Monitoring Structures with Teams of Mobile Robots

ALIREZA FATH, YI LIU, BRANDON GAMBLE, TIAN XIA
and DRYVER HUSTON

ABSTRACT

This paper addresses the problem of monitoring structures with potential emergent damage through adaptive sensing provided by teams of mobile robots. Advantages of mobile robot teams for structural health monitoring include: 1. Multiple views of a given structure, 2. Adaptive movements that focus attention in response to observed conditions,3. Heterogeneous sensing and movement, and 4. Federated health monitoring and prognosis assessment through networked sharing and processing of information. Towards this end three cases of the use of mobile robot teams will be presented: 1. Heterogeneous robot teams for home and small building maintenance – Identifying, diagnosing and mitigating damage to homes and small buildings is a vexing set of problems for the owners. As an aid small controlled bristlebots and quadruped robot dogs (QRDs) carry sensors throughout a small building, assess conditions, provide prognoses and networked links to repair options; 2. Culverts are primary components of stormwater and flood prevention infrastructure. Inspecting small culverts is difficult for humans and large culverts are accessible but dangerous due to issues of confined spaces. Low-cost mobile robots have emerged as a competitive inspection option for accessible culverts with straight or short runs that permit wireless telemetry. Longer culverts and those with bends, branches and drop inlets pose challenges to the telemetry. Teams of robots extend the range of inspection through multi-hop video and control telemetry; 3. Ground penetrating radar (GPR) is a method of sensing subsurface infrastructure conditions with high-frequency electromagnetic waves. Conventional GPRs operate in a suboptimal monostatic or bistatic mode, are tedious to operate and have limitations in sensing congested utility subsurface conditions. Coordinated multi-static ground penetrating radar operated with mobile robot teams alleviates some of these concerns and provide better subsurface assessments with automated methods that focus attention on subsurface features of interest. Results from laboratory and field tests of these robot teams, as well as organizing principles of control and automated information processing are presented.

Alireza Fath, Yi Liu, Brandon Gamble, Dryver Huston, Mechanical Engineering, University of Vermont, Burlington, VT 05405, U.S.A.
Tian Xia, Electrical and Biomedical Engineering, University of Vermont, Burlington, VT 05405, U.S.A.

INTRODUCTION

Mobile robots provide a convenient, safe and potentially more effective means of structural health monitoring versus the use of humans [1] [2] [3]. As noted in [5] robots can be especially advantageous in cases where the geometry, amount of information, tedium, sensor manipulation and safe access are not convenient for humans. The advent of technologies, such as small footprint wireless networking, improved local machine intelligence, economics of mass production, and improved electric batteries all favor increased use of robots in SHM. Teaming of robots provides a means of further increasing performance, possibly at the expense of increased expense. Advantages of teaming include: 1. Multiple views and/or multi-point sensing of condition, 2. Heterogeneous sensing and mobility, Figure 1 [7], 3. Collective intelligence, 4. Improved telemetry, 5. Facile sensor placement, servicing and replacement, and 6. Framework for including repair robots as a team upgrade.

Figure 1 HeSARIC (Heterogenous Swarm Augmented reality Robotic Inspection Cyber physical system) [7]

STRUCTURAL CONFIGURATION SENSING WITH MICROROBOT SWARM

Structural geometry is a key indicator of structural health. Deviations from geometric norms, including cracking, can be detected by optical means. One approach is to use multiple cameras to view the structure from multiple views, mount the cameras on microrobots, transmit image data for analysis, move robots to positions that provide more information and continue to monitor and reanalyze the data [4].

Figure 2 shows the overall concept with microrobots, swarm and middleware that connects the robots to analysis, movement control and human interactions. Such a swarm is observing a laboratory model structure undergoing loading by a press in Figure 4. Heavy loading causes the columns to buckle, Figure 5. Multiview edge detection extracted from images provided by the swarm provides a basis for analysis, Figure 6.

