Delivering Maintenance and Repair Actions via Automated/Robotic System

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Submitted by:

Jie Gong
Professor, Ph.D.
Rutgers University

Xiao Liang
Assistant Professor, Ph.D.
University at Buffalo

Matthew Bandelt
Associate Professor, Ph.D.
New Jersey Institute of Technology

Center for Advanced Infrastructure and Transportation
Rutgers, the State University of New Jersey
100 Brett Rd, Piscataway, NJ 08854

External Project Manager
Robert Kumapley, PE
Chief of Enterprise Asset Management
Port Authority of New York & New Jersey
150 Greenwich St, New York, NY 10007

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16. Abstract

This study explores the emerging role of robotics in infrastructure inspection and repair. Through a multidisciplinary workshop and a series of proof-of-concept field studies, we evaluated the capabilities of advanced robotic platforms—particularly quadruped systems like Boston Dynamics' SPOT—and AI-powered remote sensing tools. Results showed strong potential for improving inspection accuracy, safety, and efficiency. Quadruped robots demonstrated excellent mobility in hazardous environments, while AI integration enhanced data analysis and defect detection. These findings highlight the promise of robotics in infrastructure management and the growing impact of AI in enabling autonomous, intelligent inspection systems.

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INTRODUCTION

Description of the Problem

Maintenance of the vast network of transportation infrastructures in the United States, with many of them approaching the end of their life, is an enormous challenge to infrastructure stakeholders. To date, deliveries of maintenance and repair actions to these infrastructures have relied heavily on construction crews equipped with machinery tools. Often these traditional ways of doing infrastructure maintenance and repairs need shutdown of roads and bridges, creating costly disruptions to the traveling public. In many cases, construction crews also have to work in live traffic conditions under limited protection. There are also cases maintenance and repair actions cannot be effectively delivered to hard to reach areas by human workers. At last, the construction work force in the United States continues to shrink, which leads to the growing concern about whether there will be enough work force available for infrastructure maintenance and repair tasks.

Relevance to Strategic Goals

The focus of this project is particularly relevant to several USDOT strategic goals, which are also the primary focus of this consortium. The focus of this project on enabling more cost-effective life-cycle management of transportation infrastructures directly relates to "improving durability and extending the life of infrastructure" and "preserving the existing transportation system".

Research Goals and Objectives

Robots have become an emerging force in some of the most challenging working environments. Whether they are flying drones or climbing robots, rigid machinery systems or soft robots with a mix of mobility, strength, and configurability, robots are poised to revolutionize the field of infrastructure maintenance and repair. Nevertheless, there is currently no systematic investigation on how robots can be leveraged to deliver maintenance and repairing actions to transportation infrastructures. In particular, there is a lack of understanding on how robotic systems can be used to go beyond detecting detects in infrastructures and to actually deliver repairing actions. This project aims to identify and evaluate the feasibility of developing and deploying autonomous systems to streamline and enhance the quality of common repair and maintenance activities. The robotic systems currently used in construction offer examples of the feasibility of such robotic systems to safely conduct physical interventions. This project aims to build upon these examples to examine how autonomous systems will be able to intervene and take corrective actions to enhance the durability of transportation infrastructure. The results of this project have the potential to spawn a new research direction that may revolutionize the way infrastructure is managed, preserved, and renewed.

Methodology

This collaborative research proposal involves Rutgers University, New Jersey Institute of Technology, The State University of New York at Buffalo, and Rowan University College. To set the stage, the researchers hosted an introductory workshop to bring all the collaborators and industry partners together. The purpose is to align the vision of this working group with the needs of the industry partners. The workshop also involved reviewing current technological solutions and infrastructure problems and document examples of "robot solutions for delivering maintenance and repair actions" in infrastructure management.

A major activity in the project is also on conducting small-scale studies related to actual development/deployment of robotic solutions for infrastructure repair and maintenance. We leveraged the state of art facilities at Rutgers and SUNY Buffalo to experiment with research prototypes. These research tasks are served as proof of concept and to characterize emerging research needs. We evaluated the tools and techniques in terms of their strengths and weaknesses for delivering maintenance and repairing actions. More specifically, the research team conducted development and evaluation of advanced sensing systems and associated data analytics for robotic inspection, conducting experiments to assess the mobility of emerging robotic systems to meet the need of inspecting and repairing infrastructure systems in challenging environments, and development of advanced human robot collaboration mechanisms to deliverable inspection and repair actions. The research results are documented in ten peer-reviewed journal and conference publications. Several center-wide newsletters are also generated to disseminate the research results. In the following chapter, we details the findings from these research activities.

FINDINGS

Findings from dialog with the Industry and workshops

A half-day workshop with industry partners was organized on May 30, 2019 to identify use cases, characterize research priorities in robotic systems, align research visions, and to form sub-committees on various identified research dimensions. The team used the workshop as a venue to share the research findings on existing solutions for robotic delivery of maintenance and repairing actions to physical infrastructures. The workshop featured a mélange of three communities: R+D, practitioners and end-users. It brought more than 70 researchers, government officials and business owners to Rutgers University to discuss the applications of robots in infrastructure management, as well as new ways to overcome inertia in the market.

