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Fundamentals and Prospects of Four-Legged Robot Application in Construction Progress Monitoring

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Progress monitoring in the construction industry is mostly a manual process through in-person visual inspection and it leads to inconsistent, time-consuming, labor-intensive, and error-prone data acquisition. The key in progress monitoring is accurate, timely, and regular data collection and analysis during the construction process. Automating the process of regular data collection in progress monitoring can enable systematic recording of construction progress. To achieve this goal, mobile robots with autonomous navigation and high-performance locomotion capabilities can potentially navigate dynamically changing construction workspaces to perform regular data collection. This study identifies fundamentals of robot-enabled procedures for automated construction progress monitoring and explores the opportunities and challenges of utilizing a legged robot in this process. Through collaboration between academia and industry, this study conducts a set of experiments with a four-legged robot equipped with a 360° image capture technology to automate data collection in construction progress monitoring. The results of these experiments have identified the opportunities and operating procedure for robot-enabled image capturing. The study has also discussed current limitations in the automated construction progress monitoring including safety limitations, operation limitations, and mission limitations.

Key Words: construction robotics, legged robots, progress monitoring, Spot, quadruped robots

Introduction

Applying automated solutions and robotics has become critical in construction. Construction teams started employing advanced robotics to simplify complex construction processes, eliminate mundane tasks and improve human safety in construction sites. Studies indicate that productivity and efficiency in the construction industry has declined in recent decades. Defect rates, cost overruns, dangerous jobsites, and ineffective construction management processes result in both poor productivity and risky working conditions in construction (Kim et al., 2015; Bock, 2015). Efficiency issues and safety problems of the construction sector can be addressed by construction automation using robots and computer enabled solutions (Bock, 2015). Construction has a high number of injuries and fatalities

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(OSHA, 2019). Automation in construction can relieve human workers from repetitive and dangerous tasks to improve construction safety (Afsari et al, 2018). Delgado et al. (2019) have categorized construction automation and robotic technologies to off-site systems, on-site systems, drones and autonomous vehicles, and exoskeletons (Delgado et al., 2019). For control systems, robots in construction can be categorized to teleoperated or remote-control robots, programmable robots to enhance operation by their human operator, and unmanned intelligent robots with semi or fully autonomous mode (Saidi et al., 2016). This paper first investigates the importance of automated progress monitoring in construction and identifies current technologies for the automation. It also investigates mobile robotics and features of the legged robots for navigating construction sites. Through collaboration between academia and industry, this research conducts a set of experiments with a four-legged robot equipped with a 360° camera and an image capture technology for automated construction progress monitoring. The results of these experiments in controlled environments and on an active construction site are then presented. Then, the required on-site procedure is specified and current opportunities and limitations are discussed.