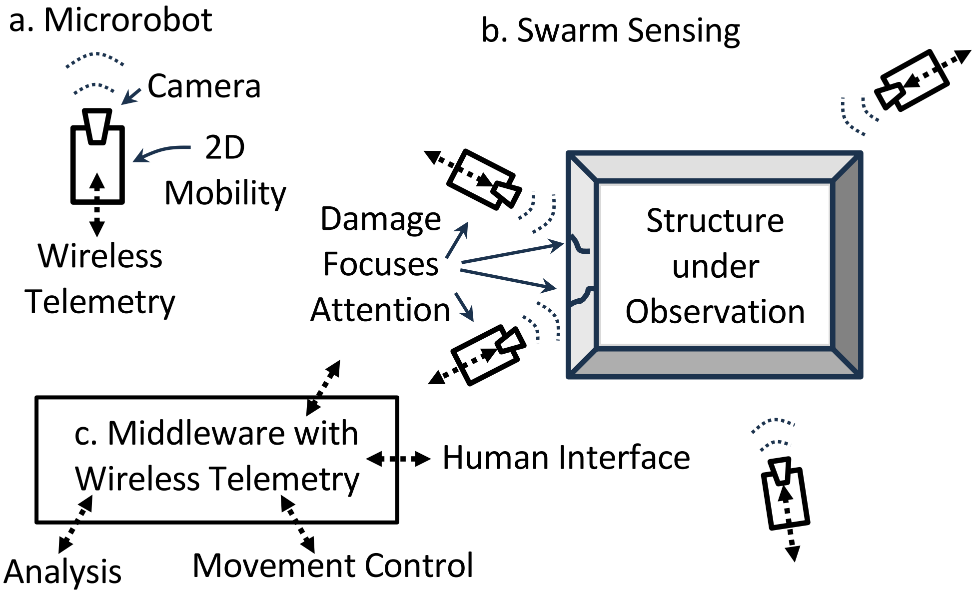
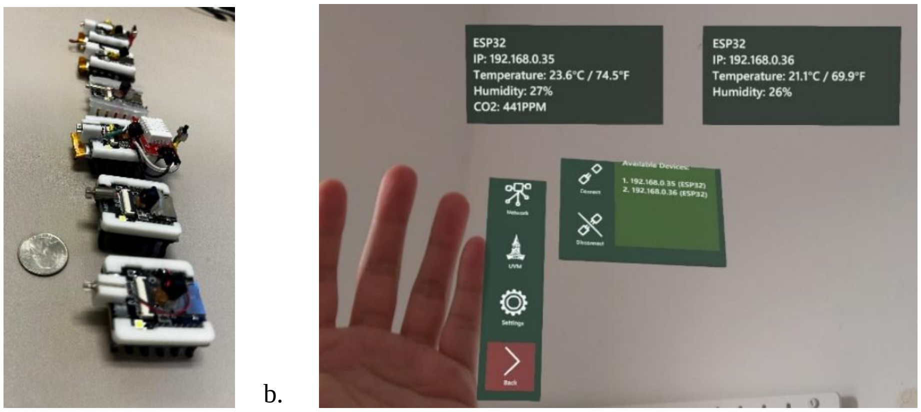


Figure 2 Concept of structural swarm sensing: a. Microrobot, b. Swarm sensing, and c. Middleware with wireless telemetry to analysis, movement control, and human interaction.


a.

b.

ESP32
IP: 192.168.0.35
Temperature: 23.6°C / 74.5°F
Humidity: 27%
CO2: 441PPM

ESP32
IP: 192.168.0.36
Temperature: 21.1°C / 69.9°F
Humidity: 26%

Available Devices:
1. 192.168.0.35 (ESP32)
2. 192.168.0.36 (ESP32)

Figure 3 Augmented reality (AR) positional control of swarm of Marsbot microrobots: a. initial position of swarm, and b. AR interface

