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A WORKFLOW INTEGRATED, ADAPTIVE HIGH-RES HIGH QUALITY ROBOTIC 3D CAPTURE ENVRIONMENT - SHIVA

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Abstract

We present Shiva, a workflow-integrated, robotic 3D capture tool for 3D scanning small to medium sized objects. Addressing challenges in speed, flexibility, and automation, Shiva integrates 3D scanning with robotic position, enabling a precise and rapid point cloud generation with automatic alignment with support for single and dual robot configurations. Implemented as a Grasshopper plugin, it can be easily integrated in computational workflows in need of feedback loops with physical objects, such as in fabrication with conformal or adaptive 3D printing. The developed tool is validated in use cases with bio-based materials to automate and enhance the quality of digital inspection, adaptive reuse, and real time feedback through projection mapping.

Introduction

The transition of the building industry into a circular economy requires new methods to inspect, analyze and fabricate with reclaimed materials. While the industry has developed standardized practices for sourcing and processing of novel materials, automated methods for registering and selecting reclaimed materials are only beginning to emerge. 3D scanning plays here an important role, as it generates a broad range of applications based on 3D models of artefacts for inspection, monitoring, and other purposes across both large and small structures. An important aim for any 3D registration is that the overall workflow is as fast and easy as possible in generating high quality data that captures all necessary parts of an object. To ease the 3D registration, automatization techniques have been developed, such as robots that scan an object from all sides. This approach is particularly suited for industrial application, where identical objects such as cars, must be repeatedly scanned and subjected to quality control.

In a circular economy context, reclaimed materials often vary significantly in size and are available in small batch sizes. Similarly in research environments, the scale necessary to justify the effort of programming robots and developing new analysis workflows is often lacking. In contrast, manual 3D registration processes are labor-intensive and require expert knowledge of several distinct yet sequential steps, including 3D capturing, alignment, data management, and post-processing of large datasets to efficiently produce high-quality 3D data.

To tackle this challenge, we present an integrated and fast robotic 3D scanning method with a focus on small to medium sized objects. Integrated in a user-friendly graphic programming UI, it allows for quick manual as well as customizable automated 3D registration. The method ensures precise alignment of multiple consecutive scans taken. The paper focuses on integrating the method for fast 3D scanning in additive and subtractive manufacturing as well as the repair of bio-based materials. However, its applications are not bound to these areas.

State of the art

3D scanning using structured light approaches (Kutulakos and Steger, 2008) offers high-resolution and fast scanning of both 3D shape and surface color properties, especially in comparison to other computer vision approaches that use ambient light and reconstruct 3D information from multiple images (Chen and Medioni, 1992).

The technology today is widely used in industry for inspection, and structured light devices are now lightweight, handheld, and relatively affordable (Skotheim et al., 2015). The size and robustness of structured light scanners allows them to be mounted on robotic arms, automating the capturing process and integrating them into workflows such as quality inspection, pick and place tasks or other applications requiring fast and yet precise 3D feedback. All major vendors of structured light scanners and robots, including Artec, Atos, ABB, Zivid, offer robotic adapters. However, the coordination of robotic movement with the capturing process and integrating these into workflows are highly project specific and requires expertise across multiple domains. There are two established methods for integrating robots with cameras, which are implemented based on the specific application: the eye-in-hand method and the hand-in-eye method and the necessary calibration methods(Chen and Zheng, 1993; Wu et al., 2014; Zhang et al., 2021). In the eye-in-hand approach, the camera is mounted on the robot, whereas in the hand-in-eye approach, the camera remains in a fixed position, observing the robot.

This approach enables capturing complete 3D geometry of parts with minimal human intervention creating high-fidelty digital twins (Jacobs et al., 2023). One recent study (Antolin-Urbaneja et al., 2024) demonstrates a full inspection pipeline using structured light to capture large 3D printed aeronautical mold parts with a capturing time of 38 seconds with industrial robots. An alternate method produces scan viewpoints from CAD models for path planning (Jia et al., 2024). A graph-optimization based registration framework is developed by (Lai et al., 2024) They establish a global consistency cost that considers all pairwise overlaps (multi-path registration), and use both geometric fitting errors and even color differences as weighted terms in the optimization. More versatile automated 3D scanning solutions have been developed for cultural heritage. Here mass 3D digitization of versatile cultural objects on conveyor belts has been developed (Santos et al., 2014). Further development of these techniques are today employed to decontaminate parts of decommissioned nuclear plants (Santos et al., 2023).