Construction Progress Monitoring and Automation

One of the major construction tasks that is expected to be automated is progress monitoring (Delgado et al., 2019). Construction progress monitoring involves an on-site observation to (a) verify percentage completion of work performed, (b) verify that construction work completed is consistent with project requirements including drawings and specifications, (c) verify that work completed is consistent with project schedule and requested funds, (d) adjust the performance of construction process in terms of schedule and cost when needed, and (e) avoid unpredicted costs, delay or rework (Kopsida, Brilakis, & Vela, 2015). Progress monitoring in the construction industry is mostly a manual process through in-person visual inspection thus it leads to inconsistent, time-consuming, labor-intensive, and error-prone data acquisition that relies mainly on the inspector's level of experience (Alizadehsalehi & Yitmen, 2019). The key in progress monitoring is accurate, timely, and regular data collection and analysis during the construction process (Kopsida, Brilakis, & Vela, 2015). In fact, automated progress monitoring of construction projects using emerging technologies can address existing limitations and inefficiencies of the manual processes (Alizadehsalehi & Yitmen, 2019) and can enable systematic recording and analyzing construction progress (Lin, Han, & Golparvar-Fard, 2015). Kopsida, Brilakis, & Vela (2015) identified four areas in automating the process of progress monitoring: data collection from the actual construction work, extracting required as-built data for analysis, comparing the as-built data with as planned information, and visualizing and reporting the results. Specifically in order to automate data collection in this process, studies have used various technologies, for example, a combination of Radio-Frequency Identification (RFID), laser scanning, photogrammetry with a digital camera, barcoding and a mobile device (El-Omari & Moselhi, 2011), a combination of camera-equipped UAV, 4D Building Information Modeling (BIM), and 3D point cloud model (Lin, Han, & Golparvar-Fard, 2015), and a data fusion framework that combines multiple data sources including 3D CAD model, ultra-wideband (UWB) receivers data, and laser scanned data (Shahi, Safa, Haas, & West, 2015). In this regard, collecting photo images of the actual construction status is very important for the reporting stage (El-Omari & Moselhi, 2011) and for supporting communication of the identified issues with the stakeholders. Utilizing 360-degree panoramic images to visualize construction performance and facilitate construction progress monitoring is becoming popular and some example applications include HoloBuilder, StructionSite, Reconstruct, VisualPlan, CUPIX, OpenSpace, OnSiteIQ, and ContextVR. These web-based applications have different internal tools and functions but all focus on job site documentation. 360° cameras are being utilized in these applications to increase visibility and decrease the capture time. A main functionality that all these platforms have is the increased organization of progress documentation by linking the images to a floor plan or model. The 360° images captured on a regular basis during the construction process can be compared with either the BIM model or renderings of the BIM model to provide the opportunity to review as-planned with as-built conditions. These solutions mostly allow extended collaboration by integrating their platform with Procore, Autodesk BIM360, Bluebeam (Eiris Pereira & Gheisari, 2019) and some with PlanGrid. Some of these applications like CUPIX can capture single or video walkthrough 360° images and transform them to a walkthrough space. Some like OnSiteIQ and OpenSpace use computer vision to locate and search objects in the 360° images. These solutions currently have limitations such as accuracy and limited integration with the BIM models but they can improve communications among project's stakeholders (Eiris Pereira & Gheisari, 2019). Recent advances in automation has enabled robotic and autonomous inspection and monitoring (Delgado et al., 2019). Mobile robots can be deployed to release the human from the laborious task of constant on-site image capture. This study explores fundamentals of robot-enabled data collection for automated progress monitoring.

Mobile and Legged Robots

Autonomous navigation through the unstructured and dynamically changing construction environments requires mobile robots that can carry out high-performance locomotion tasks. Mobile robots use various types of locomotion to navigate an environment. Typical locomotion types used for mobile robots are (Lattanzi and Miller 2017; Zang et al. 2016) (a) wheeled robots using multiple wheels for navigation as the most stable robots with high payload capacity but they can operate on limited uneven surfaces and cannot move between levels through the stairs independently, (b) crawler-mounted robots using crawlers with continuous tread bases that can operate on unlevelled and unfinished ground, (c) climbing robots using suction mounts or magnetic adhesion to stick to walls that are typically used for façade inspection but their challenge is to stay affixed to the surface reliably while being able to avoid obstacles, (d) Unmanned Marine Vehicles (UMV) mechanically sealed to operate in water and typically used for underwater inspection with special sensing devices, (e) Unmanned Aerial Vehicles (UAV) using rotors to fly and more suited for outdoors but in an enclosed construction environment there is a potential safety risk for workers and they may even collide with building materials, columns, or overhead cables, (f) legged robots using one or multiple legs inspired from terrestrial mammals to move but maintaining balance while moving is a major challenge for legged robots, (g) hybrid robots using a combination of locomotion systems e.g. a leg-wheel robot. Legged robots increase the field of different accessible terrains and are more versatile than wheeled robots (Hutter et al., 2017; Grandia et al., 2020) providing good potential to traverse construction sites. Mostly used and developed legged robots are two-legged robots, biped or humanoid robots (Lin et al. 2016), four-legged robots or quadruped (Hwangbo et al. 2019), and six-legged robots or hexapod (Faigl and Čížek 2019). Legged robots have become an important research direction in the field of robotics in recent years (Hutter et al., 2017; Grandia et al., 2020). Numerous legged robots have been developed by companies, institutions, and individuals including NASA, MIT, IIT, ETH, Boston Dynamics, Ghost Robotics, ANYbotics, etc. But due to high technological complexity to build and control such robots there are only few teams who have developed legged robots that can be applied outside laboratory settings (Hutter et al., 2017). Examples of four-legged robots include ANYmal C by ANYbotics, Spirit by Ghost Robotics, and SPOT by Boston Dynamics. Multi-legged robots can achieve better locomotion performance in terms of speed, efficiency of movement, and obstacle avoidance (Hutter et al., 2017). Legged robots have better adaptability on rough terrains, better mobility and flexibility because of many Degrees of Freedom (DoF) of the legs, and are able to move their body independent of underlying terrain (Grandia et al., 2020) making them a good potential for traversing construction environments.

