

Automated Quality Assessment of Precast Concrete Elements Using LiDAR and Augmented Reality

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ABSTRACT

This paper presents an innovative system for enhancing quality assessment of precast concrete elements through the integration of LiDAR scanning technology and Augmented Reality (AR) visualization. Current precast concrete inspection practices often rely on random sampling due to time and cost constraints, which increases the risk of undetected defects. Our approach addresses this challenge by combining a mobile robotic platform (Cyclop) equipped with an RGBD camera for collecting 3D point cloud data, with an AR application that enables inspectors to visualize and interact with digital representations of the precast elements. The AR interface provides an intuitive experience where inspectors can manipulate holographic models through natural hand gestures, allowing them to examine complex geometries from multiple angles and identify dimensional deviations using visualizations. Laboratory testing conducted at the University of New Mexico's Vicon laboratory and field validation at Castillo Pre-Stressed in Belen, NM demonstrated the system's capabilities in accurately capturing dimensional data and generating interactive holograms for inspection. This technology offers significant advantages for precast concrete quality control by enabling more comprehensive inspections, reducing decision time, and providing permanent digital records of structural elements. The standardized procedure developed through this research provides clear guidelines for inspectors to effectively implement these advanced technologies in routine quality assessments.

INTRODUCTION

Quality assessment of precast concrete (PC) elements is a critical aspect of construction quality control that directly impacts structural integrity and project timelines. Traditional inspection methods, primarily relying on manual measurements and visual assessments, are often time-consuming and limited to random sampling due to resource constraints. In the case of PC segmental girders, even small dimensional errors of a few millimeters can be magnified to several meters at the end of a bridge span, necessitating extensive rework [1]. This underscores the importance of accurate dimensional quality control throughout the manufacturing process. Recent advancements in scanning technologies and Augmented Reality (AR) present opportunities to transform inspection practices by providing more comprehensive, accurate, and efficient assessment methods. While some research has explored computer vision and photogrammetry for precast inspection [2, 3, 4], these approaches have not reached practical implementation due to accuracy limitations, operational complexity, or lack of interactive visualization capabilities for inspectors.

Our research addresses these gaps by developing an integrated system that combines a mobile robotic platform for 3D point cloud data collection with an AR interface that allows inspectors to visualize and interact with digital representations of precast elements. This approach enables rapid dimensional verification, automated volume calculations, and direct comparison between as-built conditions and design specifications.



Figure 1: The three-step software development workflow.

The software development workflow shown in Figure 1 illustrates the three main stages in creating our AR inspection application. First, we develop the core visualization functionality in Unity, which provides tools for creating interactive 3D environments. Next, the application is refined through debugging in Visual Studio, allowing us to test and optimize code performance.

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Finally, the completed application is deployed to the HoloLens 2 headset, providing inspectors with an intuitive interface to interact with holographic representations of precast elements.

HARDWARE

The hardware component of our system centers around Cyclop, a custom-designed mobile robotic platform developed for collecting 3D point cloud data of PC elements, addressing challenges of scanning large structural components in both laboratory and field environments.

Cyclop integrates an Azure Kinect RGBD camera mounted on a ground robot with enhanced mobility. The Azure Kinect device features a 1MP depth camera with a range of 0.5-5.0m, a 12MP RGB camera with rolling shutter, and a 7-microphone array that enables precise spatial mapping. The platform employs a 6-channel FlySky receiver for precise navigation around complex structural elements and incorporates strategic weight distribution to optimize stability. A key innovation in the hardware design is the integration of a gimbal system featuring a Hexfly servo enabling continuous 360-degree motion, allowing comprehensive scans while compensating for vibrations that could compromise data quality. The platform includes a custom-designed 3D-printed laptop support for real-time data processing.

