Quality inspection of clay car modeling using collaborative robot

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Abstract

In the automotive industry, clay modelling of car exterior is commonly used to visualise the designer's concept. Modelling clay is hand laid on a metal and foam frame and then milled to ensure the correct exterior form. To shorten the clay model production and minimise clay consumption, we propose a robotic system for quality inspection of the modelling process. Collaborative robot UR5e with linear laser scanner SICK Trispector1000 is used to obtain a digital model of the physical clay model. The Digital model is compared to the desired CAD model. The mismatched areas are projected to the clay model, thus indicating the problematic areas to the sculptor. The whole procedure is demonstrated on a mock-up model, while a simulation of a real-life case is also presented.

1 Introduction

In the automotive and product design industry, clay modelling is commonly used. It translates a designer's vision into a tangible reality. This way, design concepts can be visualised, which helps in decision making before taking the products further for manufacturing [1].

A modelling clay, also known as industrial plasticine, is a mixture of wax, oil, and clay minerals. As opposed to potter's clay, it can not be fired in an oven as it becomes softer, loses its shape, or even disintegrates with heat. In clay model production, the pre-warmed modelling clay is laid onto a pre-shaped frame of steel and high-density polystyrene foam and then manually shaped using simple tools. For 3D models, the clay sculptors use initial 2D design as a reference, where the experience and skills of the sculptors often play a significant role in the successful production of the clay model. Clay shaping is followed by two-step milling: in the first step, the model is milled into a rough shape, followed by the second step, where a final shape is milled using smaller and more precise tools. The model is finished by hand, smoothing the edges left behind by the mill [2].

3D scanning is a successful tool for reverse engineering techniques where a digital CAD model obtained by scanning the physical model can be modified and upgraded [3, 4]. The application of this technology is suitable for fields such as rapid prototyping, inspection and quality management, and restoration [5]. 3D scanning is frequently used in the automotive industry, mainly for quality inspection of individual parts from early stages of design to pre-productions [6]. This way, an adequate quality of parts is ensured to prevent any inconveniences, such as water ingress, wind noise, or unwanted rattles.

Hand-held 3D laser scanners offer an excellent solution to obtain a point cloud of the model. When the laser is operated manually, the resulting accuracy might be degraded due to non-uniform scanning speed, and non-stable movement around the scanning object [7]. As an alternative, automatic scanning can be introduced where additional hardware, such as a five-axis CNC machine, is used to move the scanner. Additional hardware must be safe to operate around workers; otherwise, the working area around the machine needs to be cleared for each scan, adding additional latency to clay model production. Instead of traditional multi-axis CNC machines or cartesian robots, collaborative robots can be used. They represent a safe, flexible, and easy-to-operate solution [8].

In this paper, we propose using a collaborative robot equipped with a 3D line profiler for scanning an area of interest on a clay car model. Scan data are compared with a 3D model. Results of the comparison are projected to the clay model, thus indicating the problematic areas that need to be addressed by the sculptors.

2 Methodology

The robotic cell for quality inspection (Fig. 1) includes a robotic manipulator with a 3D laser scanner extended with custom software modules for collaborative scanning of the actual model.
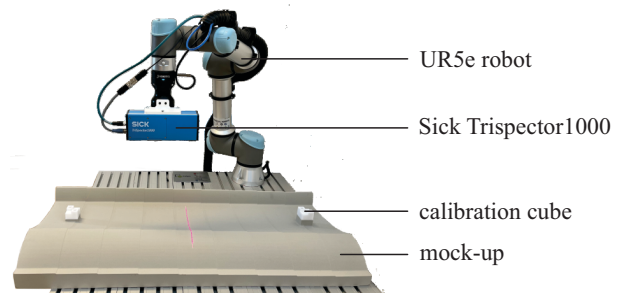

Figure 1: Preliminary measurement setup consists of Universal Robot UR5e, 3D line scanner SICK TriSpector 1030, and a mock-up of clay model with calibration cubes

2.1 Hardware setup

The experimental setup comprises a collaborative robot UR5e (Universal Robots) with Force Copilot extension (Robotiq) that enables advanced force control of the robot. With the reach of 850 mm the scan area is limited to approximately (0.6×0.6) m.

A 3D linear laser scanner Sick TriSpector 1030 is used for accurate model scanning. The maximal width of the scan is 330 mm at the height of 541 mm (scan angle $\psi_S = 0.6$ rad). The height resolution is at least 280 μm. However, at best, the 3D resolution (along the other two axes) is 0.215 mm/px. The latter heavily depends on the field of view and relative scanned object velocity. We compromise and use a resolution of 1 mm/px to ensure quick scans. Communication with the scanner is done via Ethernet TCP/IP for transferring scans and via digital I/O for triggering.