More specifically, the workshop, "Emerging Robotic Solutions for Infrastructure Management," began with a keynote speech from Carl Haas, Ph.D., a Professor of Civil Engineering at the University of Waterloo and Fellow of the Canadian Academy of Engineering, who spoke about robots, risk and rework.

Dr. Haas has specialty in the areas of advanced construction and transportation technology, sustainability and construction productivity. In his speech, he said that robots can help agencies and companies make maintenance work more affordable and efficient, but that there are other reasons why the technology is not always easily adopted. He recalled a time early on in his career when he was working on an automated crack-sealant system. The robotic technology he developed worked and was successful in addressing the need, but it was the implementation of the technology into the industry where he faced a roadblock.

Researchers from CAIT and partner universities also discussed the vision for delivering robotic inspection and repair to infrastructure systems. Dr. Frank Moon, a Professor in the Department of Civil and Environmental Engineering at Rutgers, said that being able to talk with owners about issues they are facing is important in developing innovative and relevant technology. "Owners have an enormous amount of heuristic knowledge," he said. "I think probably half of the body of knowledge that's part of the civil engineering profession is not written down in books. Talking with owners about events that happened, partial failures, full-failures, what did they do, what worked, what didn't work — you learn an awful lot from that."

Following the keynote speech, a panel of experts discussed both current and emerging solutions in robotics. From flying drones to climbing robots, and from rigid machinery systems to soft robots, these technologies have a mix of mobility, strength and configurability that can make them valuable to construction projects as well as infrastructure maintenance and condition monitoring. Carson Carney, Vice President of TyBot, discussed a robotic solution from his own company. He said that TyBot is an autonomous robot that can tie rebar at a fast, automatic rate, therefore reducing labor needs in bridge deck construction, for example. Other panelists included Dr. Nenad Gucunski, Professor and Chair of the Department of Civil and Environmental Engineering at Rutgers who discussed autonomous bridge deck inspection; and Zheng Wu, Director of Research at Bentley Systems Inc. who covered AI-assisted infrastructure digital twins.

Throughout the day, tours explored the recently-opened Richard Weeks Hall of Engineering and some of the robotics inside, including the CAVE Visualization Lab. Dr. Jie Gong, an Associate Professor of Civil and Environmental Engineering at Rutgers University, demonstrated some of his work in the lab using Augmented Reality (AR) and Virtual Reality (VR) technology including his project on AR in the life-cycle management of transportation infrastructure projects. He worked to develop two fully-immersive virtual environments modeled after two real facilities: The Stan Musial Veterans Memorial Bridge, which crosses Mississippi River between St. Clair County, Illinois, and the city of St. Louis, Missouri, and an in-service pump station. The virtual training environments can be used to simulate bridge inspections and improve workforce training, among other real-world applications. These applications can be used to improve safety of the work zone too. For example, construction crews can use the bridge VR environment to simulate the setup of work zones and experience the traffic flow in a safe way.

Among other tools and technologies, participants also got the chance to tour the Bridge Evaluation and Accelerated Structural Testing lab (The BEAST), located on the Livingston campus, in the afternoon. The workshop concluded with a series of lightning talks where researchers presented their latest work, and a discussion session about opportunities identified in the workshop and ways to move forward. Dr. Moon said that while owners and academia might have different focus areas or timelines on some projects, it is important to collaborate to ensure that research is impactful, relevant and moving down the right path. "It takes effort to build trust and relationships," Moon said about the importance of working together. "And to me, all of the successful interactions I've had with owners has been because there is a relationship that is there and I can speak my mind, and they can speak their mind, and we sort of come up with something valuable at the end."

At the end, we conferred with workshop attendees on the questions identified by the research team. These questions were used to guide our search for and evaluation of tools and techniques. They helped the research team and infrastructure stakeholders to understand how we can use "robotic solutions" to support the delivery of maintenance and repairing actions to physical infrastructure systems, what are the fundamental challenges hindering the design and implementation of such robotic solutions, what are the requirements in ensuring these systems to deliver quality services, what are the potential limitations of these systems, and what could be the unintended consequences of the use of these systems?

Findings from research prototype studies

The research team explored actual development or deployment of prototype robotic systems in realizing delivering maintenance and repairing actions to infrastructure elements. More specifically, our work was conducted from two aspects: (1) developing and demonstrating robotic/AI inspection technologies for bridges, buildings, and other types of infrastructures: and (2) developing and evaluating the mobility of emerging robotic systems such as quadruped robotic systems for delivering bridge inspection and repair actions.