Methodology

In this study we have first set up an industry-academia collaboration to align the theoretical research with practical uses of technology for progress monitoring in construction sites. The main goal, set through the collaboration, is to enhance progress monitoring for facility owner's representatives in a construction project. Effective progress monitoring requires reliable, fast, high-quality data collection from the construction site on a regular basis with minimized human intervention. Therefore, we studied the features of an existing legged robot technology that enables automated data collection in construction progress monitoring through a series of experimental investigations. In the experiments we have used a four-legged robot i.e. Spot by Boston Dynamics equipped with a 360° camera i.e. Ricoh Theta V along with a construction progress monitoring tool i.e. SpotWalk by HoloBuilder to study automated unmanned progress monitoring. This research has then identified operational procedures to deploy the technology in the field. The research has also identified opportunities and current challenges of the robot-enabled data collection in automated construction progress monitoring.

Experimental Investigation and Results

In this study, to investigate robot-enabled data collection in automated construction progress monitoring we used a legged robot, Spot, and the HoloBuilder SpotWalk application to perform progress documentation. We performed preliminary testing and experiments in the controlled environment of the research lab at Virginia Tech. Then, we conducted an experiment in the real-world construction site of Student Athlete Performance Center (SAPC) with 10,800 SQF new construction on VT campus in Blacksburg, VA. In these experiments we used, Spot, a legged robot manufactured by Boston Dynamics. Spot's anatomy is shown in Figure 1. In each Spot's leg there are multiple sensors and 3 motors so that it can navigate in indoor and outdoor environments and maintain its balance and postures (Boston Dynamics, 2020a). Spot's ingress protection is rated as IP54 (Boston Dynamics, 2020a) so it has partial protection against limited dust ingress and from water spray from any angle tested for min 10 minutes (IEC, 2013). This limited feature prohibits Spot's operation in the rain outdoors or in construction environments with higher levels of dust such as silica dust existing in common construction materials like concrete or granite during cutting, drilling and similar processes. Spot can operate in light rain for a short period of time but with IP54 rating, it is not protected against direct rain in outdoor areas. Spot's operating temperature is between -20° to 45° Celsius, its operating humidity is 0-70% RH, and its horizontal field of view is 360° for terrain sensing while its range is 4 meters (13 foot) (Boston Dynamics, 2020a). Spot can traverse a variety of terrains but it can become unstable on slippery surfaces such as wet grass or moving platforms such as moving walkways or elevators (Boston Dynamics, 2020a). Its operation also requires the lighting to be above 2 Lux. Spot is equipped with a robust collision avoidance system which maintains set distance from stationary obstacles. Its distance for obstacle avoidance can be changed through the Spot controller within a range between 0.1m to 0.5m (4 in to 1.6 ft). But Spot cannot detect glass or clear objects and it cannot predict trajectories of moving objects (Boston Dynamics, 2020a). Spot's object avoidance can be compromised around overhanging obstacles and it may not detect objects less than 30 CM (11.8 inch) high such as paint buckets or pipes laid on the floor, neither thin objects less than 3 cm (1.2 inch) (Boston Dynamics, 2020a). Spot can move on sloped surfaces with up to 30°. While Spot can move up and down the stairs with 7" (18 cm) rise for 10-11" (25-28 cm) run, if it loses balance on the stairs or an incline, it may slip and fall and it should not navigate on stairways with open sides either (Boston Dynamics, 2020a) such as scaffolding stair systems. When Spot is in operation, anyone around it should keep 6.5 feet (2 meters) distance from Spot from all sides and at all times to avoid risk of collision (Boston Dynamics, 2020a). According to Boston Dynamics, Spot's movement and behavior during its operation can unexpectedly change at any time and cause accidents (Boston Dynamics, 2020b). QR code-like fiducials placed along Spot's path can assist with its localization to adjust its internal map with the real world. Spot's mission requires at least one fiducial at the starting point of its navigation path (Boston Dynamics, 2020a).