Similar to industrial systems, the developed methods are purpose made and cannot be easily adapted by non-specialists to other tasks such as scanning of reclaimed materials. Moreover, there is no human robot collaboration and the trade-off between time and accuracy is a significant constraint which limits their application in near real-time robotic operations. Furthermore, existing approaches do not incorporate multi-robot configurations.

Objective

The developed method attempts to overcome the identified challenges in the high-quality 3D capture of small to middle sized objects in indoor environments:

- lack of speed of the overall process, as the 3D capturing, alignment and analysis are conducted as separate steps.
- inflexibility of the automation, as existing systems cannot easily adapt to different scanned objects.
- Lack of Integration of 3D capturing processes into data management and other workflows, such as design and fabrication. If required extensive multi-domain expertise and advanced programming skills are necessary.
- Manual approaches offer greater flexibility but are time-consuming and lack repeatability. The accuracy of scans is highly dependent on the user's skill level and patience.

Methodology

We present a method for the automatic capturing, alignment and processing of point clouds using real-time robot positioning. The method is design integrated and evaluated through use cases emerging from our work with bio-based materials. It is encapsulated into a plugin, called Shiva in the Grasshopper environment. As a 3D input device, we use a Zivid 3D scanner mounted on a Universal Robots collaborative six axis robot (Fig. 1). However, our methodology is device agnostic and can be extended to accommodate other 3D scanners and six axis robots.

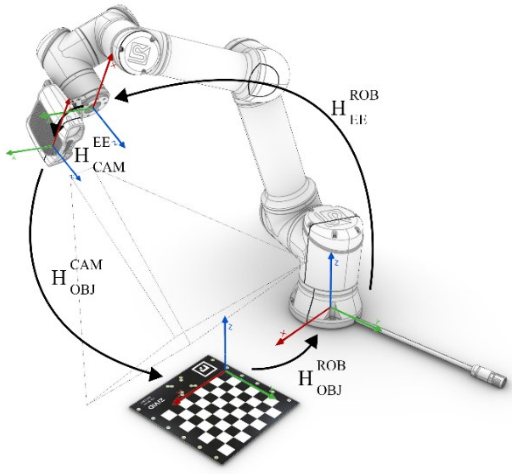

Figure 1: 3Dscan transformation process

For the control of the Zivid scanner, we integrate the Zivid SDK into our tool and use the Universal Robots Client library to extract information from robot such as Denavit Hartenberg parameters from factory calibration for accurate hand-eye calibration to TCP pose calculation for pointcloud alignment. Initially, in our tests, 3D scans took up to 7 seconds to capture, save, and display point clouds in Rhino and Grasshopper. This delay was primarily caused by the initialization of the Zivid application and the connection to the camera. Additionally, the Zivid SDK lacked a function to close the application, meaning it could only run once per session, as the Python environment in Grasshopper runs continuously. Consequently, the code was triggered within Grasshopper but executed externally in Visual Studio Code.

To resolve this issue, initialization and connection now occur only once at the beginning, with the remaining time being the camera acquisition time. In our case, using an NVIDIA GeForce A1000 graphics card with the inspection-close setting on the camera, the total time to capture and display the point cloud was reduced to 0.93 seconds. This optimization resulted in a significant reduction in 3D scan capture time, achieving sub-one-second capture and display within the Grasshopper environment, which meets our requirements for real-time monitoring of 3D printing.

Workflow

The tool supports the key steps in a robotic 3D scanning workflow, including:

- 3D scanning operations, which can be performed manually or through two automated methods.
- Calibration of the setup and alignment of point clouds captured from multiple positions, supporting configurations with one or two robots.
- Processing and analysis of point clouds, enabling their integration into project workflows.
- feedback loop to physical processes via projection, facilitating real-time interaction and adjustments

using the built-in projector of the structured light scanner.