Development and Evaluation of Robotic/AI Inspection Technologies

Spatially resolved infrared thermography for bridge deck inspection

Detecting subsurface defects in bridge decks is a critical yet challenging task in bridge maintenance. Infrared thermography (IRT) is a useful technology that can be potentially used for non-intrusive and automated inspection of bridge decks due to its capability in detecting thermal contrast caused by subsurface defects in bridge decks. Both passive and active infrared thermography testing has been shown to identify deficiencies in elements of bridges, such as delamination in bridge decks. LiDAR technologies in infrastructure assessment, especially for bridges, have been increasingly explored in the recent past. In more recent studies, infrared images have been combined with LiDAR with GPS for 3D Thermal Modeling to form 3D representations of buildings and infrastructures [1, 2]. For the NDT bridge assessment purpose, the fusion of LiDAR and Infrared imagery allows for high-resolution subsurface delamination localization and region dimension estimation. In this prototyping study, we fused infrared thermography and LiDAR mapping to produce spatially resolved infrared thermography, and evaluated its potential in detecting defects in bridge decks under a variety of environmental conditions.

There were two types of experiment setups in this study. First of all, it was to monitor variation in the surface temperature of a concrete bridge deck during a typical sunny day. The observation was done between 8:30 am to 9:00 pm with periodic imaging every 30 minutes. The second setup was for the periodic monitoring of variation in the same deck’s surface temperature during different seasons. The observations were performed at different times of the day and under different weather conditions. A thermal IR camera (FLIR T650sc) was used for conducting infrared scanning of the bridge deck, and its proprietary software was used to process the infrared images. The testing was conducted on a full-scale bridge superstructure, known as the ANDERS Validation Bridge (AVB) (Figure 1). The bridge structure consists of a concrete deck supported by three steel girders with typical steel cross-frames and diaphragms (see Figure 2). The concrete deck is 9 m long, 3.6 m wide (30 feet by 12 feet), and 203 mm (8 inches) thick. The concrete deck was built with two mats of uncoated reinforcing steel at 50 mm (2 inches) and 165 mm (6.5 inches) depths, respectively. The concrete deck contains a number of artificially introduced defects: delaminations, vertical cracks, ducts of various types and grouting conditions, concrete segregation, and an area undergoing accelerated corrosion. Delaminations, which were simulated by two layers of plastic foam pieces covered by a thin plastic film, are of various sizes and at three different depths. Due to the deck's orientation and the proximity of a nearby building structure, different sections of the bridge deck stay in shadow as the sun rises and sets. This introduces the opportunity to study the shadowing effects, which mainly manifest themselves as non-uniform heating and cooling processes in the bridge deck as it receives solar radiation during the day.

Figure 1 The Anders Validation Bridge Facility

The data collected during the experiment include digital images, infrared images, and videos from the infrared camera (FLIR T650sc), which has a thermal sensitivity of 0.02℃/0.036 °F. All infrared images and videos were captured with a 480x640 pixel focal plane array with a temperature range from -40 °F to 2732°F (-40 ℃ to 1500 ℃). The LiDAR point cloud was extracted from a LiDAR scanner (FARO Focus 3D Laser Scanner), ambient humidity and temperature captured from a moisture meter (FLIR MR77), ambient wind speed from an electronic wind speed meter (Mastech MS6252A). Real-time sky condition and the exact data collection time were recorded for each observation. The data collection time and site location were used to retrieve other weather conditions relevant to the thermal contrast change process on the same day, such as ambient air temperature, ambient air humidity, wind speed, solar radiation, from the weather station near the test site. Table 1 provides a complete list of environmental condition data recorded in this research.

Table 1 Environmental factors collected from weather stations

	Data Type	Environmental Factors from Weather Station
Same day continuous monitoring	Every 5 min	Air Temperature; Humidity; Wind Speed; Solar Radiation;
Long-term monitoring in different seasons	Daily and Real-time	Real-time Air Temperature; Real-time Air Temperature Change Ratio; Daily Temperature Range; Real-time Humidity; Daily Average Humidity; Daily Sky Condition; Real-time Sky Condition; Hours from Sunrise; Real-time Wind Speed; Daily Average Wind Speed; Daily Total Solar Radiation; Daily Maximum Solar Radiation; Daily Precipitation

The overall purpose of data processing is to facilitate the later 3D thermal model analysis and statistical analysis for the retrieved data. This is necessary as the original data need to be converted to ensure data consistency. After each data collection trip, the data processing steps include IR image re-ranging, IR image stitching, and infrared data fusion with terrestrial LiDAR data. The details of each step are provided in Table 2.

Table 2 Data Processing Steps

Data processing Steps	Description
Infrared Image Re-ranging	Output temperature matrix from FLIR SDK or FLIR Tools. Set one fixed optimal temperature range for each video and export infrared images with the same temperature scale and color palette (e.g., Iron, Black and White, Arctic palette) through MATLAB.
Image Stitching	Stitch all the infrared images together to generate a panoramic image covering the entire bridge deck.
Infrared Image Mapping on Point Clouds	Select 4 points from the stitched infrared image and link these points with their counterparts in the LiDAR data; projecting the images onto the point cloud model to generate a 3D thermal model of the deck.