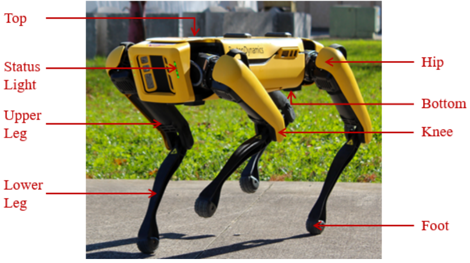

Figure 1. Spot Anatomy

This study also uses a construction progress monitoring application called HoloBuilder SpotWalk that pairs with a 360° camera (i.e. Ricoh Theta V used in this study) mounted on top of the Spot robot. SpotWalk extends the functionality of the HoloBuilder Jobwalk app that is a 360° image capture mobile application for construction progress monitoring. To capture photos, a 360° camera needs to be connected to the mobile device that runs the JobWalk App with 2D floor plans loaded. Then in the regular workflow of the app, the operator needs to mark a location by tapping on the required point on the floor plan as a waypoint linked to the 2D plan and then, capture the image. Captured images need to be uploaded to the cloud database when the mobile device is connected to Wi-Fi. SpotWalk in fact allows a Spot robot to perform image capture to replace the human operator in this procedure and to automate the data collection process. SpotWalk application provides the functionality for the human operator to record Spot's navigation path on construction sites as well as the waypoints that is selected and saved by the operator so that the path and waypoints can be reused every time there is a need for on-site data collection during the construction process. This allows Spot to capture 360° images automatically and autonomously on the same saved waypoints and on the same navigation path each time Spot's mission is performed. Figure 2 shows a screenshot of the JobWalk app with SpotWalk functionality that allows Spot to take 360° images while on autowalk on the exact same waypoints linked to the 2D PDF floor plan of the SAPC project. Note that the walking path in Figure 2 (Right) is not shown on the SpotWalk interface. The red dotted line is shown to illustrate Spot's walking path here. The walking path is determined on the initial programed route.

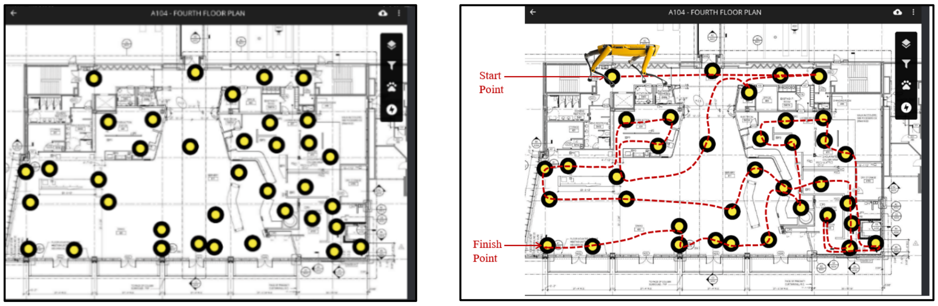

Figure 2. Left: HoloBuilder app interface with the saved waypoints for Spot saved on the 2D floor plan; Right: Spot's starting point, end point and its navigation path during the mission

In this research, we first applied Spot and SpotWalk for automated data collection in construction progress monitoring in the controlled environment of the research lab. This allowed the research to study "what if" scenarios and to allow the research team to prepare for unexpected conditions on the construction site. Total of four fiducials were used in these experiments. As examples are shown in Figure 3, the team studied Spot's performance and trajectories in (a) traversing different types of stairs and different types of surfaces, (b) detecting objects with multiple lower heights simulated with safety cones and cardboard boxes, (c) dynamically changing environments, (d) narrow spaces, (e) in spaces with elevated objects such as tables, (f) situations where fiducials cannot be placed or wrongly placed, and (g) darker spaces. The study then performed an experiment in the SAPC construction site where six fiducials were used in three rounds due to the need to perform emergency stop twice. The result i.e. captured images does not differ in multiple rounds but if changes happen to the construction site and Spot cannot complete the mission, data capture will remain incomplete and the mission has to start over. Figure 4 shows examples of 360° images captured by Spot with SpotWalk while on autowalk mode in the SAPC construction site. The required operating procedure of Spot for automated 360° image capture on the real-world construction site is described below.

