Swarm Cyber-Physical Systems for Digital Twins of Structural and Underground Monitoring

Metrics and framework for Integration of Cyber-Physical Systems for Structural Health Monitoring

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Introduction & Summary

Despite the advancements of robotics, sensing technologies, and wireless networks, the challenges of applying low-cost application-based Structural Health Monitoring (SHM) inspections prevent many industries from incorporating them into their applications.

The Cyber-Physical Systems (CPS) metrics are required to assess the systems and solve the challenges regarding the specific applications. In this research, a summary of the technologies required for each application, including network connectivity, CPS metrics, and intuitive user-friendly Augmented Reality (AR) interfaces, is presented. Evaluation metrics assist the users in quantifications and selecting the most appropriate choices for their application [1].

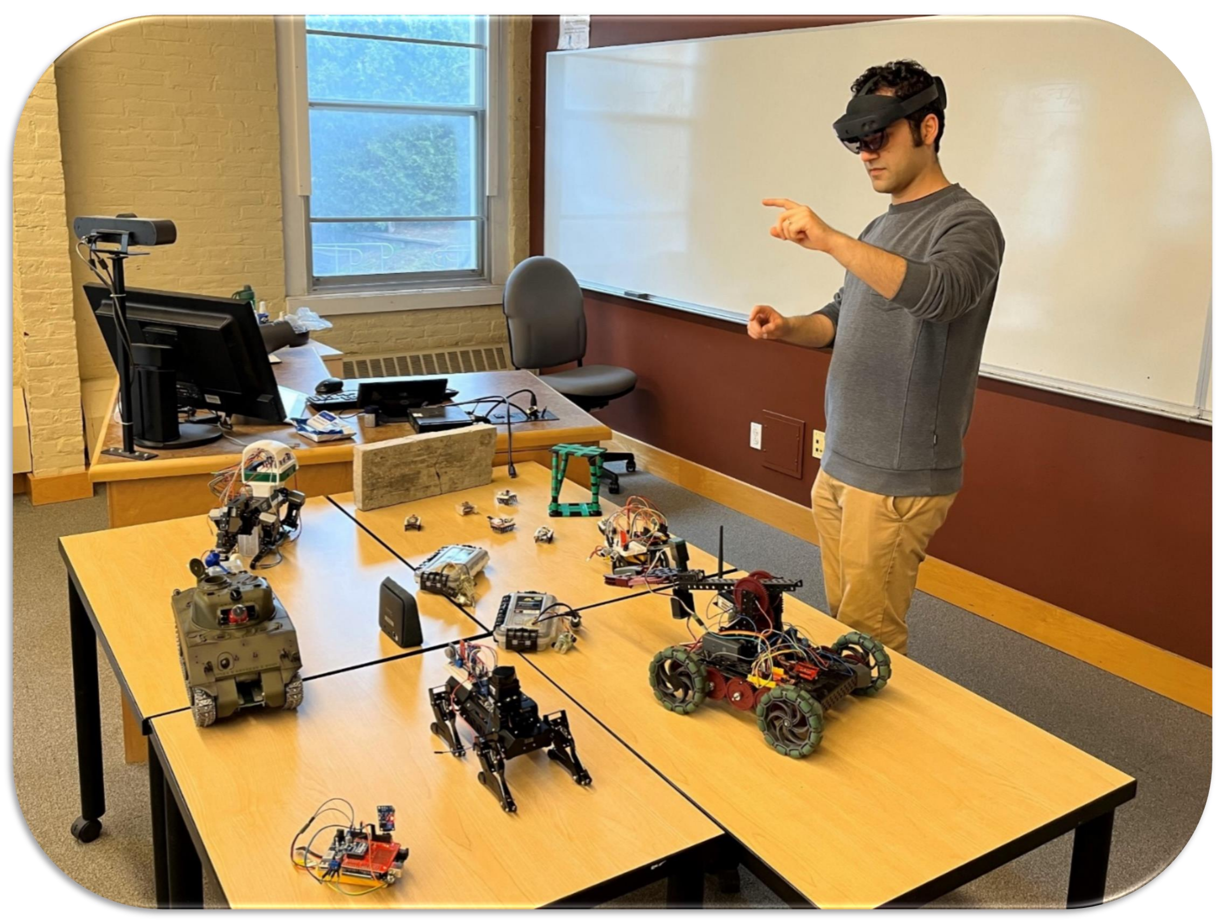

Figure 1. Heterogenous swarm of distributed wireless robotic and sensing augmented reality inspection cyber-physical system.