This step includes the detection, localization, thermal contrast value extraction, and dimension extraction of the subsurface defects of the studied deck. The use of LiDAR point cloud can provide accurate geometric (GPS) and precise dimension information to the infrared data. After all the processing steps, the defects are located based on the observed thermal contrast. That is, if an area has a maximum thermal contrast higher than 1 ℃/1.8 ℉, it will be treated as a potential defect. The area of defects was measured from a 3D thermal model (Figure 2) and estimated based on the ATSM D4788 standard that a minimum

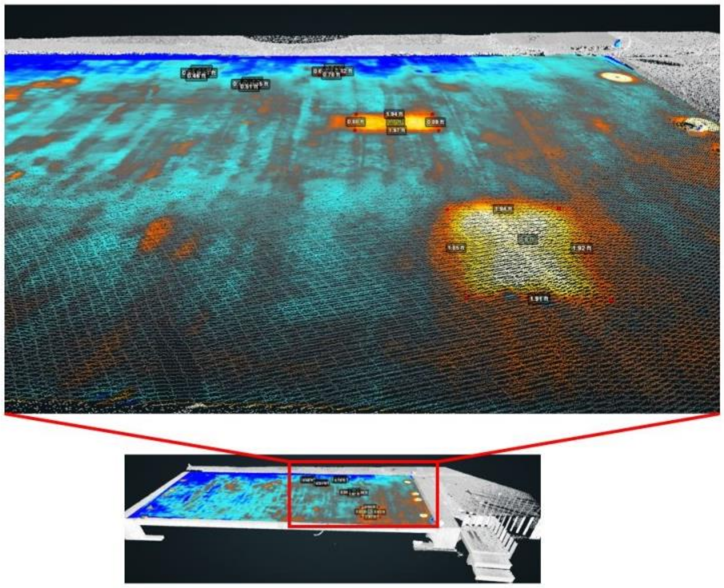

Figure 2 3D Thermal Model

The surface thermal information for the bridge deck was collected from 8:30 am to 9:00 pm every 30 minutes. The sunrise and sunset time of the day was 5:27 am and 8:32 pm, respectively. Due to the building near the test site, the sun started to shine on the deck at 8:20 am. To learn the effect of sunrise on the IRT inspection result, we defined the sunrise differential as the number of hours after sunrise. Figure 3 is the time series of infrared images for the observed bridge deck after going through the data processing steps outlined above, and the large thermal contrast areas were labeled out as potential delamination (Figure 5a). For better visualization and presentation of the results, an optimal color scale and color palettes were applied for each data collection trip. It can be noted that infrared images taken at 2:30 pm provide the highest visible thermal contrast, followed by the infrared images taken at 12:30 pm. The thermal images taken at 8:30 pm have the least visible thermal contrast of the day. Based on the IR images, a total of four areas (D1-D4) were identified as delamination with clear pattern, and nine areas (D5-D13) as potential delamination need further analysis. A comparison between these selected areas with the ground truth (Figure 5b) reveals that one small deep delamination area was not detected. This means infrared thermography-based concrete deck inspection may not be sensitive enough for picking up small deep delamination in bridge decks, in this case, 6.5 inches. The comparison also reveals that D8 is false positive detections as there were no defects planned at the time of deck construction. With this said, although D8 is not the delamination designed in the experiment, it still might represent anomalies in the bridge deck (Figure 4a). As expected, surface roughness and different materials that visible in the color image and appeared in the infrared images were falsely identified as defects. However, these areas were not part of the concrete deck thus should not be identified as subsurface detects. This is evident in potential defects in area D11-D13 (Figure 4). To explain it, areas D11 and D12 are possible correct delamination detection. There were no defects placed in the marked area (Figure 4b). However, a high amount of salt was added during concrete pouring to that particular portion of the deck. Therefore, additional defects may have developed since the deck was built. As can be seen in Figure 4b, area D13 is caused by the material difference on the deck surface. The last note is that the optimum time for detecting defects at different depths varies significantly. This is evident since, in some infrared images, certain types of defects are highly visible, while others are completely indiscernible.