3D scan operation

The developed method allows users to perform 3D scanning in three different modes. In this way, users can choose a capture mode, that best suits their project needs, as well as, their level of expertise:

- **Robot in free drive mode**, allowing users to manually move the robot to the required location and capture 3D scans. Shiva records the necessary TCP and other relevant data at each point and automatically registers each scan with previously captured ones.
- **Pre-programmed robot movement**, enabling the robot to move to specific locations relative to the object which is done through Grasshopper plugins such as Robots or HAL.
- **Fixed camera mode**, where a stationary camera captures 3D scans without alignment.

In addition to this, another component stores and displays the camera's TCP plane position and the resulting 3D scans. This feature enables users to reproduce identical 3D scans for future monitoring of changes in scanned object or improve repeatability by resolving any issues with previous scans. The visualization of captured 3D scans allows users to adjust the robot's position to capture previously unscanned areas, ensuring a comprehensive data acquisition.

The output of this process is a set of aligned individual scans stored on a local hard drive. The 3D scans are also displayed in the rhino environment along with the TCP plane of the robot for each scan which can be saved as a Rhino file.

Alignment of Point Clouds

Two methods were developed for the automatic alignment of captured point clouds according to a reference frame. The first method moves the 3D scanner robotically over a static artefact to be scanned. While this method has many applications, parts of the artefact are obscured, preventing complete scanning. This also occurs when the artefact is close to or larger than the maximum reach of the robotic arm. In the second method the artefact is therefore moved by a second robot, allowing the registration of all sides of the object, as well as larger or more complex geometries, enabling detailed scanning from all angles.

The first alignment method uses one robot, and the object is fixed on a surface. The camera can move around object using the robot as shown in the figure 1. To align the point clouds, the robot's base coordinate serves as the reference frame. The transformation matrix to align the point clouds is calculated using the mathematical equation (1) below:

$$H_{OBJ}^{ROB} = H_{EE}^{ROB} . H_{CAM}^{EE} . H_{OBJ}^{CAM} \tag{1}$$

$$\begin{bmatrix} R_o^r & t_o^r \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R_e^r & t_e^r \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} R_c^e & t_c^e \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} R_o^c & t_o^c \\ 0 & 1 \end{bmatrix} \tag{1}$$

Each transformation matrix consists of 3x3 rotation vector R_o^r and 1x3 transformation vector t_o^r which together form a 4x4 transformation matrix between each plane. First the transformation matrix from the robot's base and its Tool Center Point (TCP) is calculated. Most robot software development kits (SDKs) provide functions to compute the pose of the robot's end-effector or TCP relative to its base, denoted as H_{EE}^{ROB} in the equation (1). The transformation matrix from the robot TCP to the camera TCP is denoted as H_{CAM}^{EE} and is obtained through hand-eye calibration. The calibration process may vary depending on the camera, but in our case, a checkerboard pattern is used. The hand-eye calibration is performed by positioning the robot to view the checkerboard from 10 different positions for eye-in-hand calibration. Finally, the object's location, H_{OBJ}^{CAM}, is derived from the 3D scan. By applying equation (1), each time the robot moves to a new position, the 3D scan is automatically aligned relative to the robot's fixed base coordinate system, ensuring consistent alignment across multiple scans as illustrated in figure 2.