In the experiment, a mock-up model made of high-density polyurethane foam produced by milling was used. The mock-up design includes different contours representing a part of the car. The model is segmented into nine equally shaped parts with different heights (2 mm height difference between two consecutive parts) to provide controlled data for comparing the CAD model vs. scan model.

2.2 Software

To provide needed functionalities for the robot a custom script was designed using URScript programming language. Five different modes were developed.

a) Move the robot to the center point of the scan area: Robot received desired center position of the scan area $\mathbf{p}_{S,C}$ and the normal $\mathbf{n}_S$ perpendicular to the desired scan area expressed in the model's coordinate system. From the received data the robot pose $\mathbf{p}_{R,C}$ is determined:

$$[\mathbf{p}_R, 1]^\mathrm{T} = \mathbf{H}_M^{R}{}^{-1}[\mathbf{p}_{S,C}, 1]^\mathrm{T} \tag{1}$$

$$[\mathbf{n}_R, 1]^\mathrm{T} = \mathbf{H}_M^{R}{}^{-1}[\mathbf{n}_S, 1]^\mathrm{T} \tag{2}$$

$$\mathbf{x}_R = \mathbf{n}_R \times [0, 0, 1]^\mathrm{T} \tag{3}$$

$$\mathbf{y}_R = \mathbf{x}_R \times \mathbf{n}_R \tag{4}$$

$$\mathbf{z}_R = -\mathbf{n}_R \tag{5}$$

$$\mathbf{R}_R = [\mathbf{x}_R, \mathbf{y}_R, \mathbf{z}_R]^\mathrm{T} \tag{6}$$

$$\mathbf{p}_{R,C} = [\mathbf{p}_R, \mathrm{ax}(\mathbf{R}_R)], \tag{7}$$

where $\mathrm{ax}(\mathbf{R}_R)$ represents axis–angle representation of orientation calculated from rotation matrix $\mathbf{R}_R$. If the calculated pose cannot be reached, the robot raise an error, otherwise the robot moves to the point.

b) Hand repositioning: When the robot moves above the center point of scan area, a red laser is lit indicating the selected point. If this point needs to be modified, the user can move the robot parallel to the scan area to adjust the center of scan. The pose is confirmed by manually applying force greater than 20 N in tool's z axis.

c) Scan area: To determine appropriate path for the robot to cover the desired scan area, user needs to provide the following: width d_X and height d_Y of the de-

sired scan area, and predicted minimal h_{min} and maximal distance h_{max} between the model and the 3D scanner. Those distances are used to determine the maximal scan width where no part of the scan area is missed. Algorithm checks if the $h_{min} > 141$ mm and $h_{max} < 541$ mm and then tries to optimize the scan height in a way to get the $h_{max} = 520$ mm with 21 mm safety margin. The scan width w_S is calculated as

$$w_S = h_{min} \tan\left(\frac{\psi_S}{2}\right). \tag{8}$$

Number of passes n_S with a 10 mm overlay between scans can then be determined as

$$n_S = \mathrm{ceil}\left(\frac{d_X}{w_S - 10 \text{ mm}}\right). \tag{9}$$

With that the path of the robot can be designed as presented in Fig. 2. Position part of first point $\mathbf{p}_{S0}$ is

$$\mathbf{p}_{S0} = \mathbf{p}_{R,C} - \left[\frac{d_X}{2}, \frac{d_Y}{2} - \frac{w_S}{2}, 0\right]^\mathrm{T}. \tag{10}$$

Following points are translated for the d_X in the direction of scanning, or translated for $w_S - 10$ mm perpendicular to the scan direction. Prior running the scan every point
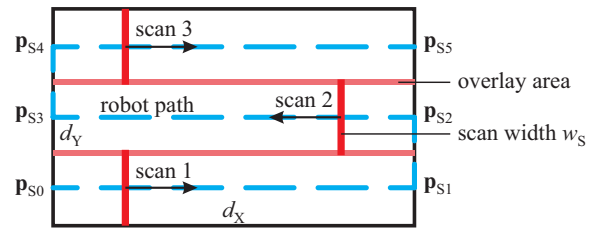

Figure 2: Planned path of the robot (blue dashed line) for the selected scan area (black rectangle)

is checked for reachability; if the robot can not reach it an error is raised.

d) Reset of the robot: This functionality moves the robot in predefined home pose in case that the working process is interrupted and/or the robot is stopped.

e) Stop of the robot: With stopping the current task of the robot is interrupted and the robot in smoothly stopped. Robot enters the idle mode and waits for further commands.

