Augmented Reality with Live Video Streaming for Beyond Visual Line of Sight Inspection for a Steel Bridge

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ABSTRACT

A Bridge inspection is routinely conducted to enhance its useful life and ensure user safety within prescribed standards. In this paper, an automated inspection of steel bridges beyond the visual line of sight (BVLOS) is explored with the use of a climbing robot providing live video streams in an augmented reality (AR) environment. We anticipate a reduction in computational complexity involved in stabilizing video feeds due to camera jitter and rolling shutter effects, improved image resolution of observed defects hence their early detection, and reduced training effort to operators through our intuitive interface. Previously, AR has been employed in bridge inspection to visualize building information modelling (BIM), evaluate impact echo delamination, observe bridge deterioration information, update BIM data with higher precision, reduce ambiguity in data collection, support in-office preparations, and extract 3D measurements, using ground robots in collaborative systems. To the best of our knowledge no previous attempt has been made to investigate a collaborative bridge inspection system aided by AR for teleoperation of climbing robots on steel bridges in BVLOS scenarios. The outcome of this research is anticipated to guide future bridge inspection standards towards more computationally efficient systems, minimizing the cognitive workload of the robot pilots compared to unmanned aerial vehicles (UAV) pilots, improving cost effectiveness, with minimal disruption to traffic. Use of real-time audio-visual augmentations will be initially evaluated for a two-person human-robot collaborative system. Visual feedback will be employed to teleoperate the robot on a lab-based steel bridge model while audio feedback is employed to coordinate the two operators across a wireless communication network.

Keywords: Augmented Reality, Bridge Inspection, Beyond Visual Line of Sight, Human-Robot Collaboration

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INTRODUCTION

Bridge inspections preserve infrastructural health, prevent unforeseen structural failures [1], while ensuring user safety. Bridges have historically been inspected by scaffolding methods which tend to be labor-intensive, with hard-to-reach areas. Recently, inspection vehicles with robotic arm(s) have been employed, but these tend to be expensive, disrupt traffic, and require specialized training. Hence, use of mobile robots to allow real-time remote visual inspection [2], to access hard-to-reach areas at significantly lower costs, minimal risk, with improved efficiency, reduced subjectivity, and facilitate automated data collection tasks [1] [3] has been explored. Unmanned aerial vehicles (UAVs) have been proposed to lower these inspection costs, with reduced disruption to traffic and high efficiency [4]. In the US, however, use of these drones is regulated by the Federal Aviation Administration (FAA), requires special pilot licenses, training, and prohibits their use out of the pilot's sight [2]. Hence, ground robots have been proposed for these inspection types [1], and in our case we investigate reliance on climbing robots for beyond visual line of sight (BVLOS) inspection. Two key concerns arise in BVLOS scenarios, (a) robot safety and (ii) effective inspection task completion.

Augmented reality (AR), a technology that contextually overlays virtual content in real-time within a physical scene, facilitates objective human centered data collection for health monitoring of bridges and improves efficiency, and safety while minimizing costs [2] [5]. These complement the traditional in-person observations with manual data collection that are inefficient, expensive, subjective, and labor-intensive [2] contributing to infrequent inspections as well as unreliable decision making. Further, overlaid AR virtual content can be in either audio, visual, haptic, or olfactory form. To date, most AR studies have centered upon collaborative visual inspection aids with little or no exploration of other virtual overlays.

Infrastructure inspection often involves more than a single individual [2]. Hence, the need for effective collaboration between multiple inspectors and robots cannot be over-emphasized. However, most AR studies on inspection have either focused on collaboration between the human and the machine or machine-to-machine while neglecting communication between the inspectors and with the robots. We, therefore, propose a real-time audio-visual communication system between inspectors augmented with a live video feed of the robot to aid teleoperation for beyond visual line of sight inspection scenarios. To illustrate this, we propose a two-person bridge inspection setup where the first inspector transports the climbing robot to the site, ensures its safety, and monitors traffic, while the second inspector conducts remote inspection while tele operating the robot. This setup will be hosted on a lab-based mock-up bridge girder. It is expected that the outcome of our study will improve real-time coordination between inspectors in BVLOS to enhance robot safety, while supporting semi-autonomous data collection tasks in real-time, at lowered cost, and with objectivity.

The rest of the paper is organized into 4 sections. Section 2 describes previous studies related to the current work, the third section details the approach followed to undertake the study, the following section shows the results and corresponding discussion and finally, the conclusions made from this study are presented in the last section.

RELATED STUDIES/LITERATURE REVIEW

Bridge inspection has been conducted by either scaffolding, inspection vehicles, unmanned aerial vehicles (UAVs), or ground robots. [4] present a bridge inspection approach that uses an optimized UAVs system to conduct safe and low-cost inspection. A remotely controlled gimbal camera is attached to the UAV to inspect underneath bridges by providing stable images to inspectors. On the other hand, [1] present a framework to automate navigation of a ground robot based on simultaneous localization and mapping (SLAM) for efficient execution of inspection plans. Our study explores the use of a climbing robot over a steel bridge to facilitate inspection in BVLOS cases.