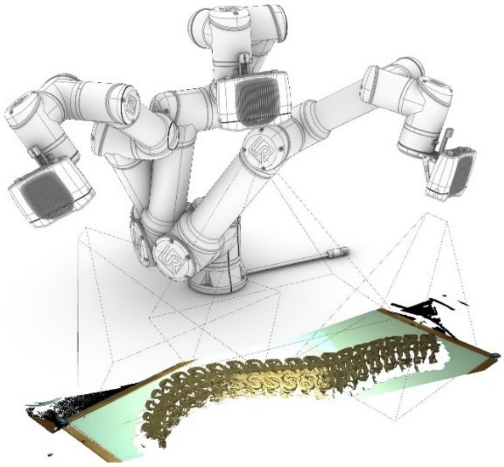

Figure 2: Aligned 3Dscans from multiple positions

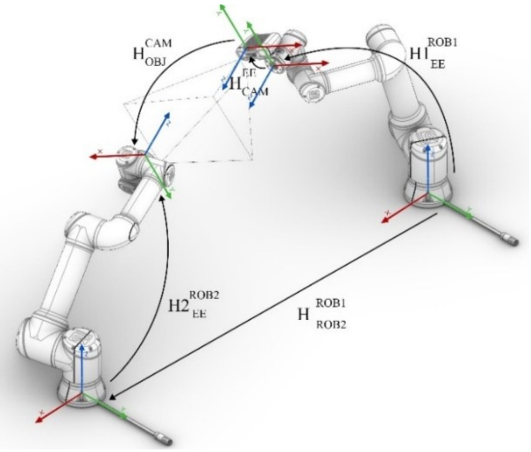

Figure 3: Multirobot 3Dscan Transformation Process

To align the 3D scans an Iterative Closest Point (ICP) methods is employed to correct possible subtle misalignments caused by the Robot and 3Dscanner inaccuracy in the end.

The **second alignment method** uses two robots. The 3Dscanner is mounted on the first robot and the object is mounted on the second robot as illustrated in figure 3. This configuration provides greater flexibility, allowing both the object and the camera to move freely and capture all facets of the object.

To calculate the transformation matrix for point cloud alignment in a dual robot setup, equation (2) is applied:

$$H_{OBJ}^{ROB} = H1_{EE}^{ROB1}.H_{CAM}^{EE}.H_{OBJ}^{CAM}.H2_{EE}^{ROB2} \qquad (2)$$

$$\begin{bmatrix} R_o^r & t_o^r \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R_e^r & t_e^r \\ 0 & 1 \end{bmatrix}.\begin{bmatrix} R_c^e & t_c^e \\ 0 & 1 \end{bmatrix}.\begin{bmatrix} R_o^c & t_o^c \\ 0 & 1 \end{bmatrix}.\begin{bmatrix} R_e^r & t_e^r \\ 0 & 1 \end{bmatrix} (2)$$

Considering the object's position on the second robot which aligns with the TCP of the second robot, the transformation matrix from the first method needs to be multiplied by the transformation matrix that transforms the robot's base coordinate system to its TCP position, defined by $H2_{EE}^{ROB2}$ in equation (2). Every time a new 3D scan is captured, all the previous captures need to be multiplied by the transformation matrix of the second robot to move the point clouds according to the second robot's TCP position. The point clouds can be stored independently or merged after each capture depending on the application requirements. Independent captures allow for ICP post processing while merged point clouds reduce the computation time, as only one point cloud requires transformation in each iteration. As depicted in Figure 4 the camera and object can move to various positions to cover all facets of the reclaimed timber beam, producing a complete point cloud model that can be used for analysis. The output of the alignment process is point clouds that are stored on local drive and placed in Rhino based on the second robot's final TCP position.

Processing and analysis of Point clouds

The captured point clouds can be further processed and analysed using native Rhino and Grasshopper tools, to interpret the point cloud, annotate it with vector information or develop design and fabrication data from it. GH Plugins such as point cloud processing tool Volvox (Zwierzycki et al., 2016) allow down sampling or refinement of the point clouds. Additionally, custom components allow feature detection or meshing of the point clouds.

Feedback Loop (Projection Mapping)

The Zivid 3D scanner utilizes structured light technology, integrating both a camera and a projector: This allows the scanner to function both as a 3D scanner and as a robotic output device via projection mapping in addition to its primary function. However prolonged use of the Zivid scanner's projection capabilities is not recommended, as it may cause overheating of the scanner's internal components which can be solved by using a normal projector. By employing a rapid 3D scanning method, the acquired 3D data can be analysed and projected onto physical surfaces. To facilitate the integration of projection mapping with the 3D scanner, a custom calibration method was developed.

This method relies on the detection of features on the 3D model. The features can be detected using different image-based feature detection algorithms, such as OpenCV and Scikit or for more simpler geometries defined by the user manually such as corners or specific points. These features are then manually selected using the scanner's projector by displaying a black image of similar size on a computer screen and projecting it on the real model with the mouse pointer highlighted as a point on the physical model, allowing the user to select the identified features directly on the model. Subsequently, the image is distorted to align the identified features and the manually selected point. Since the position of the camera and the projector are different the distortion is required to fix the transformation between them in addition to the depth distortion. The image then can be projected on the model to visualize the point cloud-based analysis.