Methods

Complex CPS requires new methods to define metrics and measure the performance parameters such as latency.

The visual method called photon to photon [3] calculates differences in timing between the images captured of an FPGA clock from the display of separate devices.

CPS-1: A visual latency measurement method for CPS, consisting of an AR headset, microrobot [2], a wireless network hub, and display device, is investigated.

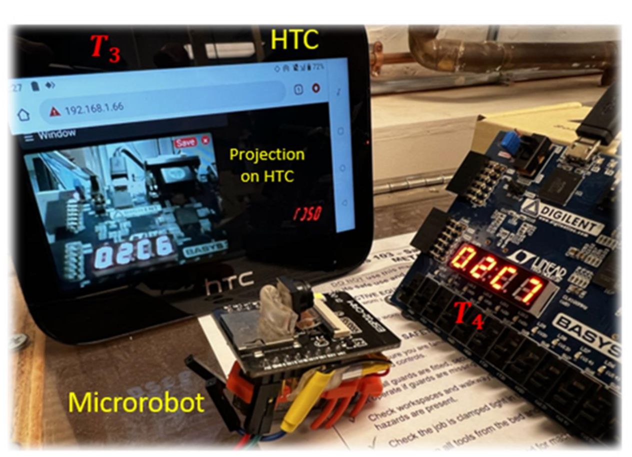

Figure 2. A latency case where the microrobot captures the video of an FPGA and transmits it through the wireless network to be displayed on the HTC hub's screen.

The monitoring of the damages in confined spaces is usually overlooked in typical human inspections. Low-cost camera-based microrobots (MARSBot [2]) can be fabricated to monitor the confined spaces.

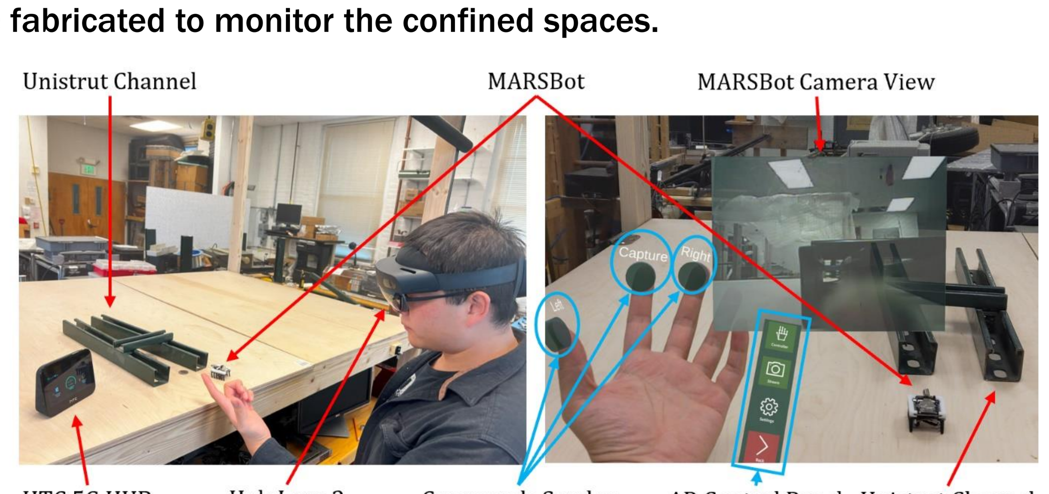

Figure 3. MARSBot [2] visual inspection with AR steering regulated by the operator connected to the same Wi-Fi hotspot (shown on the left), and the AR interface with visual feedback from the MARSBot inspecting Unistrut channels (displayed on the right).

CPS-2: The growing usage of AR headsets allows for designing intuitive interfaces for operators to control the robot while being able to have a first-person view of the camera for SHM.

In locations where connectivity to 5G and 4G networks is not possible, the edge processing for Ground Penetrating Radar (GPR) scanning of underground structures requires alternative fast, high throughput networks. In this section, we evaluated the possible alternatives to perform similar tasks by using long-range, high-throughput, and low-power IEEE 802.11ah (Wi-Fi HaLow).