A graphical user interface (Fig. 3) was developed that is used to send desired commands via TCP/IP communication. User can provide position of the center point of the scan area, normal of the scan area, scan area dimensions, and minimal and maximal scan distance. In addition, calibration protocol can also be triggered.

3 Demonstrator

The demonstrator includes calibration between the robot and the real model, scanning the real model, and comparing the CAD model (reference) and the scan of the real model.
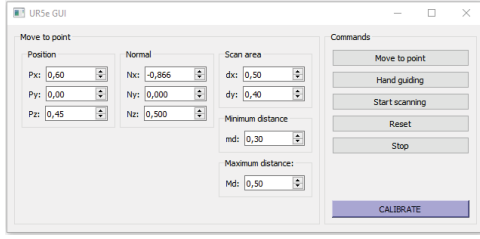
Figure 3: Graphical user interface where user can select different modes of the robot and send custom point of interest

3.1 Calibration

Special calibration markers (cube $(40 \times 40 \times 40)$ mm) with predefined calibration planes are used for setting the model's coordinate system as presented in Fig. 4a. The robot is hand guided into the vicinity of the cube, which is then scanned. From the scan (Fig. 4b) the coordinate system of the real model relative to the scanner $\mathbf{H}_M^T$ is determined.
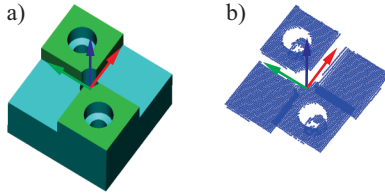

Figure 4: Calibration cubes are used to determine the model's origin: a) CAD model, b) 3D scan of the calibration cube used for determining the origin

As seen in Fig. 5, the transformation between the model's coordinate system and the robot $\mathbf{H}_R^M$ is determined as

$$\mathbf{H}_M^R = \mathbf{H}_R^{M-1} = \mathbf{H}_T^R \mathbf{H}_M^T, \qquad (11)$$

where $\mathbf{H}_T^R$ represents TCP to the base (robot's direct kinematics), and $\mathbf{H}_M^T$ indicates the pose of the calibration marker relative to the 3D laser scanner.
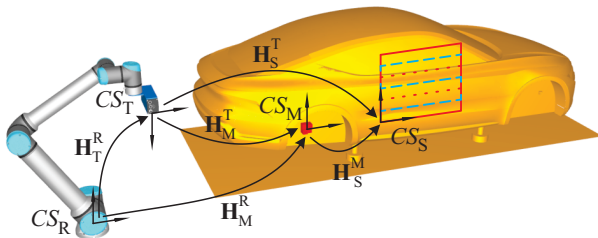

Figure 5: Transformation used for determining the relation between the robot and the model; blue dotted line represents the robot's path during the partial scan of the car; scan area is denoted with a red rectangle (R – robot, T – Sick Trispector, M – calibration marker, S – scan of the model)

After the scan of the part of the model, the resulting point cloud is expressed in the sensor coordinate system $(\mathbf{H}_S^T)$. The scan results must be expressed in the model's

coordinate system to compare the scanned data with the CAD model. The transformation between the scan and the model's coordinate system $\mathbf{H}_S^M$ is

$$\mathbf{H}_S^M = \mathbf{H}_M^{R-1} \mathbf{H}_T^R \mathbf{H}_S^T . \qquad (12)$$

3.2 Scan of the real model

First, a desired centre point of the scan area and the normal of the scan area need to be defined. That can be done in various ways, e.g., by measuring the distance between the model and the robot, using a depth camera to detect the user's hand pointing to the desired point, or simply using a CAD model and selecting the desired point by clicking. Additional parameters also needs to be defined: scan area (d_X, d_Y) and minimal/maximal distance between the model and the robot's scan plane (h_{min}, h_{max}).

After those parameters are sent to the robot via TCP/IP communication, the robot moves to the selected point. The user then checks if the selected point is sufficient by visually inspecting the position of the red laser line from the SICK Trispector. If the pose is acceptable, the robot can continue with the scan; otherwise, the user can use hand guiding to reposition the scanner to the correct position.

When the scan of the whole area is complete, scan data and the initial robot pose are uploaded to the FTP server. Matlab (Mathworks) is then used to merge individual scans into one. Merge is based on the known pose of the robot at the beginning of the individual scan. Additional averaging is applied to smooth the overlying areas.