Evaluation of method in use-cases

To evaluate the performance of Shiva and its adaptability to project requirements, it was beta-tested and improved in use cases of the EU funded project Eco-Metabolistic Architecture (EMA) and a master's student workshop.

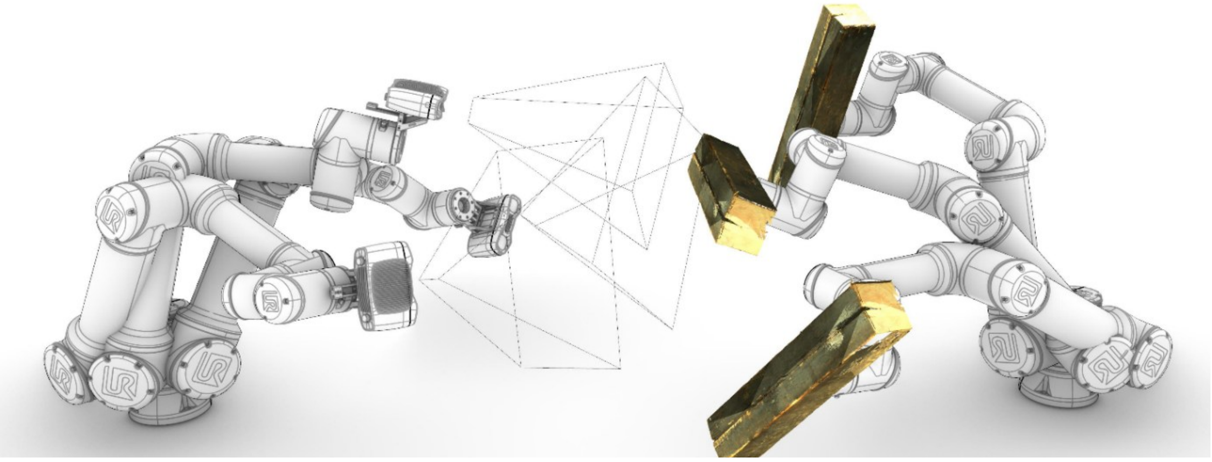

Figure 4: Multirobot 3Dscan Capture

Focusing on the scanning of bio-based artefacts – namely made of biopolymer and timber, we measure a range of parameters:

- Quality of scan
- Speed of scan
- Maximum covering range
- Ease of use – effort to calibrate, setup, and adapt to project requirements.

It is important to note that parameters such as resolution, speed, and other factors depend on the system executing the code and material properties (e.g., reflectivity or transparency), which necessitate adjustments in camera settings and, consequently, influence the quality and speed of measurements. In all the experiments conducted, the same laptop, UR5e robot and Zivid 3D scanner was used for 3D capture and post processing to ensure comparability in hardware setup.

Metrology workshop

Biobased materials have been in the focus of a metrology workshop with Master's students of the Computation in Architecture course. The students collected 3D bio-based samples and used various measuring devices such as Mecmesin force gauge and a 3Dscanner to determine material properties. The aim of the use of our 3D capture method was to understand the resulting scan quality with bio-based materials, as well as the speed, adaptability, and ease of use of our method.

- **Material**: timber, reed, red brick and 3D printed objects from a mixture of alginate (binder) with mussels, algae, seagrass. The aim was to assess the quality of the 3Dscans on different materials with different transparency and reflectivity. The Zivid 2 M70 Scanner was able to capture all the materials with high detail, using different camera settings as shown in figure 5.
- **Size**: The size of the registered 3D samples ranges from 3mm thick Reed pieces to 10x10x80cm timber pieces. While Zivid 3D scanner works best for close inspection of small objects at the distance of 35cm, it could cover all the objects. In case of the timber beam multiple 3D scans were taken to capture the full beam.
- **Speed**: Shiva can take a single 3Dscans in under one second. In case of reflective materials, the acquisition time is longer but still under 3 seconds.
- **Ease of use**: Using Shiva's single 3Dscans the students were able to produce point clouds, however they had difficulty using point cloud editing tools such as CloudCompare to align the point clouds, especially for larger objects, such as timber beams. A similar issue arose with the reed, as the overlapping space between captures was insufficient. We found that alignment algorithms such as ICP rely primarily on point cloud rather than camera position and do not function effectively when there is only little overlap between the 3D scans. The problem got solved, when Shiva took 3D scans with auto-alignment based on robot position.

