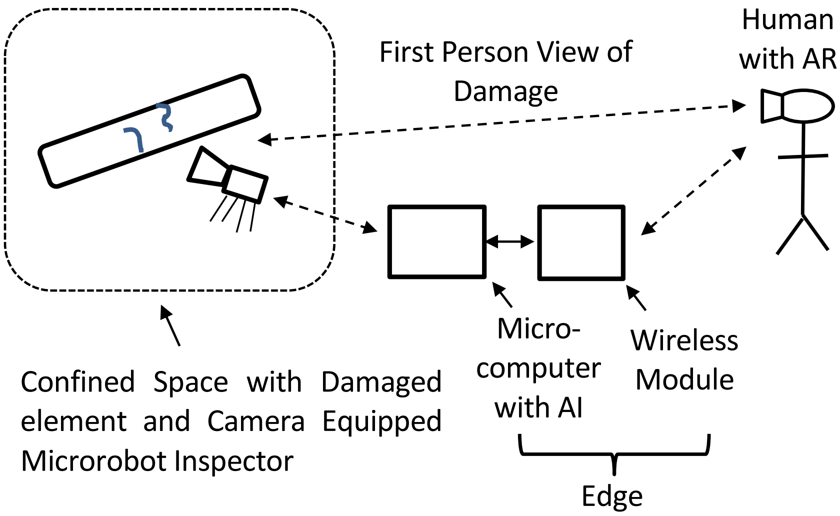

Figure 7 Architecture of robotic structural inspection system with wireless telemetry to edge processor with augmented reality interface to human on site.

Figure 8 Use of augmented reality interface with first person view on microrobot to visualize conditions inside confined space.

TEAMING

The teaming of robots with humans appears to be a fruitful method of increasing overall system performance. For structural health monitoring teams of small and larger robots, Figure 4.b, open the possibility for more facile approaches to inspecting confined spaces where the larger QRD places and services the smaller microrobots. Also teams of robots can improve telemetry in challenging situations, such as culverts with bends, by using transponders to relay delay.

CONCLUSIONS

Structural health monitoring continues to pose a host of technical challenges. The increasing capabilities of mobile robots, combined with onboard sensing, edge computing, artificial intelligence, augmented reality interfaces and teaming of robots, computers and humans will likely further extend the reach and capability of structural health monitoring.

ACKNOWLEGEMENTS

This research was supported in part by U.S. National Science Foundation Project 2119485 and U.S. Department of Transportation, Transportation Infrastructure Durability Center Project C20.2020.

REFERENCES

1. Esser, B., N. Pelczarski, D. Huston, and S. Arms. (2000) "Wireless Inductive Robotic Inspection of Structures" Proc. IASTED, RA 2000, Honolulu, HI.
2. Esser, B. and D. R. Huston. 2005 "Versatile Robotic Platform for Structural Health Monitoring and Surveillance" *Smart Structures and Systems*, Vol. 1, No.4, Oct
3. Huston, D. 2010. *Structural Sensing Health Monitoring and Prognosis*, Taylor and Francis, Boca Raton
4. Burton J., D. J. Orfeo, L. Griswold, S. K. Stanley, M. Redmond, T. Xia, D. Huston. 2021 "Culvert Inspection Vehicle with Improved Telemetry Range" *Transportation Research Record*, Volume 2675, Issue 11
5. Huston, D., T. Xia, J. Burton, D. Orfeo. 2020. "19-3 Hydraulic Inspection Vehicle Explorer (HIVE) Culvert Upgrade" Vermont Agency of Transportation, Montepelier, VT, U.S.A.
6. Youngblood D. 2017. *Enhanced Culvert Inspections - Best Practices Guidebook*. Minnesota Department of Transportation, pp. 25-27.