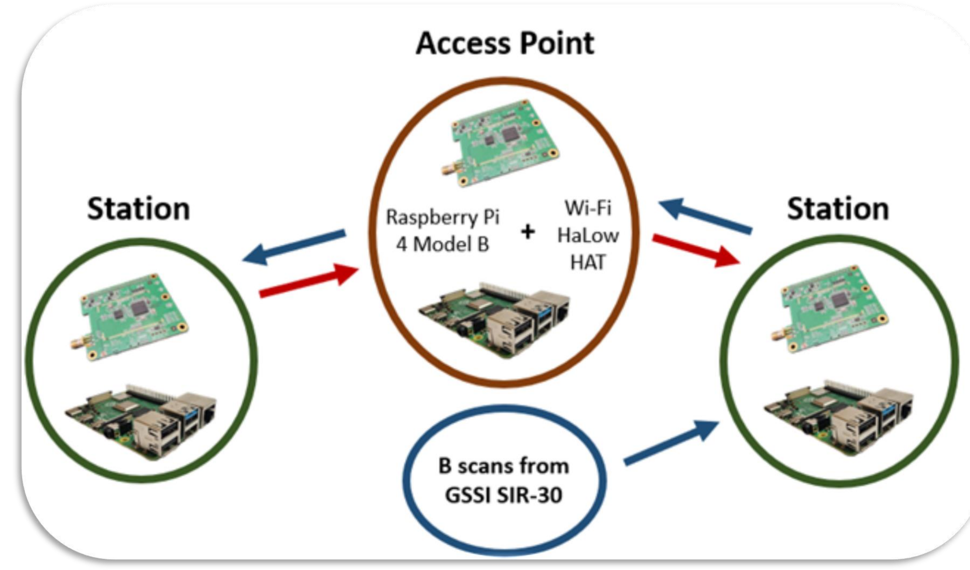

Figure 4. . Network setup for transmitting data over Wi-Fi HaLow

CPS-3: To verify the functioning of this network for GPR B-scans, a setup was configured by having a single board processor with HaLow HAT as an access point and send the B-scans from one station to another one through the access point and measure the latency while on the HaLow network.

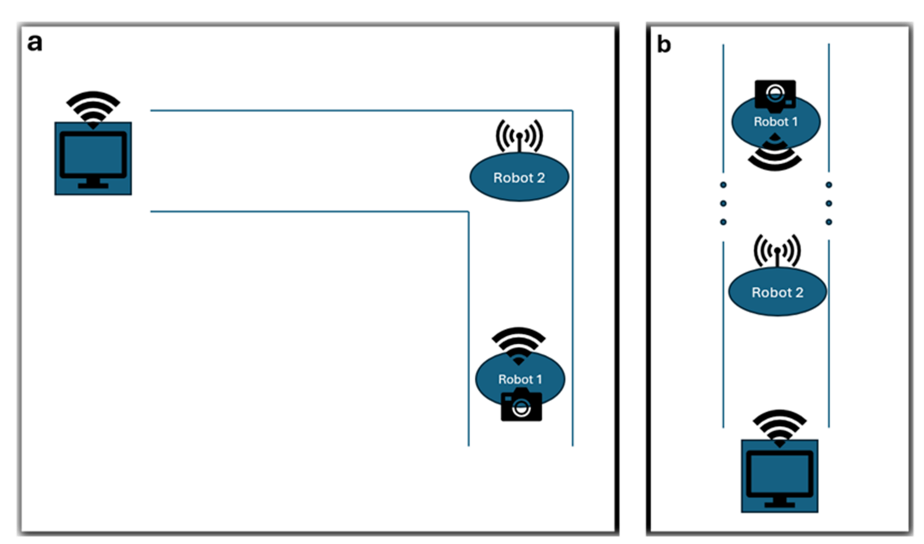

Figure 5. a) Multi-robot monitoring of a culvert with a corner, b) Long culvert monitoring using a multi-robot wireless repeater configuration.

Successful wireless telemetry requires consideration of the operating environment. Culverts are particularly challenging as the walls tend to be electromagnetically lossy and do not act as conventional electromagnetic waveguides

CPS-4: A multi-robot configuration with an access point in the middle can solve this issue by either increasing the range in a long culvert or stopping at the corners of the culvert with complex shapes. The proposed modular wireless system can be attached to any mobile robot capable of moving in the culverts.

Additional technologies can be integrated into the robots to assist in classifying underground infrastructures. For this purpose, orbital angular momentum (OAM) [4] is tested with a variety of shapes to investigate the difference between receiving signals.

