CaMea: Camera-Supported Workpiece Measurement for CNC Milling Machines

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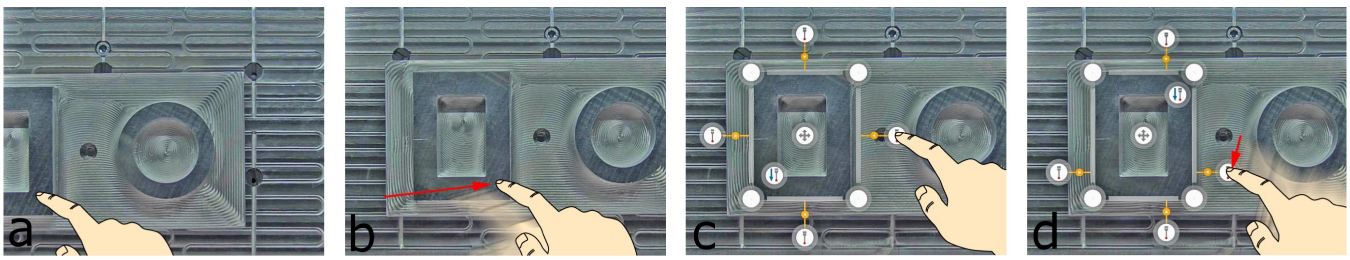

Figure 1: CaMea supports users in the process of initializing a workpiece in a CNC milling machine. We mounted a camera inside the machine and allow the user to move (a,b) the camera though touch gestures to align the camera with the workpiece. Once aligned, the user can select (c) and move (d) the touch points for the probing tip on screen.

ABSTRACT

We are experiencing a trend of *personal fabrication* that allows non-experts to produce highly individualized objects. Beyond 3D printing, this *maker movement* also approaches larger-scale production machines such as computer numerically controlled (CNC) milling machines that are available in local fabrication laboratories (FabLabs). While the user interfaces and interaction techniques of small-scale 3D printers for household use adapted to the new requirements of non-experts in the last years, such an overhaul of the interfaces for larger machinery is still missing.

In this work, we explore the use of augmented reality methods to support novice users in the operation of CNC milling machines. As a first step towards better support for users, we provide a camera-supported graphical and easy-to-use interface for the measurement of raw workpieces inside the machine. In this paper, we contribute our concept CaMea alongside its' prototype implementation. We further report on the findings of a first early user study.

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CCS CONCEPTS

• **Human-centered computing** → **Graphical user interfaces**; **Gestural input**;

KEYWORDS

CNC Machine; Graphical User Interface; Human Computer Interaction; Worpiece Measurement; Digital Fabrication

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1 INTRODUCTION

The emergence of *Personal Fabrication* [11] empowers users to rapidly prototype and produce highly individualized or entirely custom-made objects. With affordable 3D printers for home usage and further fabrication machinery available in so-called fabrication laboratories (FabLabs) [1], users can control and accompany the complete fabrication pipeline from design to the machining of the final object. However, the traditional fabrication process in design tools and interactions with the machine is highly complex and lacks support for novice users [23]. While the user interfaces of small-scale 3D printers for household use were adapted to the needs of non-experts, especially the user interfaces of larger machinery available in FabLabs are still designed for expert users.

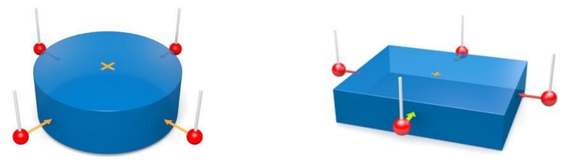

Figure 2: Typical probing points for different geometries of workpieces. From left to right: (1) circle, outside and (2) square, outside

Driven by this transformation in the fabrication process and to overcome the limitations for non-expert users, research proposed novel user interfaces to support users in the complete process; from the design of the objects [8, 21, 24] to the final machining step [19, 20] on different machines. Further, research proposed to bridge the gap between the design and machining step of an object by integrating them more tightly together [15–17]. Following this stream of research augmented reality has the potential to further close this gap between the digital and the physical world through superimposing the physical world with additional (digital) information [3, 7] as shown in manufacturing [6, 18], robotic fabrication [14] or support for impaired workers [9, 10].