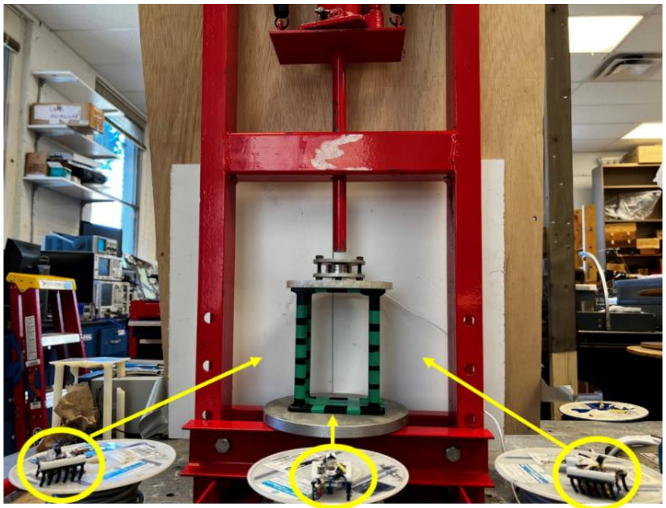


Figure 4 Model structure undergoing loading by a press with deformation observed by microrobot swarm [7]

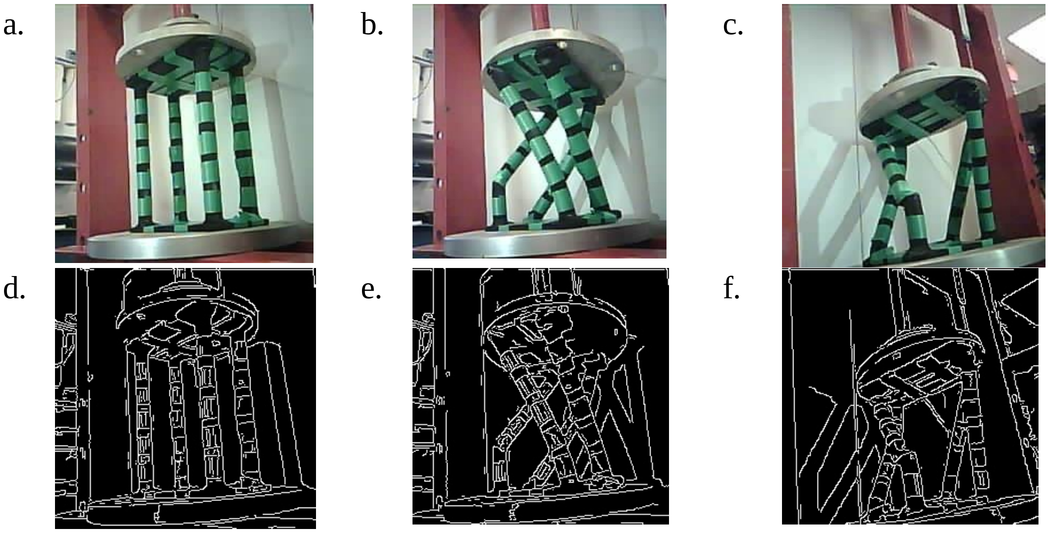
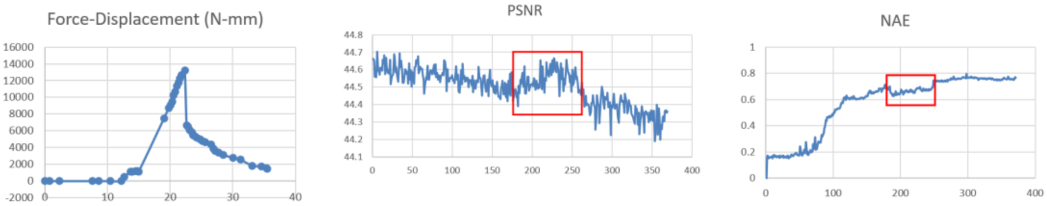


Figure 5. Swarm visual monitoring of collapse of model structure in laboratory: a. right side view of intact structure, b. right side view of buckled structure, c. left side view of buckled structure, d. right side view edge detection of intact structure, e. right side view edge detection of buckled structure, and f. left side view of buckled structure [7].



a. b. c.

Figure 6 Data and Multiview analysis from model load test: a. Force v. displacement, b. Peak Signal-to-Noise Ratio (PSNR), and c. Normalized Absolute Error (NAE) [7].