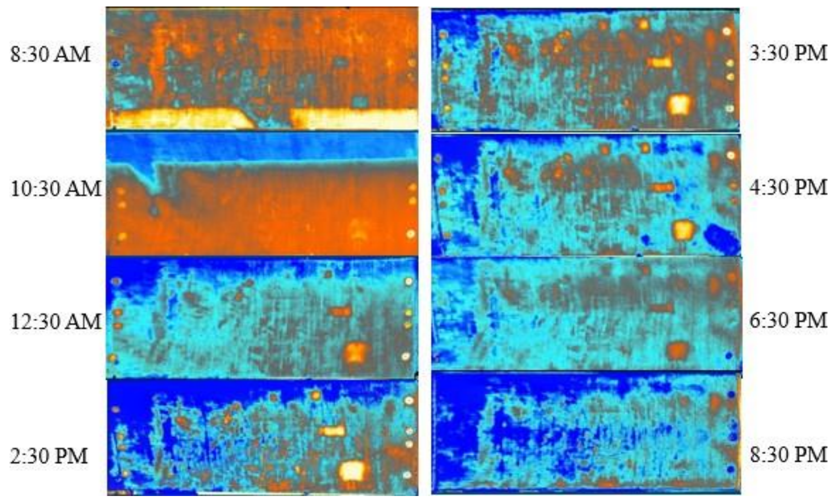

Figure 3 Concrete deck surface temperature changes during a day

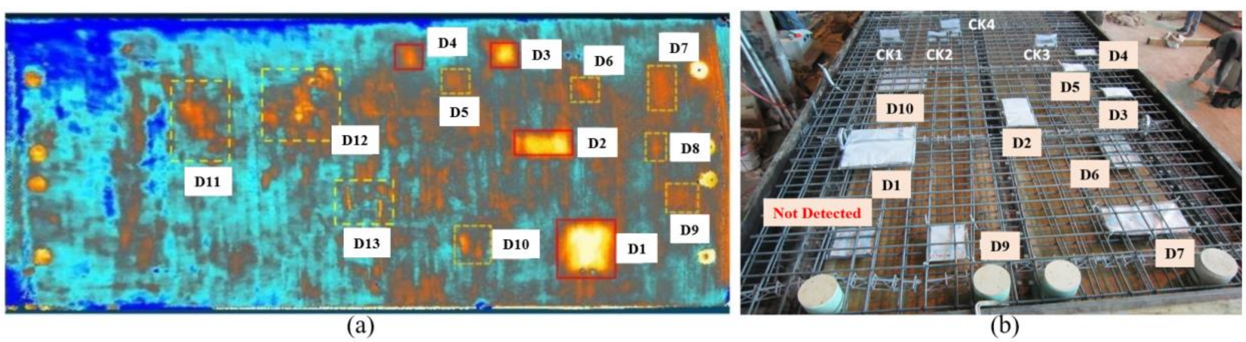

Figure 4 (a) Location of the potential delamination (D1-D13) and (b) location of the designed delamination (D1-D10; D: Delamination; CK:vertical crack)

In conclusion, the fusion of LiDAR and infrared imagery enabled the building of the 3D thermal model and high-resolution localization and dimension information extraction for concrete deck defects. The study results also suggest that the effectiveness of passive infrared thermography for concrete bridge deck inspection is highly dependent on both hours after sunrise and ambient air temperature. Lastly, the study established the relative importance of various environmental factors to achieving adequate thermal contrast.

LiDAR based inspection methods for characterizing operational vibrations of bridges

This research prototyping activity is motivated by the need for rapidly deployable remote sensing technologies for evaluating bridges under operating conditions to minimize the data collection time, avoid the disruption of traffic and increase the inspector's safety. The primary objective of this research is to investigate the potential of remote sensing technologies—specifically Light Detection and Ranging (LiDAR)—for characterizing structural vibrations in bridges, with the ultimate goal of enhancing and supporting existing bridge assessment methodologies. To achieve this, a comprehensive field study was conducted on a 12-span steel stringer bridge located in the Philadelphia region. The structure underwent extensive terrestrial LiDAR scanning, alongside traditional vibration data acquisition using accelerometers, which served as a benchmark for validating the LiDAR-based measurements.

Analysis of the collected data demonstrated that LiDAR is capable of capturing the dynamic behavior of the bridge, particularly its vibrational characteristics. The comparative results between LiDAR and accelerometer measurements revealed an error margin ranging from 1.9% to 10%, indicating a reasonable level of accuracy for LiDAR-based vibration detection in structural applications.

To complement the fieldwork and gain deeper insights into the interaction between the LiDAR scanner and the vibrating structure, a numerical model was developed using MATLAB. This model simulates a simply supported single-span bridge represented as a vibrating plate, while a stationary terrestrial LiDAR sensor positioned beneath the plate continuously scans its motion. The simulation assumes uninterrupted vibration without attenuation to isolate and examine the sensor's response under idealized conditions.

Based on the findings from both the field study and the numerical simulations, a set of practical recommendations has been formulated to guide the use of LiDAR technology in the evaluation of bridge vibration frequencies. These guidelines aim to support the integration of LiDAR into structural health monitoring systems, offering a non-contact, data-rich alternative to conventional methods. This prototype activity resulted in two peer-reviewed publications [3, 7].

LiDAR based bridge structural element assessment

Traditionally, the application of laser scanning in bridge assessment has been largely confined to capturing overall geometric dimensions of large-scale structures. Given the relatively coarse scale of these measurements in comparison to the standard accuracy thresholds of LiDAR sensors, such data can typically be obtained with minimal error—often less than 1%. However, this study extends the scope of LiDAR utilization by evaluating its ability to: (a) accurately estimate smaller, cross-sectional dimensions of a functioning bridge, and (b) assess the resulting errors not merely in percentage terms, but in terms of their impact on structural capacity calculations.

To address these objectives, a total of sixteen terrestrial LiDAR scans were conducted on an eleven-span steel girder bridge under normal service conditions. From the resulting point cloud data, a range of geometric parameters were extracted using both direct measurement techniques and established plane-fitting algorithms, including standard Plane Fitting and RANSAC (Random Sample Consensus).