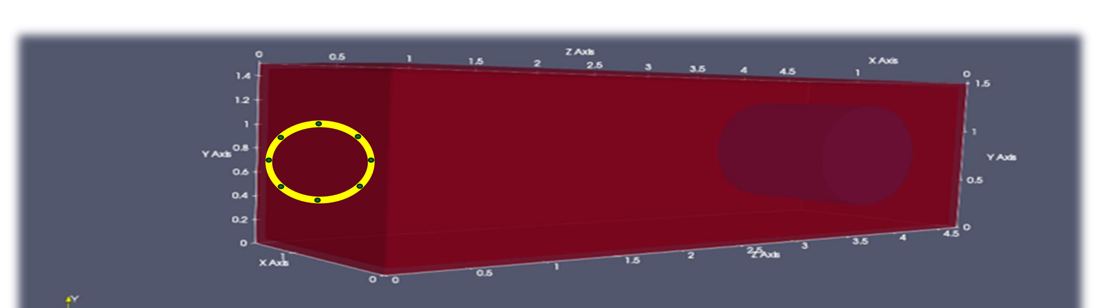

Figure 6. GPRMax geometry visualization of a 0.5 meter diameter cylinder placed at 4 meters away from the 8 antennas positioned with 45 degrees phase delay.

Results

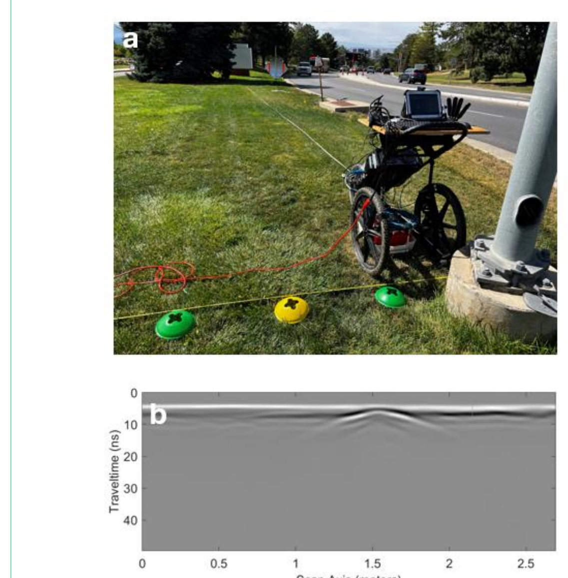

Figure 7. a) Experimenting with the University of Utah POWDER platform with the GPR, b) A sample B-scan edge processed using the POWDER network.

The early tests of successful implementation of GPR edge computing and transmission of B-scans were conducted using the University of Utah's POWDER platform's 5G network. However, the need for a mobile, low-cost, local network that is not geographically restricted paved the way for developing the Wi-Fi hotspot networks and HaLow Wi-Fi networks.

The edge computing and displaying the underground B-scans into the AR headsets enables simple visualization of GPR scans. This allows the user to inspect the subsurface thoroughly in the corresponding physical environment.

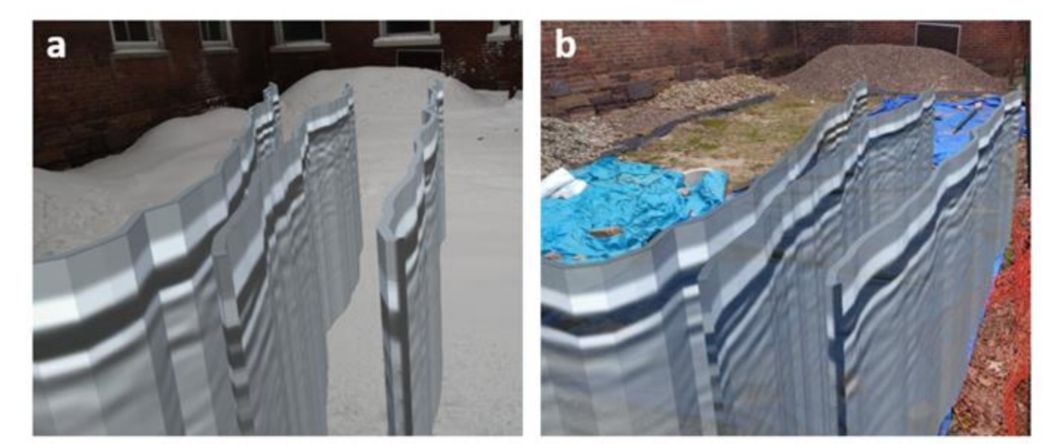

Figure 8. A hologram representing F-scans in AR displayed over a) snow-covered ground and, b) uncovered ground.