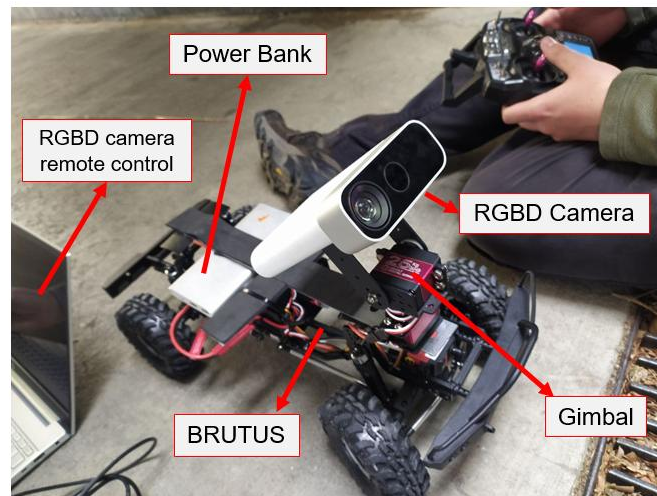


Figure 2: The complete Cyclop robotic platform with labeled components.

Figure 2 presents the complete Cyclop system with its key components. The platform can be operated either autonomously or via remote control, making it more adaptable to various inspection scenarios, including hazardous or difficult-to-access environments. An onboard power bank ensures uninterrupted operation during fieldwork, enhancing the system's mobility and deployment options in diverse environments without requiring external power connections.

SOFTWARE

The software architecture of our system comprises three integrated components: (1) data acquisition software for capturing point cloud data, (2) point cloud processing algorithms for dimensional analysis and volume calculation, and (3) an AR visualization interface for inspector interaction.

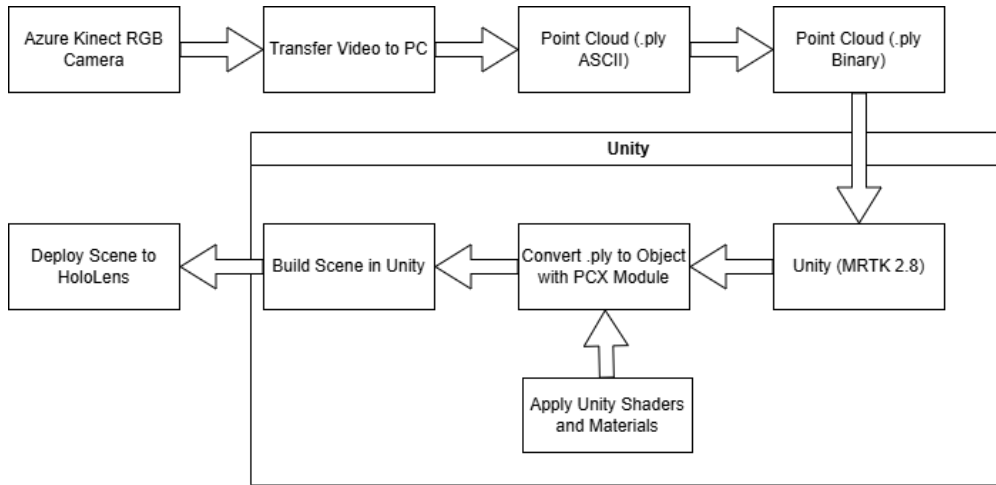


Figure 3: The data processing and visualization pipeline flowchart.

Figure 3 illustrates our complete data processing and visualization pipeline. The workflow begins with the Azure Kinect camera capturing raw video data, which is processed in ASCII format, and then converted to binary format for module compatibility. Using Unity (MRTK 2.8), the point cloud data is then converted to 3D objects through the PCX module [10]. After building the scene in Unity with appropriate shaders and materials for optimal visualization, the final step deploys the interactive model to the HoloLens device for inspector use.

For data acquisition, we developed a custom application using the Azure Kinect SDK to control camera parameters such as resolution, frame rate, and exposure settings. This software streams data to the laptop mounted on the Cyclop platform. The robotic platform control system uses Arduino-based firmware that translates signals into precise movements for navigation around precast elements.

Point cloud processing presented challenges due to large files sizes (approx. 300 MB for 5 seconds of recording). We developed an optimized workflow that selectively processes frames with unique content while maintaining 20% overlap between consecutive frames for accurate registration, substantially reducing processing time without compromising data quality.

