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INTEGRATING PARAMETRIC MODELING, COMPUTER VISION, AND MIXED REALITY: REAL-TIME QUALITY CONTROL IN CRAFTSMANSHIP

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Abstract

European craftsmanship suffers from shrinking apprenticeships and skill shortages while project demands continue to grow. High tech, hands on workflows can both modernize existing practices and renew interest among potential future workers. We present and evaluate an end-to-end framework that couples Parametric Modeling, Artificial Intelligence (AI) in the form of Computer Vision (CV), and Mixed Reality (MR) to support real time assistive quality control in stone paving, serving as a representative, under-digitized craft domain. The work also demonstrates how the core CV pipeline can be embedded in a course format for students or craftspeople to cultivate practical AI skills, highlighting the demand for high-tech integration in craftsmanship and related education.

Background and Motivation

As the European construction sector progresses toward Construction 4.0, it faces severe labor shortages driven by an aging workforce and a demographic decline in available apprentices (Brucker Juricic et al., 2021). Concurrently, the industry struggles to attract and retain young professionals, often due to a disconnect between modern digital ideals and traditional working conditions. Recent research identifies educational reform and innovative teaching methods as the strongest factors in improving the sector's career attractiveness (McDonough, 2026) In parallel, automated construction inspection and progress monitoring has been widely identified as a promising means improve reliability in quality control, with computer vision emerging as a core enabling technology (Samsami, 2024). Prior construction research further shows that AR/MR systems are well suited for contextual, task-level guidance at the point of work (Asmar et al., 2021). Together, these findings motivate the integration of CV-based inspection with mixed reality feedback in this work, enabling quality-related information to be communicated directly in the worker's field of view under controlled conditions. Consequently, embedding assistive technologies like AI and MR into manual trades is not merely a technical upgrade, but a strategic way to modernize curricula and secure a future-ready workforce.

Method: Interconnected Technologies

This work demonstrates a closed loop framework for quality control in paving that links the digital model and real-world status: (1) a parametric as planned model en-

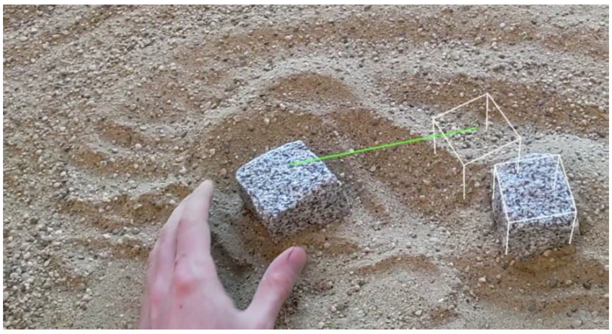

Figure 1: View through MR device view with AI-based guidance

codes per stone geometry and rotations; (2) a real time instance segmentation pipeline infers as built stone states from a monocular video stream; (3) QR based registration maps pixel detections into model coordinates via homography; (4) deviation metrics (position/rotation) are computed against tolerances and the model is updated; (5) MR overlays communicate per stone status and deviation to the worker. The framework is validated in a controlled experiment setting and embedded in an academic course to generate labeled data, train models, and test the pipeline.

Experimental Setup and Workflow

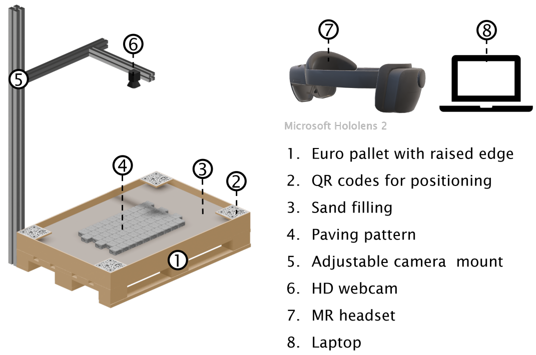

Figure 2: Schematic laboratory setup

The experimental setup consists of a portable paving box with sand bedding mounted on a Euro pallet, a consumer grade HD webcam, and a standard work laptop that hosts both the AI and the parametric pipeline; MR output is streamed to a MR-Device (HoloLens 2) over WLAN. The planned paving pattern is authored in Rhino 8 with Grasshopper as a data driven parametric model in which each stone is assigned an ID, Cartesian coordinates (X, Y, Z), and rotations (Rx, Ry, Rz). Within this environment, Grasshopper components structure the input and output, perform perspective rectification, compute tolerances, and drive MR materials and state logic so that feedback appears immediately in the headset. For execution, a YOLOv11n seg model tracks stones (centroid, Z rotation) via a custom Python script, streaming results to Grasshopper. Four corner QR markers establish a 2D homography, allowing the system to map these video detections to model coordinates and compute deviations against the planned pattern. Finally, Fologram on HoloLens 2 visualizes this feedback, overlaying per stone status (e.g., position/rotation error) and providing interactive controls for the worker to adjust tolerances or reset the workflow.

Educational Integration

The framework was embedded in an academic course in which master's-level civil engineering student teams produced labeled datasets and trained vision models for the demonstrator. The course exposed students to the full CV pipeline, including data acquisition, labeling, training/validation, and deployment. By experimenting with different labeling strategies, including synthetic data, students generated multiple individual vision models as well as a shared dataset enabling more robust combined model training. This approach enables scalable training data generation while illustrating the practical steps required to apply CV methods in a traditionally low-tech craft.

Demo-Test and Results

The integrated setup was tested in a laboratory setting by a small group of experienced paving professionals using the full technology stack, including live CV inference and MR feedback. Under these controlled conditions, the pipeline achieved interactive update rates, providing stable 2D position feedback within centimeter-level tolerances for most stones. The configuration was considered sufficiently realistic to serve as a viable demonstrator for high-tech assistive tools. The combined use of parametric modeling, AI-based instance segmentation, and mixed reality was considered suitable for addressing a central challenge in paving: placing stones precisely while maintaining the intended pattern. A more comprehensive study with rigorous scientific evaluation is planned.

Discussion and Conclusions

The prototype demonstrates that real time 2D position control is feasible with low cost, readily available hardware; coupling a parametric model with AI in Grasshopper provided a transparent logic, and MR made tolerances legible directly at the point of work. At the same time, rotation estimates were not yet robust, QR markers were sensitive to dirt and glare, and tracking stability degraded under occlusions, which are limitations that could surface on real construction sites. Planned refinements include more reliable rotation cues, ruggedized relief markers, multi camera views, and the addition of depth sensing (e.g., LiDAR) to progress toward full 3D quality assurance and a more formal evaluation in follow up studies. This work contributes (i) an end-to-end, reproducible Parametric-CV-MR pipeline for craft scale quality control built on widely accessible tools, (ii) a didactic blueprint that can be adapted from a semester course to compact workshops and transferred beyond paving to related crafts, and (iii) an experimental setup to further investigate empirical evidence to clarify current strengths and gaps, providing a concrete roadmap toward field ready systems in under-digitized crafts.

Figure 3: Laboratory testing of demo setting

Acknowledgements

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