Microrobot swarms with optical sensing can also detect and assess cracks. Segmentation identifies individual sections of the crack. Segment merging creates a complete image of a crack, which is registered and overlaid with augmented reality in Figure 7.

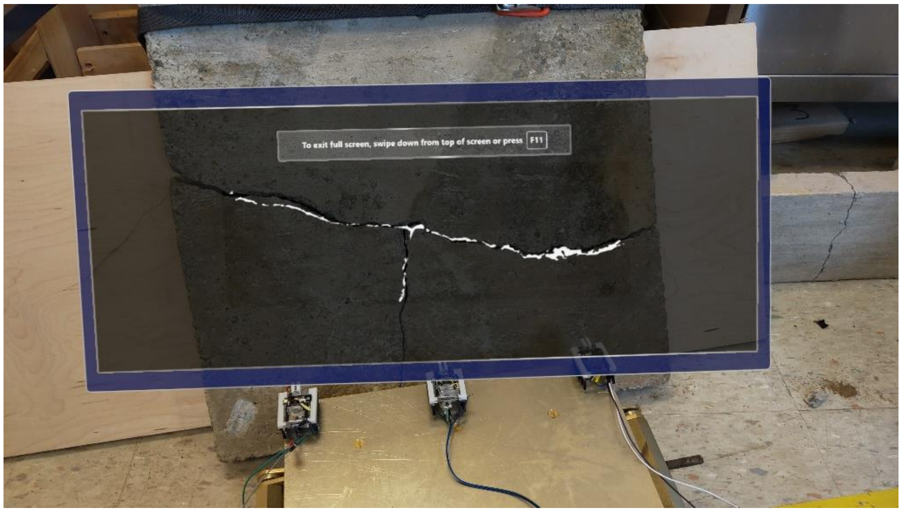


Figure 7 Crack identified by multi-view imaging with swarm robot. Segmented and merged crack image displayed on inset with augmented reality interface [7].

SMALL CULVERT ASSESSMENT WITH TEAM OF MOBILE ROBOTS

Culverts are critical infrastructure that cause considerable damage when they fail, especially during flood events. Small culverts, nominally defined as having a diameter of 1m or less, are difficult and dangerous to inspect by humans. Yet, there are many that need inspected. The Vermont Agency of Transportation has to inspect 9,600 small culverts, each at least once every five years. Mobile robots offer a solution [8][9][10]. Teams of robots enable extended inspection in complicated culvert geometries, primarily through enhanced telemetry, Figure 8.

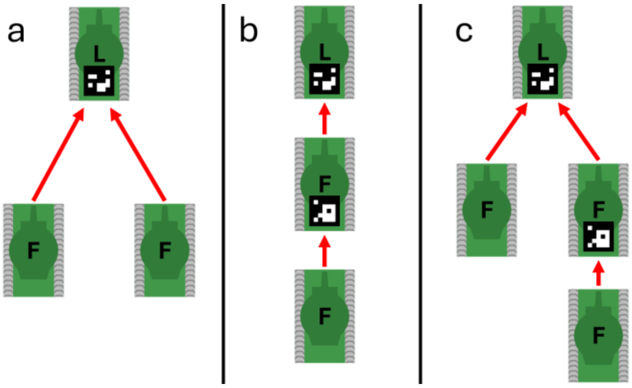


Figure 8 Leader-follower configurations for culvert inspection teams

Leader-follower teaming is a natural configuration for culverts. Two optical methods have proven viable, Figure 9. One uses aruco markers on the lead vehicle and photogrammetry to determine distance. A second technique uses a depth camera that actively projects and reads an infrared pattern to determine distance. These techniques combined with suitable leader-follower kinematics can double the telemetry and inspection range with a team of 2 robots.