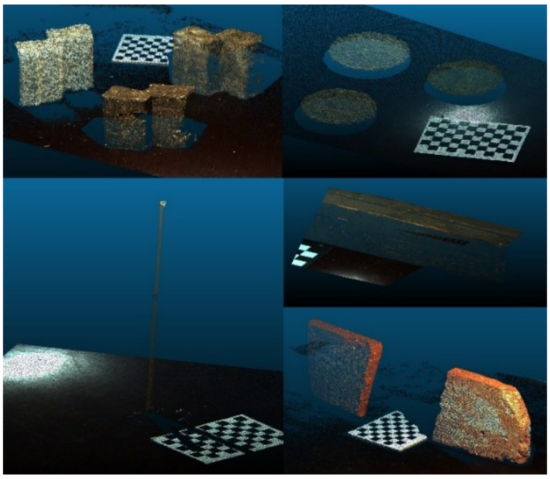

Figure 5: 3D scanned Samples from Metrology workshop

BioPolymer Panel repair

Within the context of the EU funeded project Eco-Metabolistic Architecture (EMA), biopolymer-based panels are 3D printed and exposed to natural weathering outdoors. The material is susceptible to outdoor climate conditions and changes in form. To understand these changes and to practice additive manufacturing repair strategies, the objects is closely inspected, and deviations between the original print and the weathered sample are detected and visualized.

- **Material:** Biopolymer panel with a semi-glossy surface.
- **Size:** The panels range from 60 x 100 cm to 60 x 30 cm with varying thicknesses from 5 to 15 cm. With Shiva's auto-alignment tool the size of the 3D scans is no longer limited as the camera can be moved to different positions within the robots reach.
- **Speed:** Shiva can take multiple 3D scans with auto-alignment within seconds. The capture time increases to minutes when the robot needs to move far between scans and take more 3D scans.
- **Ease of use:** since Shiva automatically aligns the point clouds based on the position of the robot in under one second, it is easy to put the robot in free drive and move the 3D scanner to different positions to capture a comprehensive point cloud of the panel. The automatic scanner can be easily planned in Grasshopper, using the robot control tools that allow manual input or programming robot movement.

We compare our new method with similar versatile capturing methods. These are based on an initial low end photogrammetry with Scaniverse on an iPhone based 3D scan followed by a inline laser scanning on the produced print paths to correct the inaccuracies of the photogrammetry based capture (Chiujdea et al., 2024). Using Shiva this process can be shortened both in accuracy, time and ease of handling of the point clouds, where less expert knowledge is required. Zivid 3D scanner according to the product specifications provides a point precision of 55µm and 0.2% trueness error which makes it currently one of the best 3Dscanners in the mid-range priced section of 3D scanners, Therefore, the captured point cloud from photogrammetry and FemtoBolt camera is compared to Zivid 3Dscans and evaluated using four key performance indicators accuracy, repeatability, robustness, and efficiency.

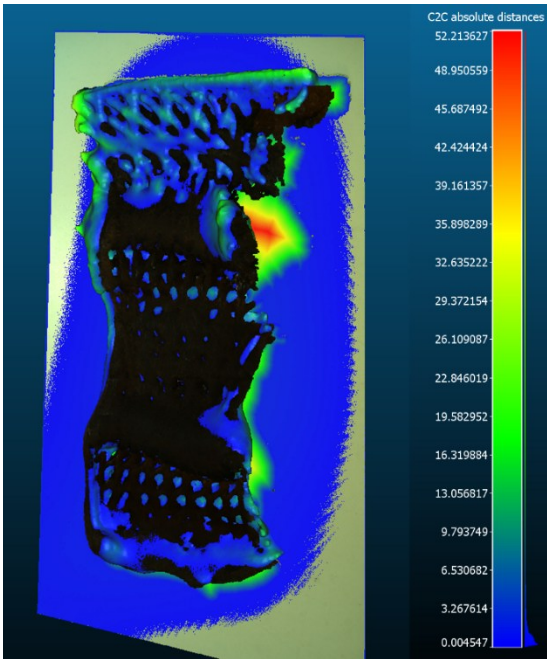

Figure 6: Cloud to Cloud distance comparison between photogrammetry and Zivid 3D scan

We execute a cloud-to-cloud distance comparison between point clouds of the same object captured with the Zivid and photogrammetry-based methods (Fig. 6) and measure deviation of 52mm in maximum distance. The majority of the points are in the range of 0 to 3.26mm which shows promising results however in 3D printing accuracy of 1mm is required considering the inaccuracies of the robot and the 3D scan. Furthermore, differences in shape are observed. We find that the photogrammetry-based scans are less accurate.