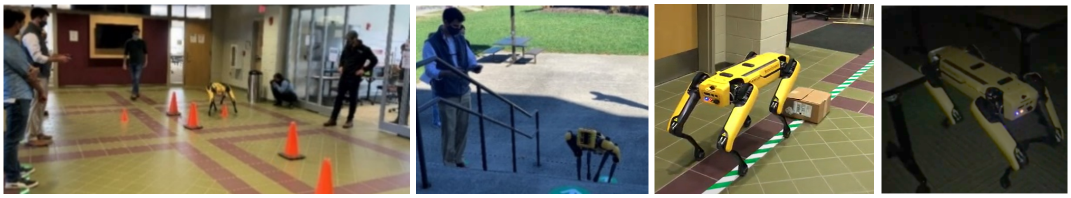

Figure 3. Example experiments in controlled environments using academia-industry collaboration

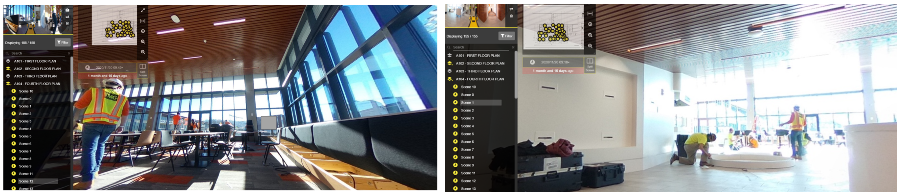

Figure 4. 360° images captured by Spot with SpotWalk in the SAPC construction site

1. Transport Spot and its batteries to the operation location.
2. Have on-site safety stand-down meeting with the workers and people who will be around Spot about Spot's performance and safety and to inform them of Spot's navigation path.
3. Investigate Spot's path and place fiducials on vertical surfaces including the starting point.
4. When safe and prepared, remove Spot from the transportation case, perform a visual inspection of Spot and its battery, notify bystanders before powering the robot, power on Spot, when on safe mode mount the camera on Spot, then connect the HoloBuilder's JobWalk app with the camera and perform pre-operation visual inspection.
5. If this is the first time with Spot on site, a new walking path needs to be created, then walk Spot along its navigation path with the controller using SpotWalk tool, record its navigation path, and save required waypoints on the HoloBuilder application.
6. If a previous programmed mission needs to be performed, locate Spot on the starting point and run Spot on autowalk mode on the HoloBuilder application. Spot walks from waypoint to waypoint during mission replay. Operator walks with Spot keeping 6.5 feet distance from it to perform emergency stop with the E-Stop button if needed and to avoid signal loss.
7. Remove the fiducials from the site. Before returning Spot to its transportation case, remove the battery and store in its designated transportation case. Transport Spot back to its designated storage location.

During the 2-hour experiment in the SAPC project 34 images out of 37 waypoints were captured. Three images were not captured due to having to E-Stop Spot's mission to avoid potential collisions with materials and people. The experiment also identified specific challenges. Rapidly changing construction environments caused potential hazards of Spot colliding with workers or damaging equipment thus, the

E-Stop needed to be deployed three times. Also, while Spot is on mission and SpotWalk is in process, the floor plan is not visible to the operator on the app interface to help with identifying the next waypoint that Spot will move to. If changes happen in the space and Spot's navigation path is blocked, it cannot skip waypoints on SpotWalk and the mission remains incomplete. While using SpotWalk, currently Spot's speed and height cannot be recorded. These findings currently limit Spot's adaptation to construction workspaces and for progress image capture.

Discussions

Utilizing robot-enabled data collection has provided several opportunities for automated construction progress monitoring including (a) accuracy and consistency of captured images, (b) integration with camera and automated image capturing process, (c) ability to calibrate robot localization through the use of fiducials, (d) possibility of reducing labor and time in the process of data collection, (e) better quality of captured images, (f) value of the captured data for inspection and maintenance, (g) ability for documentation in one source, and (h) capability to compare 360° images with BIM renderings. During the experimental investigation, the research team faced some challenges mostly due to the current limitations of technology both on the robot side and on construction progress monitoring application side. Below is a list of some of current limitations and implementation challenges.