In this work, we explore the use of augmented reality methods to support users in the operation of larger machinery. More specifically, we focus on computer numerically controlled (CNC) milling machines. In contrast to 3D printers, such machines produce objects through removing material from a workpiece instead of adding material to form the final object. Therefore, such machines need precise information on the position, orientation, and size of the workpiece inside the machine before starting the actual machining step. For the measurement of this information, a highly accurate probing tip is moved to the raw workpiece from multiple directions (cf. Figre 2). As the machine has no information about the dimensions and position of the raw workpiece, the operator has to specify the necessary approach vectors of the probing tip manually: The operator has to imagine the direction and length of the 3D probing vectors and enter them as numerical information to the machine. This process has a high mental demand for the operator of the system and is prone to errors that can damage the machine: Even advanced users are at risk of wasting time with faulty measurements or destroying the probing tip as no sanity-check is performed on the entered data.

To overcome these problems, we propose CaMea: A graphical user interface to support users in the measurement of workpieces in a CNC milling machine. Therefore, we mounted a movable camera inside the machine that provides a top-down view (cf. Figure 1, a) displayed on a touch-screen mounted on the machine. The user can move (cf. Figure 1, b) the field of view of the camera to focus on a raw workpiece. Then, the user can visually select (cf. Figure 1, c) and modify (cf. Figure 1, d) the probing points through touch-gestures. As the camera is calibrated to the machine, the system is able to calculate the approach vectors for the probing tip based on this information.

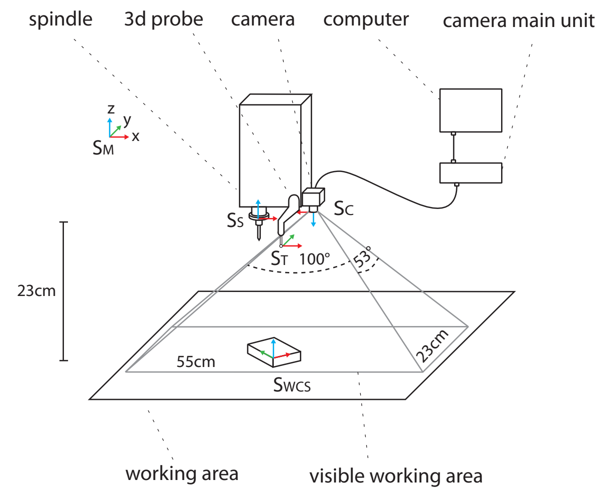

Figure 3: We mounted the camera on the spindle inside the machine. The machine coordinate system S_M is the frame of reference. The camera coordinate system S_C relative to S_S is calculated in the camera calibration. The workpiece coordinate system S_{WCS} relative to S_M is measured in the workpiece measurement step.

In this paper, we 1) contribute the design and implementation of CaMea, an graphical approach to support users for the measurement of workpieces for CNC milling machines. We 2) report the findings of a first early user study and 3) conclude with directions for future work.

2 CAMEA: CONCEPT AND PROTOTYPE

To overcome the limitations of traditional number-based interfaces for workpiece measurement in CNC milling machines, we present CaMea as an graphical user interface. We focused on easy to use and supportive interfaces for novel users.

2.1 Technical Background

The measurement of workpieces inside the machine is used to establish a coordinate system S_{WCS} for the workpiece relative to the coordinate system S_M of the machine (cf. Figure 3). This transformation is necessary, among other things, as coordinates from CAM software that are used to machine the workpiece are relative to the workpiece.

In this measurement process, distinctive geometric elements are used to define the coordinate system of a workpiece (cf. Figure 2). These geometric elements of the workpiece are approached with a highly accurate probing tip. Based on the measured offsets, the coordinate system is calculated.