The analysis revealed that geometric data derived using the Plane Fitting method produced flexural capacity estimates that were approximately 4% to 7% lower than those based on as-built dimensions from the bridge design plans. The RANSAC approach yielded slightly higher capacity discrepancies, with error margins ranging from 7% to 10%. Meanwhile, direct extraction of dimensions from raw point cloud data resulted in the largest deviations, leading to capacity estimation errors in the range of 9% to 13%.

Throughout the study, a conservative approach was taken in estimating all dimensional values to account for common sources of error, such as surface noise and occlusion. However, the data also highlighted a significant concern: distortions in structural elements caused by fabrication stresses can result in overestimated dimensions when planar assumptions are applied during data processing. This observation underscores the need for careful consideration of non-ideal surface geometries when using LiDAR data to inform structural performance assessments. This research prototyping activity resulted in four research publications [4, 5, 6, 8].

Computer Vision based Infrastructure Inspection

Many bridge structures, critical components in transportation infrastructure systems, exhibit significant deterioration and are nearing or have surpassed their initial design service life. Consequently, structural health inspections have become essential, particularly following extreme events. Recently, autonomous damage detection using computer vision and deep learning has emerged as a critical research area aimed at enhancing inspection efficiency.

We proposed a comprehensive three-level, image-based approach leveraging deep learning and innovative training strategies for post-disaster inspections of reinforced concrete bridges [9]. Specifically, convolutional neural networks (CNNs) were developed for image classification, object detection, and semantic segmentation tasks, corresponding respectively to system-level failure classification, component-level bridge column detection, and local-level damage localization. To overcome the practical limitation of small datasets, the proposed models emphasize robustness through principled hyperparameter optimization using Bayesian methods. Experimental results demonstrated promising performance, achieving accuracies exceeding 90% across all three tasks. This approach enabled rapid, accurate assessments, substantially outperforming traditional manual methods.

Building upon this success and addressing the critical need for high-resolution damage detection, we further introduced specialized twin deep-learning architectures for autonomous drone-based visual inspections [10-11]. These architectures effectively identify structural components and accurately detect subtle damage, including fine cracks, spalling, and exposed rebars. Our optimized models efficiently manage large image datasets, balancing computational requirements with high-resolution accuracy, which is crucial for timely post-earthquake evaluations.

Although deep learning-based computer vision approaches have achieved considerable success in structural health monitoring (SHM), uncertainty quantification and reliability assessment remain significant concerns due to potentially catastrophic consequences of misclassification. To address this gap, we developed uncertainty-aware frameworks employing Bayesian inference and variational methods to rigorously quantify uncertainty and substantially enhance confidence in SHM decision-making [12]. Specifically, Monte Carlo dropout sampling was utilized to quantify model uncertainty, leading to improved prediction performance and deeper insights into uncertainty behavior. Three independent case studies covering crack detection, local damage identification, and bridge component detection revealed strong correlations between uncertainty metrics (variations in softmax probability and entropy) and prediction errors.

By clearly communicating prediction reliability, these frameworks proactively alert engineers to potential inaccuracies, significantly strengthening human-machine collaboration and enhancing trust in autonomous SHM systems. Additionally, surrogate models were introduced to facilitate uncertainty-assisted segmentation refinement and prediction quality assessment. These surrogate models enhance segmentation accuracy and efficiently trigger human intervention when necessary, providing a robust and reliable approach that can be seamlessly integrated into future deep vision-based SHM inspection processes.

Development and Evaluation of the Mobility of Emerging Robotic Systems

In recent years, the development and deployment of legged robotic platforms—especially quadruped systems like Boston Dynamics' SPOT—have opened up new frontiers in the inspection and maintenance of civil infrastructure. Unlike wheeled or tracked robots, quadruped robots offer superior mobility across irregular and unstructured terrains, making them particularly suited for environments that are difficult, dangerous, or otherwise inaccessible to humans. These platforms are equipped with advanced sensors, computational power, and autonomous navigation capabilities, positioning them as revolutionary tools for infrastructure stakeholders tasked with monitoring the health of aging assets such as bridges, tunnels, and dams.

While the commercial availability of systems like SPOT marks a significant technological milestone, their application within real-world infrastructure settings remains in its infancy. Much of the existing literature and promotional material highlights the robot's versatility in laboratory or controlled outdoor environments. However, the performance of these systems under actual field conditions—such as during the inspection of a bridge located in a remote or degraded area—has not been extensively evaluated. As a result, the full extent of their potential, as well as their operational limitations, remains largely unknown. For these tools to be adopted in routine inspection workflows, it is crucial to move beyond theoretical capabilities and conduct practical, scenario-based testing.