It can be interpreted visually that higher probability density in low latencies indicates better performance. In each case, the probability density histograms follow a log-normal distribution. By this standard, Wi-Fi HaLow shows its superiority in its consistency and low latency compared with the other four cases.

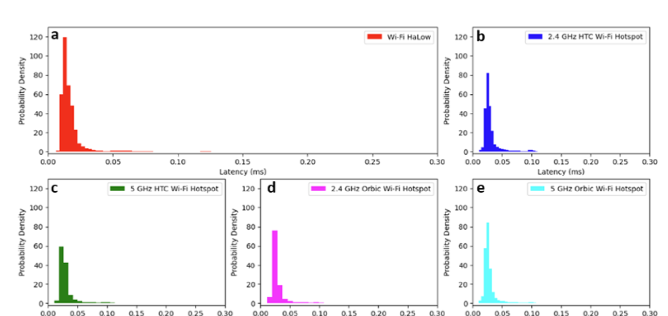

Figure 9. Comparison of latency while transmitting B-scans over a) Wi-Fi HaLow and, b) 2.4 GHz HTC Wi-Fi hotspot, c) 5 GHz HTC Wi-Fi hotspot, d) 2.4 GHz Orbic Wi-Fi hotspot, and e) 5 GHz Orbic Wi-Fi hotspot

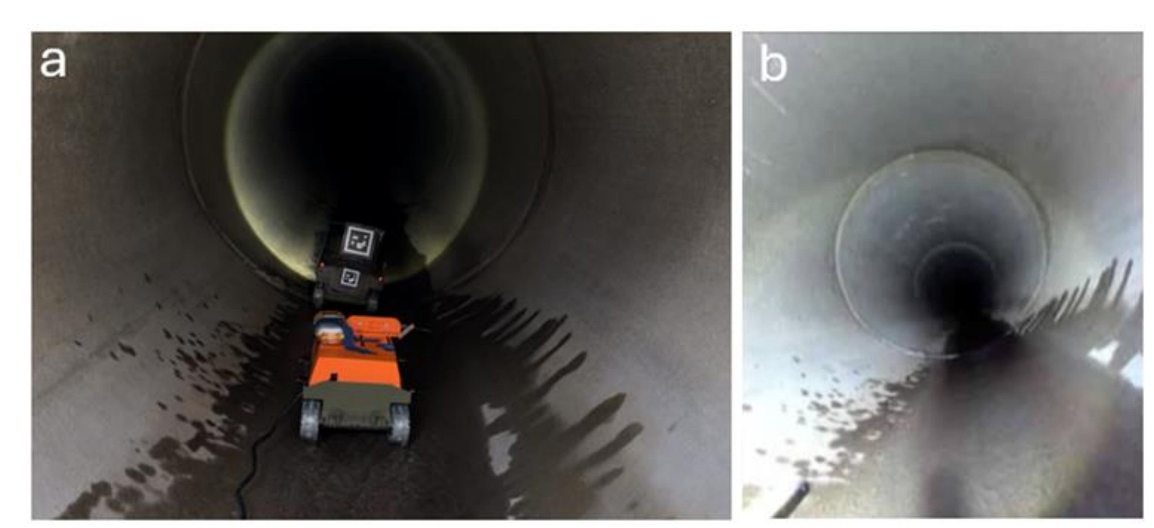

Figure 10. a) Culvert monitoring using a multi-robot system, b) Image captured by the front robot's camera transmitted back to the operator

In the multi-robot culvert test, the front robot carries the W-Fi-enabled camera and transmits the video back to the similar board, which is programmed as an access point on the rear robot. The video feed is then accessible from the outside by the operator connected to the access point on the rear robot for inspection of the culvert.

The receiving signals for the case of targets in the shape of a cylinder, plate, and sphere summed up together for each antenna. Setting the case of the Plate target as a reference, the cases of sphere and cylinder data were subtracted from the plate's data and plotted.

The comparison between the data shows a clear differentiation between both cases where AI approaches can be used to classify the objects by analyzing the receiving signals.

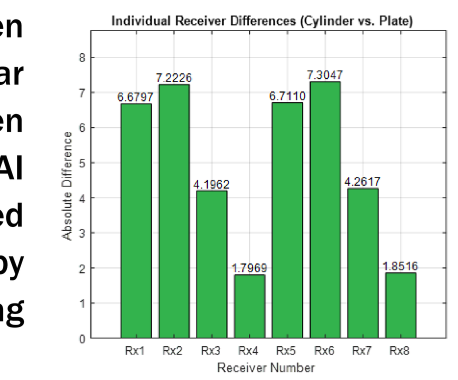

Figure 11. Difference of Sum of amplitudes for receiving signals between cylinder and plate cases.