Today, the process of measuring a workpiece involves multiple steps and is a complex task for the user. First, the user places the spindle with the probing tip roughly above the element to be measured using the hand control panel. Then, the user specifies which type of geometry (e.g., rectangle, corner, circle) to measure and if the measurement should be conducted from the inside or outside. Furthermore, the user specifies offsets to position the measurement

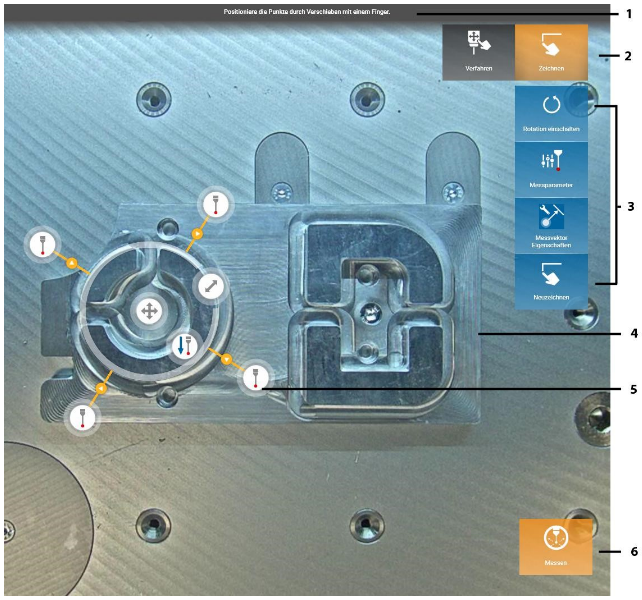

Figure 4: The user interface of CaMea superimposed on a workpiece. The user can intuitively select parts of the geometry and define probing points. The figure shows 1) Information text, 2) Mode Selection, 3) Option Buttons, 4) Workpiece, 5) Probing point handle and 6) Start measurement button.

points along the edges so that the workpiece is hit by the probe and specifies a rough search distance. Additionally, the user specifies a XY-offset for the probing of the surface height.

All of these steps are executed without graphical support. Thus, the user has to imagine the vectors and their relation to the workpiece. This is a complicated task and involves a high cognitive load.

2.2 User Interface Design

We designed the interaction with the system with novice users in mind. In contrast to traditional interfaces, we provide three easy interaction steps to support the user in the workpiece measurement. All interaction happens touch-based on a large screen mounted on the machine. For the setup of the workpiece measurement, CaMea allows the user to

(1) **move the spindle** (i.e., the camera image) to see the workpiece on the screen,
(2) **draw the geometry** on the touch screen and setup additional parameters through on-screen handles,
(3) **start the measurement** to gather the necessary touch points for the establishment of the coordinate system S_{WCS}.

The user can switch between the *move* (Step 1) and *draw* (Step 2) modes through on-screen buttons in the interface (cf. Figure 4, 2).

Step 1: Move the Spindle.

The camera cannot capture the whole working area of the machine (see Figure 3) with enough details to provide fine-grained

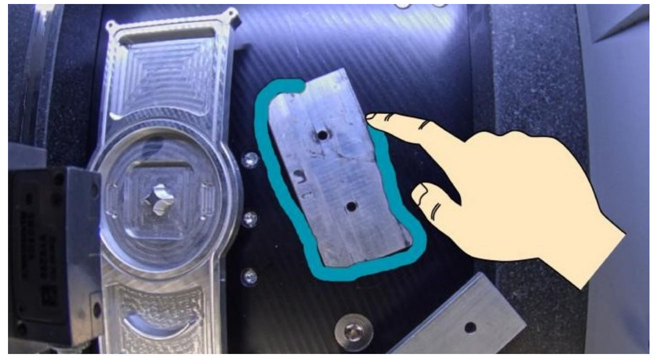

Figure 5: CaMea allows users to draw the outlines of a workpiece roughly onto the camera image. We use a template matching algorithm to extract the type of the shape.

interactions. Therefore, the first step in the interaction is to move the camera to a viable working position. We opted for a multi-touch option to control the camera to leverage the users' knowledge of such interfaces. The camera is moved by touching and dragging the finger over the screen's surface. A pinch-to-zoom gesture is used to zoom in and out (i.e., move the spindle up and down).

Step 2: Draw the Geometry.

Once the camera is in place, the user can switch to the *drawing* mode. This mode supports the user in specifying the probing points which are later used to calculate the approach vectors for the probing tip.