To address this knowledge gap, we designed and carried out a comprehensive set of field experiments aimed at assessing SPOT's operational effectiveness in conditions that mirror the complexities of real infrastructure sites (Figure 5). These experiments were focused on two core capabilities: (1) the robot's physical mobility on challenging terrain, and (2) its ability to autonomously localize itself and geo-reference the data it collects. Mobility testing was conducted on steep embankments and sloped surfaces representative of those often encountered in bridge and culvert inspections. Localization capabilities were evaluated using a combination of onboard GPS sensors and visual-inertial odometry supported by Simultaneous Localization and Mapping (SLAM) algorithms. We also examined the added benefit of using physical localization targets to enhance data referencing.

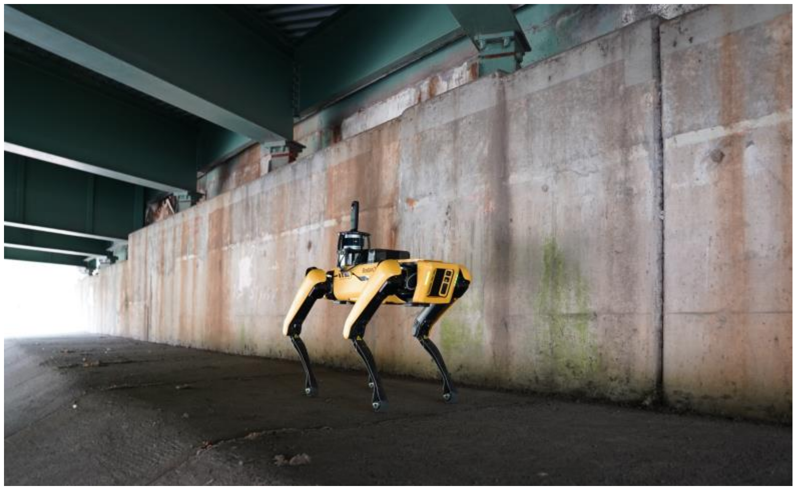

Figure 5 Testing Boston Dynamics SPOT Robot Dog at I287 Bridge Site

The results from our mobility tests were striking. SPOT demonstrated the ability to traverse inclines approaching 45 degrees with minimal loss of stability, even when transitioning across varied surface materials such as gravel, concrete, and compacted soil (Figure 6). The robot's built-in perception system allowed it to adjust its gait dynamically, maintaining balance and traction despite the uneven and sloped terrain. This level of mobility confirms SPOT's potential for accessing areas that are typically off-limits to human inspectors or conventional inspection vehicles, such as the underside of bridge decks, steep embankments, or confined spaces with limited entry points.

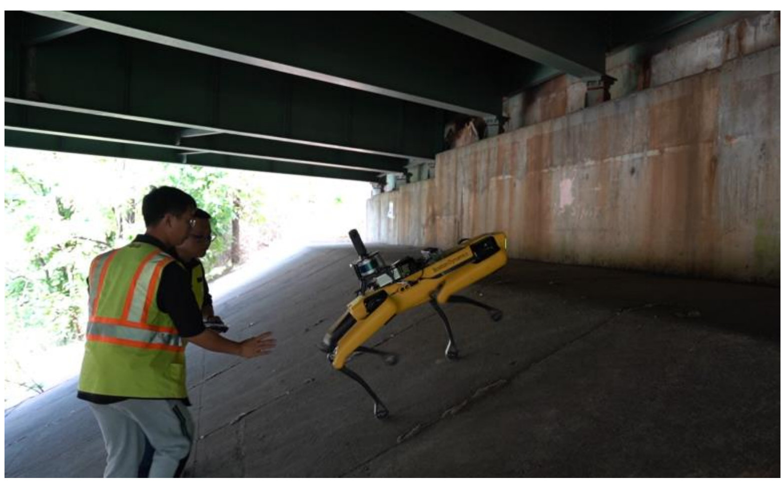

Figure 6 SPOT Climbing Steep Surfaces

In terms of localization, SPOT's performance was generally strong. The onboard GPS receiver provided adequate positioning information in open areas with clear sky visibility. However, in environments where GPS signals were partially obstructed—such as under overpasses or in heavily vegetated zones—the reliance on SLAM algorithms became more pronounced. While SLAM offered continuous localization, its accuracy was susceptible to environmental factors such as low-texture surfaces or rapid lighting changes. The use of physical reference targets—placed at known positions within the inspection environment—proved effective in improving the consistency and precision of data geo-referencing (Figure 7). These targets served as fixed anchors that the robot could recognize and use to recalibrate its position, significantly reducing cumulative localization error over time.