For AR visualization, our Unity3D application converts processed point cloud data into interactive holograms for the HoloLens 2 headset. We implemented down-sampling techniques and optimized rendering methods to address AR hardware limitations with large point clouds. The AR interface allows inspectors to manipulate holographic representations, enabling them to zoom, rotate, and compare actual dimensions with design specifications.

INDOOR EXPERIMENTAL VALIDATION

To validate the system's accuracy and functionality in a controlled environment, we conducted comprehensive testing in the University of New Mexico's Vicon laboratory. This specialized facility is equipped with ten Valkyrie [9] cameras that enable precise motion tracking and trajectory analysis, providing ground truth measurements for evaluating the Cyclop platform's scanning precision.

The indoor experiments served several critical purposes: (1) assessing the accuracy of point cloud data collection, (2) testing the robustness of registration algorithms, (3) evaluating the performance of volume calculation methods, and (4) verifying the fidelity of holographic representations in the AR environment. These tests were essential for identifying and addressing potential issues before deploying the system in field conditions.

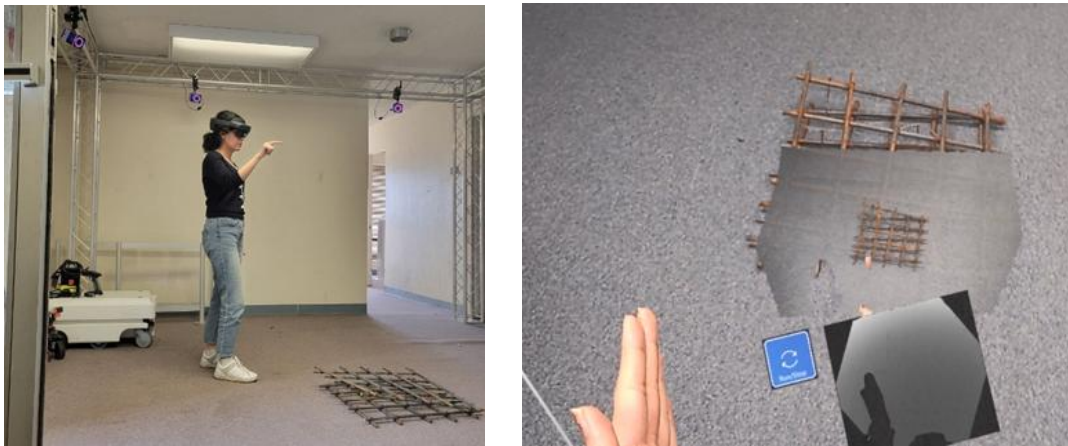


Figure 4: An inspector using the HoloLens 2 in the Vicon laboratory environment. Left image shows the inspector wearing the HoloLens. The right image shows the AR interface through the HoloLens.

Figure 4 shows an inspector using the HoloLens 2 in the Vicon laboratory environment. The right image shows what the inspector sees through the HoloLens. These holographic representations allow inspectors to examine virtual 3D models of precast elements from multiple angles without needing to physically handle them.

One of the key findings from the indoor testing was the importance of maintaining optimal scanning distance, approximately 0.75 to 1.5 meters from the target object, to achieve the highest point cloud density and accuracy. We also determined that slower scanning speeds (approximately 0.2 m/s) produced more consistent results, particularly for complex geometries with detailed features. Additionally, positioning the camera at an angle of approximately 30 to 45 degrees helped ensure that the field of view adequately captured the full height of the object.

The AR visualization component was also thoroughly tested to evaluate user experience and interface usability. Inspectors were able to successfully interact with the holographic representations, manipulating them to view different angles and cross-sections. These indoor experiments provided valuable insights for refining both

hardware and software components before field deployment, ensuring that the system would perform reliably under real-world conditions.

FIELD IMPLEMENTATION

Following successful laboratory validation, we conducted field testing at Castillo Pre-Stressed in Belen, New Mexico, to evaluate the system's performance in an operational PC manufacturing environment. This phase was crucial for assessing the practicality and effectiveness of our approach under authentic industrial conditions. Site visits were coordinated with Castillo's production and design managers to ensure access to relevant precast elements and alignment with plant operations. During these visits, we collected comprehensive 3D scans of a catch basin.