The user starts the process by drawing the rough outline of the shape that he wants to measure on top of the camera image using the touch screen (cf. Figure 5). The system recognizes the drawn shape and replaces it with a movable and adjustable representation of the shape (cf. Figure 4, the circle on the left side). Further, the system displays the minimum number of probing points for this kind of shape.

In most cases, the recognized boundary fits good enough to the geometry visible in the image. In some cases, small adjustments might be required. Therefore, users can move, scale and rotate the displayed outline through dragging-and-dropping the handles on the screen (cf. Figure 4, 5). If a wrong shape was recognized, the user could remove the current shape using the redraw button in the menu (cf. Figure 4, 3).

The system automatically calculates probing points and approach vectors and displays them in the interface (see Figure 4, 5). As no machine learning is applied, holes, gaps, or other irregularities on the surface of the workpiece can lead to probing points that are not valid. In such cases, the user can move the probing points on the screen. The same applies for the approach vectors: Depending on the contours of the workpiece, the automatically generated approach vector might collide with other parts of the structure. Therefore, the user is also able to change these approach vectors. Further, (optional) functions such as additional probing points for increased accuracy can be adjusted in context menu dialogs.

As the last point, the user has to move the z-probing point through drag-and-drop to a position, where the system can probe the z-offset (height) of the workpiece.

Step 3: Start the Measurement.

The execution of the measurement is started through an on-screen Button (cf. Figure 4, 6). The button is only available once a sound configuration of probing points was selected in step 2. No further interaction with the system is needed. During the measurement, the user can abort the process through an on-screen button. In case of an aborted or faulty measurement, all information is saved, and the user can start over again from the last configuration. This can support easy and fast failure recovery.

2.3 Prototype Implementation

We mounted a AXIS F1015 Camera[1] on the spindle inside a CNC milling machine (cf. Figure 3). The camera lens is oriented to view in the top-down direction and is moved together with the spindle. We deployed our user interface on a 27-inch multi-touch screen mounted on the side of the machine.

We implemented a fault-tolerant shape recognition system to classify and locate the user-drawn shapes. Through informal pretests, we found different requirements for this recognition system for novice and expert users. Users that worked with our system before are likely to draw the boundaries very fast and, thereby, generating smooth lines and overshooting the edges of the contour. Inexperienced users, on the other hand, draw more carefully and slowly, resulting in noisy contours. Research proposed multiple approaches for shape recognition [2, 4, 25]. However, we opted for a simple template matching method as it proofed to be sufficient to recognize the required shapes with high accuracy. In this method, we use image differences to find the best fitting shape: We normalize the drawn contour and plot it to a binary image using a thick stroke. We combine this image with an image of the reference shape. We accumulate the number of different colored pixels and select the best fitting image.

To perform the measurement, the probing tip needs to approach the workpiece at the vectors marked by the user. To relate 2D touch positions in the camera image to 3D direction vectors in the machine coordinate system (cf. Figure 3), the intrinsic and extrinsic parameters of the projection need to be determined. There exists a large body of research on calibration methods [12, 13]. In this work, we opted for a checkerboard calibration pattern with a known location. We move the spindle (with the attached camera) to different positions during the calibration process to generate non-coplanar calibration points.

The user marks the measurement vectors in the (2D) image plane. It is not possible to map these image space positions directly to the 3D space as the depth information is not available. Therefore, the user is required to specify a point on the surface of the workpiece. We measure the height of the workpiece by approaching this point on the projection ray. Finally, we transform the vectors and start the probing process.

Further implementation details of the proposed method can be accessed as part of the patent application [5].

[1] https://www.axis.com/ro/en/products/axis-f1015

3 EARLY USER FEEDBACK

To gain insights into the user acceptance and applicability of our concepts, we conducted an initial laboratory evaluation of our prototype. In the evaluation, we focused on the performance, acceptance and general user experience of our concepts and prototype compared with traditional user interfaces for the measurement of workpieces in CNC machines. In particular, we focused on if and how

(1) users can intuitively work with the system and
(2) CaMea performs faster compared to traditional number-based user interfaces.