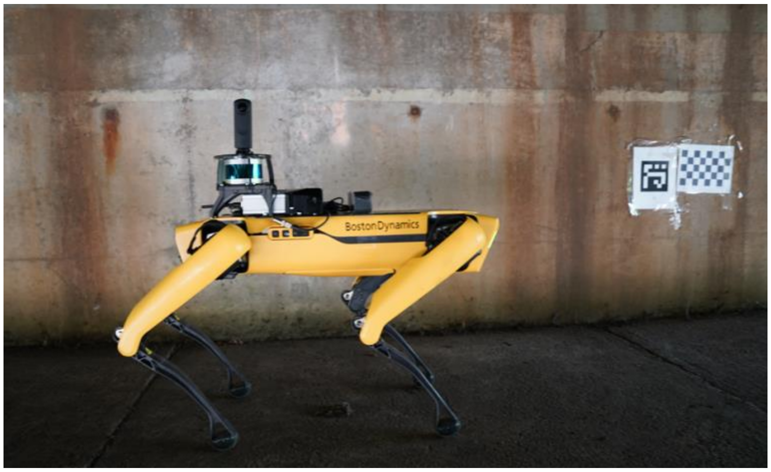

Figure 7 Use of Targets to Improve Localization

Taken together, these findings highlight both the promise and the practical considerations of integrating quadruped robots into infrastructure inspection workflows. On the one hand, SPOT's robust mobility and sensor integration offer a compelling solution for accessing and documenting hard-to-reach areas, potentially reducing the need for costly scaffolding, lift equipment, or hazardous human entry. On the other hand, the success of such deployments will depend on thoughtful planning, including the strategic placement of localization aids and the development of protocols to ensure data quality in environments with variable sensor performance.

Looking forward, future work should explore how these robotic platforms can be seamlessly integrated into broader inspection systems, possibly in tandem with drones, sensor networks, or digital twin models. Moreover, developing automated data processing pipelines—including image analysis, damage detection algorithms, and structural performance metrics—will be essential to fully realize the value these systems bring to the table. Nonetheless, this study demonstrates that the application of quadruped robots like SPOT is not just a technological curiosity but a viable, scalable solution for advancing the future of infrastructure assessment and management.

CONCLUSIONS AND RECOMMENDATIONS

The potential for robotics to revolutionize the way we inspect, maintain, and repair critical infrastructure systems is immense—yet it remains largely untapped and underexplored. As infrastructure networks around the world age and the demand for more frequent, accurate, and safer inspections grows, robotics offers a promising path forward. However, despite rapid advances in robotic technology, a wide knowledge gap persists regarding their practical applications in real-world infrastructure environments. Understanding how these systems can be effectively deployed and identifying barriers to broader adoption is an urgent priority for researchers, industry stakeholders, and public agencies alike.

To address this gap, this project convened a multidisciplinary workshop that brought together experts from robotics, civil engineering, transportation, artificial intelligence, and public infrastructure management. The objective of the workshop was to benchmark the current state-of-the-art in robotic technologies relevant to infrastructure inspection and repair. Participants shared emerging research, recent case studies, and real-world applications, with a focus on identifying both promising technologies and persistent challenges. The workshop served as a platform to surface the most impactful use cases where robotics could be deployed, such as in hard-to-access or hazardous locations, while also discussing the systemic and technological barriers to widespread adoption, including regulatory issues, integration complexity, and the need for reliable data interpretation methods.

In parallel with the workshop, the research team conducted a series of proof-of-concept studies to test and demonstrate the practical application of robotic and AI-powered technologies in the context of infrastructure inspection. These studies covered two main areas: (1) the development and demonstration of robotic and artificial intelligence systems for inspecting bridges, buildings, and other infrastructure assets, and (2) the evaluation of mobility and operational capability of next-generation robotic platforms—particularly quadruped robots—for executing inspection and minor repair tasks in the field. These experiments were designed to assess how well emerging technologies can handle the complex, variable conditions often encountered during infrastructure evaluations.

The results from these proof-of-concept initiatives were highly encouraging. The integration of remote sensing tools—such as LiDAR, high-resolution imaging, and thermal sensing—with artificial intelligence models showed clear potential to enhance the accuracy, consistency, and efficiency of inspections. By embedding these technologies into robotic systems, infrastructure assessments can be increasingly automated, reducing the need for manual inspections that are time-consuming, labor-intensive, and often risky. Notably, machine learning algorithms were able to detect defects, identify anomalies, and assist in structural condition assessments with increasing levels of reliability, even in complex environments.

A particularly promising area of investigation was the deployment of advanced quadruped robotic systems, such as Boston Dynamics' SPOT robot, which demonstrated exceptional mobility across a range of terrains and structural configurations. These robots were able to perform tasks in areas that would typically require workers to operate in dangerous conditions—such as on narrow bridge shoulders adjacent to live traffic, on steep embankments, or within confined structural cavities. By allowing robots to handle these tasks, the risk to human inspectors is significantly reduced, creating a safer and more sustainable approach to infrastructure management.

Looking to the future, the outlook for robotic technologies in infrastructure inspection and repair is bright—driven in large part by the explosive growth of artificial intelligence. As large foundation models, including large language models (LLMs), continue to advance, we are nearing a point where robotic systems could be endowed with near-human levels of perception, decision-making, and adaptability. These capabilities promise to further transform how robots operate in the built environment, enabling them to not only carry out inspection tasks autonomously but also interpret results, make recommendations, and even carry out minor repairs. Ultimately, this trajectory could lead to a new era in which robots are not just tools, but intelligent collaborators that extend human capabilities while keeping workers out of harm's way.

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