Figure 5: A catch basin in two forms, a physical concrete element (left) and its corresponding 3D point cloud model (right) from field testing.

Figure 6 presents a catch basin, and its 3D model generated from data collected during field testing. The Cyclop platform successfully navigated the precast yard environment, capturing detailed point cloud data despite challenging conditions such as variable lighting, space constraints, and industrial activities occurring in proximity.

The field implementation revealed several important insights about the system's real-world performance. First, the robotic platform demonstrated adequate mobility and stability on the uneven surfaces typical of precast yards. Second, the scanning process was efficient, requiring approximately 3-5 minutes per element, which represents significant time savings compared to traditional manual measurement methods that might take 15-20 minutes for comparable coverage. Data processing workflows were optimized for field conditions, with initial processing occurring on the laptop mounted on the Cyclop platform, followed by more detailed analysis using cloud computing resources. This approach enabled preliminary results to be available within minutes of completing a scan, allowing for immediate feedback on basic dimensional accuracy. The AR visualization component was tested by plant personnel, who provided valuable feedback on usability and practical application. Inspectors particularly appreciated the

ability to visualize internal features and complex geometries that would be difficult to assess through traditional means. They also noted the value of having a permanent digital record of each element, which could be referenced later if questions or issues arose during construction.



Figure 6: A holographic visualization of a catch basin created from 3D point cloud data, appearing as a three dimensional structure on a desk.

Figure 7 displays a holographic visualization of a catch basin created from the 3D point cloud data collected during field testing. This hologram appears as a three-dimensional structure floating above a desk, allowing inspectors to examine the precast element from any angle.

CHALLENGES AND FUTURE WORK

While our current system demonstrates significant potential for enhancing PC inspection, several areas for future development and refinement have been identified. Future work includes integration with Building Information Modeling (BIM) to enable more direct comparison between as-designed and as-built conditions; expanding the system's capabilities to include non-destructive evaluation of reinforcement placement through Ground Penetrating Radar (GPR); creating automated report generation capabilities that document dimensional deviations and standardize documentation; implementing machine learning algorithms to automatically identify common defects; and developing cloud-based sharing of inspection results for remote collaboration between stakeholders.

One significant challenge identified during field testing was the effect of bright sunlight on AR visibility, which made holographic elements difficult to discern. This issue was addressed by creating temporary shaded areas for optimal AR visualization, when necessary, though future iterations of the system will incorporate enhanced display capabilities for outdoor environments. Additional limitations include processing times up to 30 minutes for complex geometries. HoloLens 2 has memory limitations affecting performance when working with extremely large point clouds, necessitating model optimization before visualization. Environmental factors common in precast

manufacturing settings, such as dust, vibration, and variable lighting, can affect both the scanning and visualization components. The system currently works best within a range of 0.75 to 1.5 meters from the target object, which may present challenges for very large precast elements. Periodic recalibration is also necessary in changing lighting conditions to maintain optimal tracking and registration accuracy. These limitations, while not preventing effective implementation, represent areas for continued refinement in future iterations of the technology. Expanded field testing across a wider range of precast element types and environmental conditions will help validate the system's robustness and generalizability, while providing additional data for continual improvement of the algorithms and interface design.

CONCLUSION

This research demonstrated the successful development and implementation of an integrated system combining mobile 3D scanning technology with AR visualization for enhanced quality assessment of PC elements. The Cyclop robotic platform effectively collected comprehensive point cloud data, while the AR interface enabled intuitive interaction with digital representations of precast components, significantly improving inspection capabilities.

Key achievements included the creation of a streamlined workflow from data collection to AR visualization that reduced inspection time compared to traditional methods. Both laboratory validation and field implementation confirmed the system's practical value in real-world settings. The technology offered several significant advantages for PC quality control: (1) more comprehensive inspections compared to random sampling approaches, (2) reduced decision time through intuitive visualization of dimensional deviations, (3) permanent digital records of structural elements for future reference, and (4) enhanced detection of potential issues before elements are transported to construction sites.

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