- Safety limitations- According to Boston Dynamics (2020b) in Spot safety and compliance documentation, "Applications [of Spot] that are intended for frequent exposure to the robot by users or that could determine physical interaction with the robot are excluded": (a) the first part of this statement fundamentally excludes construction environments during the working hours when construction crew of multiple trades are on site unless Spot's navigation path is completely isolated from people with physical barriers 6.5 feet away from Spot in all sides and at all times, and (b) the second part of this statement specifies that Spot is not a collaborative robot since it should not have physical interactions with users. Such restriction in fact complicates the implementation of Spot-enabled construction progress monitoring. So, current implementation of Spot cannot be used as a fully autonomous robot for progress monitoring on construction sites when human workers are present. It is required that "operators maintain optimal observation of the operation most of the time" (Boston Dynamics, 2020b) therefore Spot needs to have a human operator and with added safety items e.g. alarms, caution tapes, barriers, etc. when needed. In addition, lack of safety guidelines and regulations such as Occupational Safety and Health Act (OSHA) standards for the use of legged robots in construction workspaces is another major challenge.
- Operation limitations- the operation of Spot is limited to specific conditions. When operating Spot, some environmental conditions can cause hazards (Boston Dynamics, 2020a) including the presence of (1) cliff edges that are not guarded or are not guarded with objects that can be detected by Spot, (2) sand, dust and liquids on Spot's walking surfaces that could compromise Spot's stability, (3) cords which is typical to construction sites as shown in Figure 5, (4) objects lower than 30 cm (11.8 inch) on the floor as shown in Figure 5 such as light fixtured, pipes, rebar, etc., (5) objects with less than 3 cm (1.2 inch) thickness, (6) transparent or bright objects that are not textured and mirrors, (g) moving objects like vehicles close to Spot, (7) hanging objects and elevated objects such as tables or scaffolds, (8) surfaces with incline more than 30° or less than -30°, (9) stairs with high risers or long steps, (10) darker environments with less than 2 lux lighting or high contrast environments, (11) slippery floor surfaces, and (12) environments or conditions that cause loss of wireless connection between Spot and its controller. In addition, Spot's limited field of view because of its height is another challenge when operating in construction sites.

- Autonomous mission limitations- currently SpotWalk requires the mobile device to be mounted on top of Spot when performing autonomous missions. Since the mobile device is the only controller of Spot during its operation, it is expected that the Spot operator approaches the mounted mobile device on Spot to perform emergency stop when needed. But this violates Spot's safety that requires everyone including the operator to remain 6.5 feet away from the robot. Our experiments identified that the need for emergency stop situation is possible and cannot be avoided on construction sites. So, the operator should carry the mobile device at all times and it cannot be mounted on Spot. Hidden waypoints and path on SpotWalk during Spot's operation, limitations on recording Spot's speed and height, and the fact that Spot's autowalk path cannot be edited after recording in case the path is blocked or changed, complicates the predictions and control of the operator over Spot's navigation path.

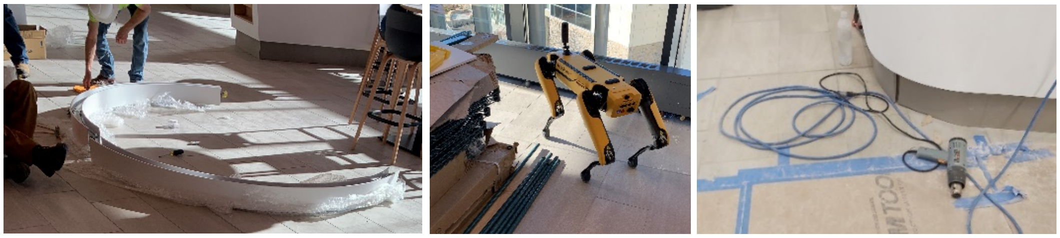

Figure 5. Presence of objects less than 11.8 inch high and cords on floor on Spot's navigation path

Conclusion

This research identifies the fundamentals of construction automation through the use of a legged robot in the data collection process of progress monitoring. The experimental investigation and study findings have identified operating procedures along with current opportunities and challenges of deploying robotic construction progress monitoring on the dynamic and unstructured construction environments. As legged robots open new possibilities for construction, their mobility feature can complicate the safety of human workers on the jobsite. Currently robot safety measures use physical barriers and multiple sensors and techniques to keep people away from robots while in operation or shut the robot down when someone approaches it too closely. Despite safety measures built into the design of legged robots, they still pose significant risks to construction workers. The robot also presents risks to the environment it is functioning in. Future studies will identify safe practices and effectiveness of the use of legged robots in progress monitoring of construction sites.

Disclaimer

The views expressed in this paper are those of the authors and do not necessarily reflect those of Boston Dynamics or HoloBuilder.

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