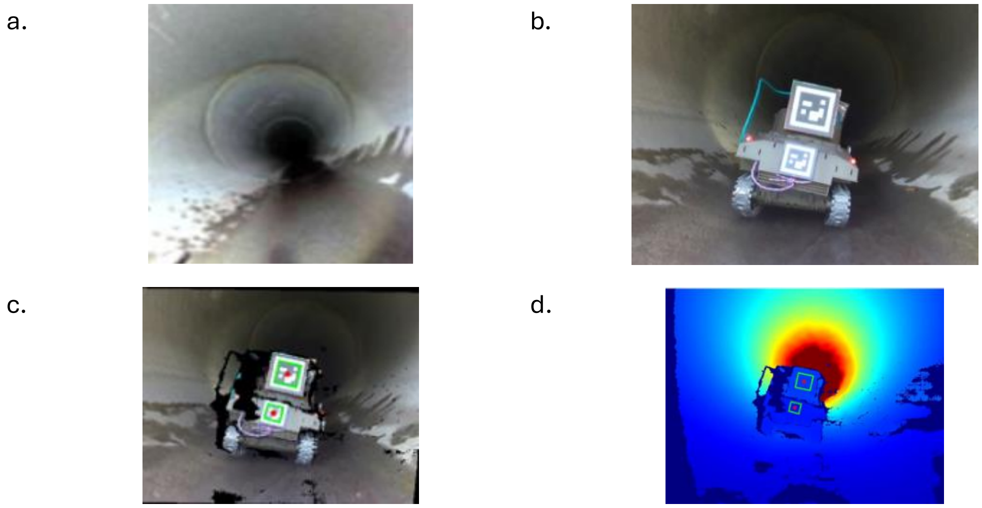


Figure 9 Small culvert inspection with leader-follower team of mobile robots: a. Forward looking view provided by leader, b. View of leader by the follower, c. Aruco marker photogrammetry determination of leader-follower distance, d. Depth camera determination of leader-follower distance.

SLANT SENSING MULTISTATIC GROUND PENETRATING RADAR TEAMS

Ground penetrating radars (GPRs) offer the ability to sense and image underground features and structures without excavation. Conventional GPRs look straight down in a monostatic or bistatic mode. Downward-looking GPRs are limited in the ability to image complicated and obscuring configurations. Multistatic slant sensing (MSS) enables sensing in some of these more challenging, but common configurations. MSS requires radar senders and receivers on spatially separated platforms, Figure 10 and Figure 11. Mobile robot teams offer the potential to realize MSS over large survey areas.

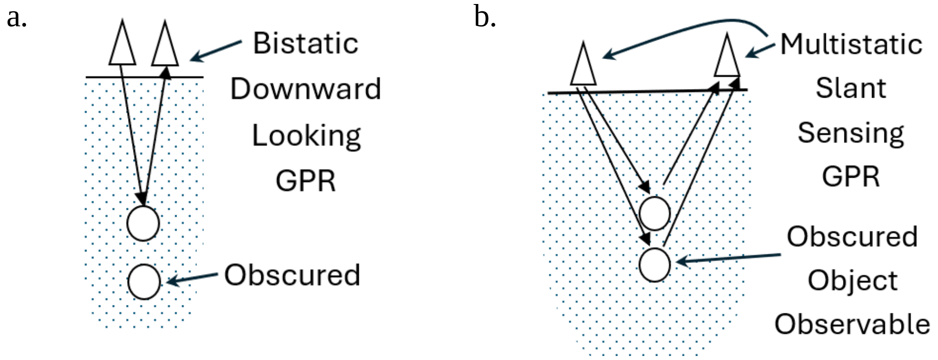


Figure 10 Ground penetrating radar configurations: a. Conventional downward looking GPR with obscured object, b. Multistatic GPR enabled by team of mobile robots observed obscured object

Figure 11 Mock-up of multi-static ground penetrating radar mounted on mobile robot with slant sensing capabilities.

CONCLUSIONS

Robot teams offer additional degrees of freedom in overall structural health monitoring system design. Some use cases include multi-view structural imaging, culvert inspection with enhanced telemetry, and multi-static GPR.

ACKNOWLEGEMENTS

This research was supported in part by U.S. National Science Foundation projects 2119485 and 2345851, and Vermont Agency of Transportation project 23-1.

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