Such visual feedback from the robots not only aids AR-based manual inspection but can also support autonomous and semi-autonomous information retrieval. For instance, [6] presents a system that captures and localizes defects on bridges objectively for reliable future retrieval and contextual visualization by onsite inspectors. Further, [7] illustrates a smart inspection system utilizing YOLO v5 model for defect detection and segmentation for quantization as well as pixel-wise measurement tasks. They propose a methodology that utilizes mixed reality to assess defect condition for subsequent transfer in cloud storage or updating digital twin systems. The scope of our study limits the scope to visual feedback for manual teleoperation task of the climbing robot in BVLOS where safety of the robot is essential and human judgement is necessary.

Use of wireless sensor networks (WSN) has been relied upon to facilitate collaborative human-machine interaction. For example, to facilitate remote inspection and maintenance of bridges, [8] develops an AR application integrating building information modelling principle to compare the models with current infrastructure state employing WSN. Further, [9] presents AR visualization of wirelessly collected strain data measurements to inspectors for their assessment and decision-making. Lastly, [10] present a system enabling collaboration between a robot collecting data and structural inspectors using a mixed reality headset in near real-time. To the best of our knowledge, little or no investigation has been done into multi-user collaborative infrastructure inspection.

METHODOLOGY

Navigation Task

To facilitate inspection BVLOS, this task involves manually teleoperating a climbing robot across a lab-based steel bridge relying on real-time visual feedback of GoPro cameras to identify potential defects as shown in Figure 1. This visual feedback is provided for proof of concept to the remote inspector within the field of view of their AR headset, to assess navigation reliability. The live feed is captured locally using OpenCV’s library and displayed as a web texture in the unity’s scene. The feed is then wirelessly transmitted to the HoloLens 2 device relying upon a virtual camera object attached to the web texture component for relaying using the Mixed Reality-WebRTC library.

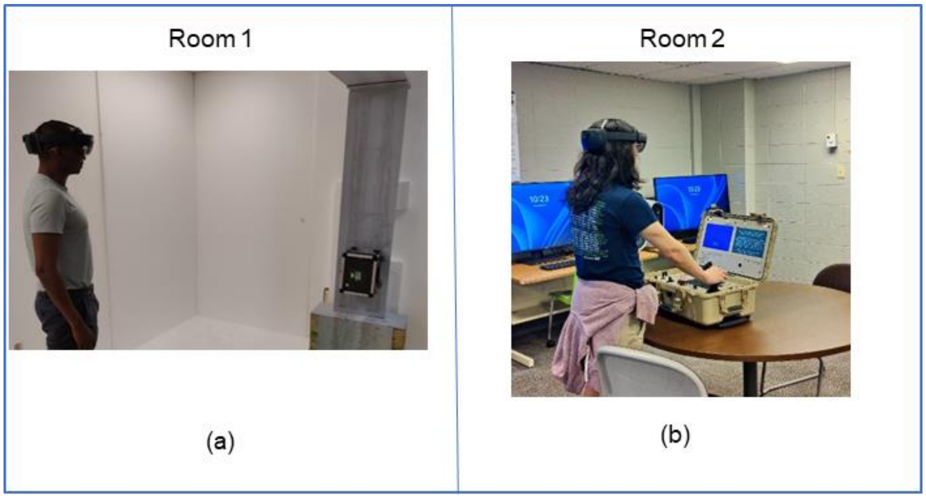

Figure 1. (a) Onsite inspector who transports the robot, ensures robot and public safety during the inspection both within VLOS and BVLOS. (b) Remote inspector to tele-operate the robot along the bridge.

System Design

Figure 1 presents the entire system setup where 2 inspectors each with an optical see-through head-mounted device (OST-HMD) are in geographically different location. The first inspector will be located within the bridge's vicinity to transport the climbing robot, mount it on the steel bridge section as well as monitor its navigation within VLOS (see Figure 1a). The first inspector's field of view will be transmitted wirelessly to the second inspector and the two will be able to communicate verbally. The second inspector will have visual feedback of the bridge to remotely navigate the robot on the bridge BVLOS as well as communicate with the first inspector as required (see Figure 1b). The second inspector's field of view is available for viewing by the first inspector hence can monitor both virtually and physically the navigation task as demanded.