3.3 Comparison between scan data and CAD model

Comparison between the scan data and CAD model is made using CloudCompare (www.danielgm.net), an open-source 3D point cloud and mesh processing software.

First, the scan data and the reference CAD model must be matched. For that, we can use known points that are the same on both models, e.g., calibration markers. When the models are aligned, the software performs the comparison and returns the colour-coded results.

Fig. 6 shows an example comparison of the mock-up piece. Reference CAD model (the shape of the mock-up at only one height) is presented in Fig. 6a. In Fig. 6b, a merged mock-up scan is depicted with well-indicated parts of different heights. The result of the comparison is shown in Fig. 6c, where green color indicates absolute error below $|e_d| < 3$ mm, red color error $e_d > 3$ mm (indicating too much material), and blue color $e_d < -3$ mm (missing material).

3.4 Use case

The presented robotic cell can be transferred to a real-life case (building a clay car model) with some additional upgrades. To scan the whole side of a car (the length of an average car is around 5 m), the robot needs to be mounted on the additional linear and vertical rails to extend its reach. In addition, the car model should be on a rotating table that enables easy switching sides of interest.
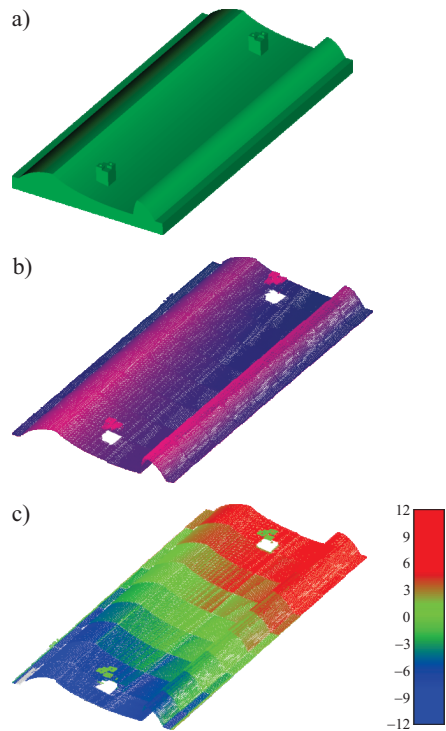
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Figure 6: Final application: a) CAD model of a reference part, b) merged 3D scan of mock-up with 2 mm height raster, c) result of the comparison (blue and red colors indicate $e_d < -3$ mm and $e_d > 3$ mm, respectively, green -3 mm $< e < 3$ mm)

An array of projectors can be used to provide feedback to the worker. By scanning the area of interest and comparing the scan with the CAD model, colour-coded information can be projected to that area. In this way, the sculptor is provided with the indication of where more clay needs to be added and removed, thus optimising the clay model building process.

In Figure 7 a use case of car's clay model production is presented. The left figure represents a model with areas with added and removed material. After scan and comparison, those areas are marked with yellow colour. In the right figure is a projection of comparison after the sculptor addressed the indicated areas. After the additional scan and the comparison the results indicate that that area of the clay model is modelled correctly compared to CAD model.
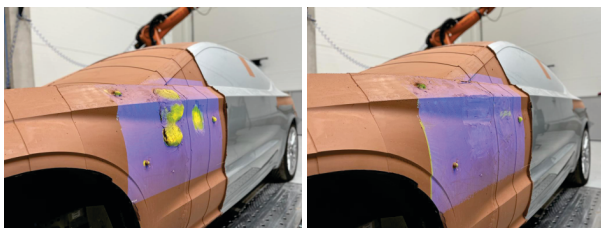

Figure 7: Use case with projection of the results after comparisons: model with added and removed clay (left, areas are marked with yellow color), and after addressing problematic areas (right, blue color indicates match with the CAD model)

4 Conclusions

Clay modelling is one of the fundamental procedures in the automotive industry to transfer designers' ideas into a physical model. To optimize the process, we introduced a robotic system for scanning the physical model, generating a point cloud, calibrating relative the calibration points on the model, and compared to the original CAD model. Areas that deviate from the CAD model are then pointed out by projecting a colour-coded error map to the physical model.

By pinpointing the problematic areas on the clay model, we indicate to the sculptor where clay needs to be added or removed. With the better transfer of the CAD model to the physical model, we ensure less clay is used. In addition, the first milling stage is omitted as the model already falls into predefined tolerances (the clay layer is up to +5 mm higher than the CAD model). Overall, the material and time consumption is reduced, which also affects the economic aspect of the clay model production.

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