- Accuracy: 2mm (Andrews et al., 2023), it depends on the size of object as the accuracy is reduced for larger objects.
- Repeatability: under 2mm - high (Chase and Liscio, 2023), however less than robot based system due to human error in repeating same position
- Robustness: Working well in dusty, dark, and uneven conditions (Rutkowski and Lipecki, 2023)
- Efficiency: highly efficient depending on user experience, up to five minutes to take 3Dscans due to its cloud based solution.

We compare as well point clouds captured with the Shiva based method and those captured with a Femto Bolt, a compact, high-performance 3D capture device with multi-mode Depth and RGB cameras (Fig. 7) based on time of flight. The comparison shows that both 3D scanners measure with equal accuracy, The majority of the points are in the range of 0 to 2.67mm with maximum deviation of 42.69mm, nevertheless the Shiva method has a way higher resolution.

- Accuracy: less than 11 mm * 0.1% distance.
- Repeatability: less than 17 mm
- Robustness: limited under direct sunlight or IR noisy environment, however it was used outdoors with closure (Tamke et al., 2024)
- Efficiency: High indoors, global shutter helps with fast motion

In the Biopolymer panel repair use case we employ as well the cameras built-in projector to establish a feedback from the digital measurement onto the physical artefact. Here we switch between high-speed 3D scanning and projection mapping. The acquired data of the scanned artefact is compared with data taken of the not weathered panel, which is the state that shall be reinstalled.

The results of the detected deviation in height between the two states is projected on the biopolymer sample (fig. 8). New modes of repair without constant measurement are possible: in the case of the biopolymer panels the repairing person is provided with real-time feedback on the areas that require action.