Climbing Robot Items

The system is designed to support manual, semi-autonomous or fully autonomous inspection of bridge defects. For illustrative purposes, we use a manual inspection method to localize defects along the path of the robot on the steel bridge. The climbing robot (see Figure 2a) is custom built with 4 magnetic wheels hence it is only functional on ferritic surfaces. Its motion backward, forward, and rotational motion is remotely controlled through a wireless radio frequency (rf) signal following a joystick's input motion on the robot controller indicated in Figure 2b. Computer vision related defect detection algorithms benefit from videos free from camera motion [11]. This minimizes the computation complexity involved in stabilizing captured videos for subsequent processing by eliminating camera jitters and rolling shutter effects.

(a) (b)

Figure 2. (a) Climbing Robot fitted with GoPro Camera. (b) Robot Controller.

Experimental Hardware and Software

AR hardware employed were 2 OST-HMDs (HoloLens 2), a laptop (Intel I7-5500U, @ 2.40GHz, RAM 8GB, NVIDIA GeForce 940M), climbing robot, GoPro camera, and robot controller device. The OST-HMD devices were selected for their hands-free interactive support ability, integrated Wi-Fi ability for wireless transmission and being among state-of-the-art AR visualization devices. The laptop is used in this experiment for proof of concept only and is expected to be replaced by robot mounted NUC intel boards in the final setup. The climbing robot and its controller were selected given their availability within our research center.

The software tools relied upon were Unity3D for scripting the overall control logic, planning the live-feed visualization, and wirelessly networking the captured streams. Unity3D facilitates cross platform development hence selected to deploy to the OST-HMD device and the windows 10 laptop. The mixed reality toolkit (MRTK) was employed to configure Unity3D scenes for deploying to HoloLens. Finally, the mixed reality-WebRTC was employed for peer-to-peer real-time audio and video communication between the three devices with the laptop designated to be the signaling server.

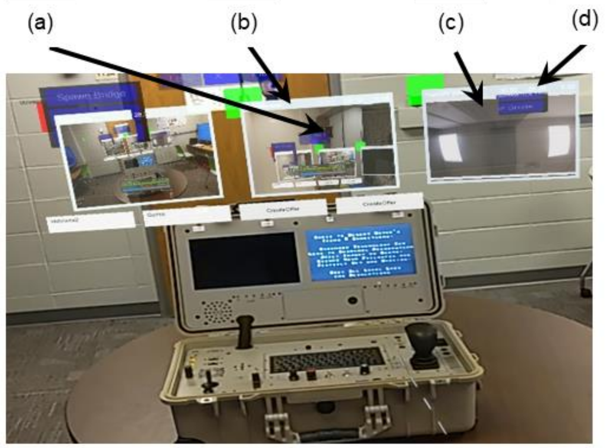

Figure 3. Inspector 2 remote view for robot teleoperation. (a) Climbing robot. (b) Onsite inspector's view of the tele-operation. (c) GoPro Hero Session 4 live view of the bridge.

RESULTS

The result of the setup shows the live views available to the remote inspector to execute a navigation task remotely through HoloLens 2. The inspector can localize the robot using two options where it is within VLOS of inspector 1 as indicated in Figure 3 (a) and (b). Firstly, relying on the onsite inspector's view (see Figure 3b), the remote inspector can approximate the global position of the robot relative to the bridge for effective manipulation. Secondly, relying on the GoPro camera's 4 live view (see Figure 3c), the inspector can approximate the local position of the robot relative to the bridge as well as examine defects potentially on the bridge. Where the robot is BVLOS then the inspector must rely on the GoPro camera's live view for both localization and examining defects. This is anticipated to result in stabilized views while utilizing climbing robots to facilitate computer vision tasks unlike onsite inspector's view that is subject to random head movements. The system's audio communication was also successfully tested to coordinate the two inspectors conducting inspection. Audio augmentation supports coordination during setup, initial placement of the robot on the scene and fast response to emergencies during inspection.

CONCLUSION

We have successfully demonstrated a collaborative AR application for inspecting bridges beyond the visual line of sight of inspectors using a climbing robot on a steel bridge. The application relies on audio-visual augmentations within the field of view of the inspectors who are remotely localized. The visual field of view of each inspector is available to the other in real-time together with any audio communication they may require relaying. In addition, a GoPro camera fitted on the climbing robot transmits a video feed to the remote inspector navigating the robot for inspection in the regions of interest. This system is anticipated to guide future bridge inspection standards towards more computationally efficient systems, increased coordination among bridge inspectors, minimizing the cognitive workload of the robot pilots compared to UAV pilots, improving cost effectiveness with minimal disruption to traffic.

In future, we anticipate that the system will be employed to support semi and fully autonomous defect detection on steel bridges by integrating machine learning algorithms to the images captured. Further, we shall integrate navigation of the robot on the AR device using haptic interaction on virtual controllers instead of the current controller utilizing a joystick. In addition, sensory feedback from steel thickness measurements will be wirelessly relayed for visualizing by inspectors in real-time. Finally, visual instructions will be overlaid on the field of view of the partner inspector to supplement audio communication.

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