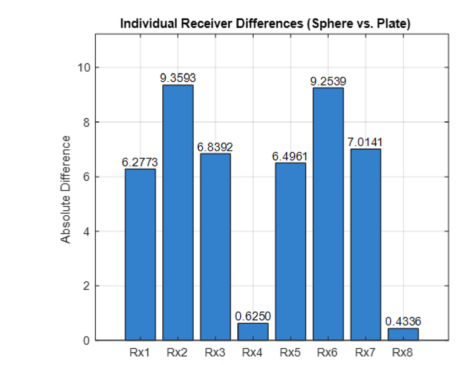

Figure 12. Difference of Sum of amplitudes for receiving signals between sphere and plate cases.

To verify the locations of antennas and their phase delays, a phase angle graph at different wavelength locations can be plotted where at the midpoint all their values sum up to zero.

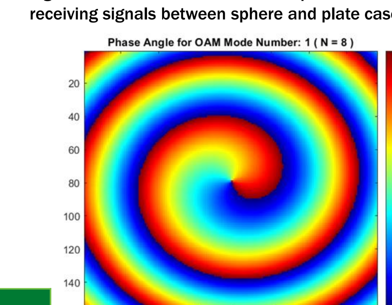

Figure 13. Phase angle at 16th wavelength of 8 antennas with 77 GHz OAM in Z direction.

Table 1. Example of a Scoring system for performance model

Metrics / CPS	Latency	Bandwidth	Interference	Signal Attenuation	Reliability	Battery Life	Overall Score
Weight	-10	+8	-3	-7	+4	+2	-
CPS-1	3.83	0.696	5	3	6	2.26	-11.827
CPS-2	5.98	0.696	6	3	4	1.86	-21.621
CPS-3	0.22	0.065	1	1	4	5	4.212
CPS-4	10	1.957	9	9	1	6.28	-46.407

$$Overal\ Score = 10\,\frac{\sum_{i=1}^{6} W_i\, S_i}{\sum_{i=1}^{6} W_i}$$

For assisting the SHM operators in selecting the best CPS for each application, different metrics are quantified with designer choice of weights [1]. The metrics for the performance are latency, bandwidth, interference, signal attenuation, reliability, and battery life. Using these metrics, a scoring system for performance model can be calculated, which results in a value from -100 to 100 based on the performance of the CPS.

Conclusions & Vision

The proposed research suggested novel methods to solve SHM challenges in complex environments and proposed a method for selecting the best hardware based on performance metrics for CPS.

Future works include robotic swarms integrated with radar for underground inspections using the OAM method to enable object classifications based on the differences in the receiving signals.

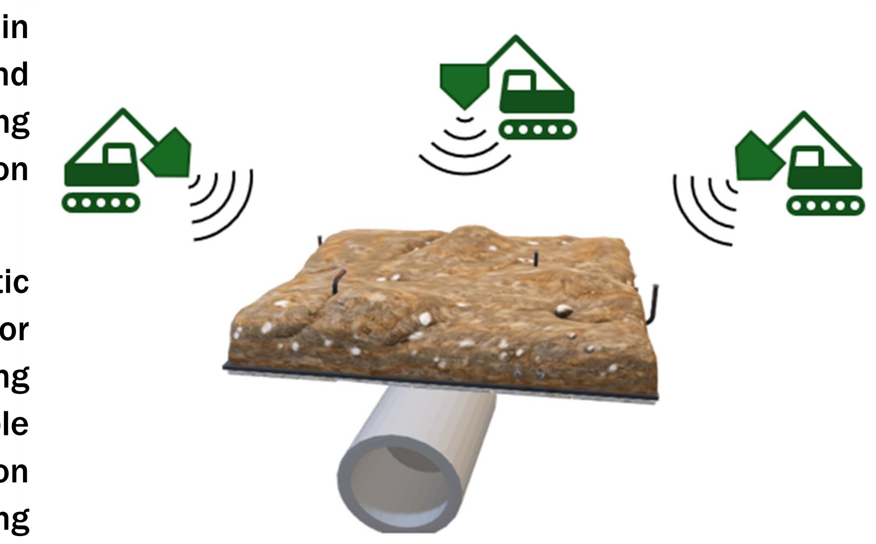

Figure 14. Schematic of swarm robots with radar to analyze the underground infrastructure.

References

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