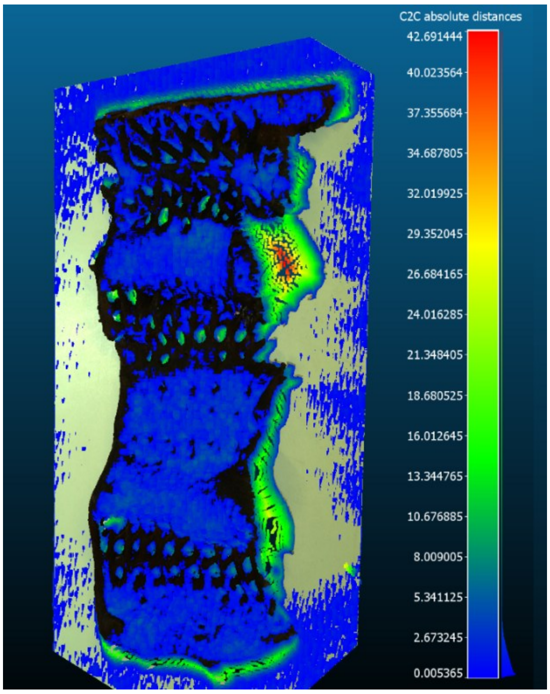

Figure 7: Cloud to Cloud distance comparison between FemtoBolt and Zivid 3D scan

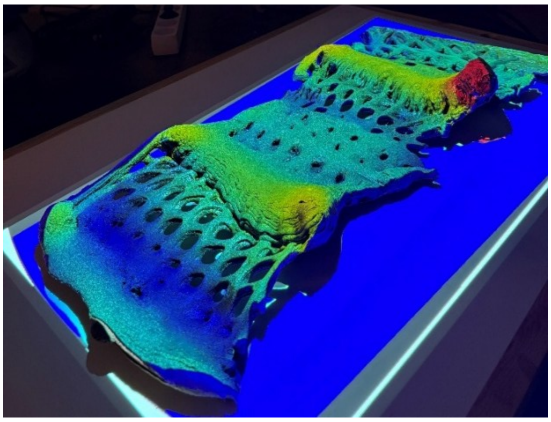

Figure 8: Projection Mapping height analysis on biopolymer panel

Timber reconstruction

Reclaimed timber pieces need to be 3D registered to be used in digital design processes. The 3D data should cover as much of the beam as possible, allowing for inspection and the detection of quality-defining features such as cracks, holes, knots, and irregularities in the usually rectangular timber volumes. This feature detection can take place manually or with detection algorithms in the digital environment. The aim of our investigation is to determine how these processes can be supported, to determine the speed and possible coverage of the 3D capture of the timber pieces using one or two robots, and to test feedback systems where dimensions and features can be projected back onto the scanned pieces.

- **Material:** Timber
- **Size:** 80cm to 5 meters
- **Speed:** Shiva can capture multiple 3D scans with auto-alignment within seconds. However, when accounting for the robot's movement, the total scanning time may extend to minutes. To cover a larger area or capture finer details, a second robot can be used. While this enhances coverage, it also reduces scanning speed, as in the dual-robot method, all previously captured 3D scans must be transformed to the new TCP position each time the robot that holds the scanned artefact moves.
- **Ease of use:** since Shiva automatically aligns the point clouds based on the position of the robot, it is easy to put the robot in free drive and move the 3D scanner or the artefact held by the robot to different positions to capture a comprehensive point cloud of the panel.
- Detected features and other information such as measures can be mapped and projected onto the piece using Shiva and provide the users with a higher-level of understanding of measured data (Fig. 9).

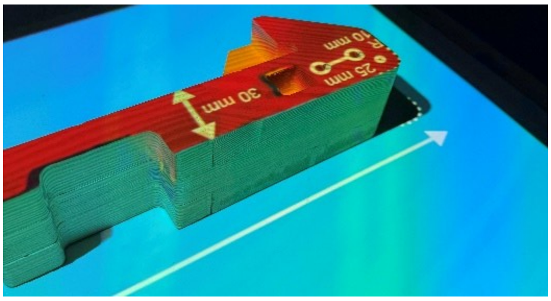

Figure 9: Projection mapping for the review of detected timber features and measurements.

Conclusion and Outlook

We develop a method that allows automation of high precision 3D scanning of objects and parses the output data into a CAD environment called Shiva. Shiva will be released by the end July 2025 under CC by NYCS license for Grasshopper users. It has the ability to 3D scan small to mid-range size objects of complex geometries and materials as Zivid 3D scanner has the ability to capture reflective and transparent objects. With the help of multi-robot configuration, the limits of object size can be extended from camera field of view to the size of the robot's field of work to auto align multiple 3D scans.

What distinguishes Shiva from state-of-the-art 3Dscanning processes is its use of robot position to align the 3D scans in high speed and its user-friendliness. Here it uses a collaborative robot, which makes it accessible for non-specialists. It keeps track of the manually positioned view points for repetition of the operation. Shiva excels over state-of-the-art industrial 3Dscanning methods, that rely on feature detection in the point clouds only. It includes in contrast the robotic position and uses such algorithms as a secondary step to auto alignment even further the 3Dscans. While using features is a useful method however in low feature objects and 3D scans with little overlaps it cannot merge point clouds efficiently. The high speed and flexibility of it to use multiple robots adds further application to the use of the 3Dscanning in near real-time feedback for adaptive or conformal manufacturing. One of the major limitations of this method is its initial hand-eye calibration which needs to be done by a specialist and the quality of the 3D scans depend on the quality of the initial calibration.

We find that the overall quality and applicability of 3D capture is not solely improved by an increase in speed and accuracy of the 3D scan. It is equally important to consider the overall time and experience for the setup, execution and potential automation of the total 3D capturing process.

The open nature of the Rhino/Grasshopper environment allows integration of 3D scanning and real-time visual and other feedback systems in a wide range of applications, including but not limited to 3D-printing. Further applications involve the analysis of reclaimed materials such as timber, using computer vision techniques, where material features in the timber can be detected, analysed, and projected onto the timber surface as illustrated (Fig. 9), facilitating rapid assessment.

Our method can as well support manual crafting, as it is possible to project precise position of drills, cuts and other fabrication operations for manual manufacturing of complicated parts, eliminating the need for Augmented Reality (AR) goggles.

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