For this, we recruited five participants (P1-P5, all male, aged between 25 and 45 years). We chose participants with different levels of experiences with CNC milling machines and the workpiece measurement process. P1-P3 where experts while P4-P5 did not work with such machines before. None of them had prior experience with augmented reality. We chose a within-subject design. No compensation was provided.

3.1 Design and Task

We tested CaMea and a traditional number-based interface for workpiece measurement as two conditions. In both conditions, the participants' tasks were:

Task 1 required participants to measure a corner (rear, right, outside). For this task, we only evaluated the positioning and the drawing of the outline; the participants did not have to set other parameters (e.g., z-elevation). We chose this design to allow participants to get used to the respective interface in an easier task.

Task 2 required participants to measure the center of a circle (inside). For this, the participants should set a z-offset of 2mm for the approach vectors. Also, the participants had to set a rotation for the approach vectors since the circle was interrupted at two points (cf. Figure 4, left top). As an additional difficulty, the participants had to be careful when selecting the length of the approach vectors so that they did not touch adjacent geometry.

For all conditions and tasks, we used the same raw workpiece (cf. Figure 4).

3.2 Study Setup and Apparatus

For both conditions, we used a Datron Neo[2] as the apparatus for the study. For the CaMea condition, we used the prototype as presented in section 2.

We videotaped the sessions with an external camera and logged the interactions with the machine. During the study, we asked the participants to think aloud and share their experiences. We concluded the study with a questionnaire focusing on usability and user experience aspects. We analyzed the data from the study using an open coding [22] approach.

For each trial, we measured the dependent variables

(1) **task completion time (TCT)** as the timespan between starting the trial and selecting the "Start Measurement" button.

[2] https://www.datron-neo.com/

(2) **error rate (ER)** as the number of faulty measurements per participant.

3.3 Procedure

After welcoming the participants, we introduced them to the general setup and goal of the study. Before each task, we moved the machine to the parking position to have a defined and reproducible starting position. In addition, we reset all system dialogs to the default values before each task.

After the first condition, the participants took a 5-minute break. The complete experiment took around 60 minutes per participant. We counterbalanced the order of the two conditions by randomly assigning the starting condition to the participants to avoid learning effects between the conditions.

3.4 Results

In the traditional condition, participants had to enter numerical values to specify the approach vectors of the probing tip. This turned out to be a very *"complicated and time-consuming"* (P4) task for novice users: All of them felt very *"uncertain"* (P5) about their actions and entered incorrect values at least once. Interestingly, this was also the case for expert users: All of them also entered wrong data during the study. When asked about this, we found that they tried to *"transfer [their] experiences"* (P2) from other machine interfaces to the current situation. However, those interfaces had *"slight differences"* (P2) in semantics and, thus, their knowledge could not be directly applied.

In contrast, we found enthusiastic reactions in the CaMea condition. Participants described the system as *"genius"* (P5) and *"very helpful"* (P4). P5 further explained: *"It was as intuitive as an iPhone app!"*. All participants were able to complete the task without further instructions. We found that all participants were able to select a contour using the drawing gesture. We saw two faulty measurements in the CaMea condition (P3, P4) that were caused by not setting the z probing point. When asked, the participants told us that they just *"overlooked"* (P3) the handle in the interface and *"forgot about that"* (P4). After the resulting faulty measurement, however, participants enjoyed that the defined probing point configuration was recovered and, thus, allowed them to continue and set the missing option directly. P3 commented: *"This was really helpful!"*

When asked about their experiences with both systems, we found a strong tendency towards CaMea from the non-experts. However, the expert users still preferred the traditional interface as they were used to such interfaces for years and CaMea felt unfamiliar. More precisely, P2 explained: *"Why would I need something new, the old one works fine for me."*

Task completion time and error rate.

Considering the TCT (cf. Figure 6), we found that users performed faster in the CaMea condition (M = 162s, SD = 66.11s) compared to the traditional (M = 299.2s, SD = 99.26s) interface. Also, we found a lower ER for CaMea (M = .4, SD = .55, traditional system: M = .8, SD = .84).

Due to the qualitative focus of our study and the low number of participants, we did not apply further statistical methods to verify our initial observations. We plan to conduct a more extensive quantitative evaluation for future work.

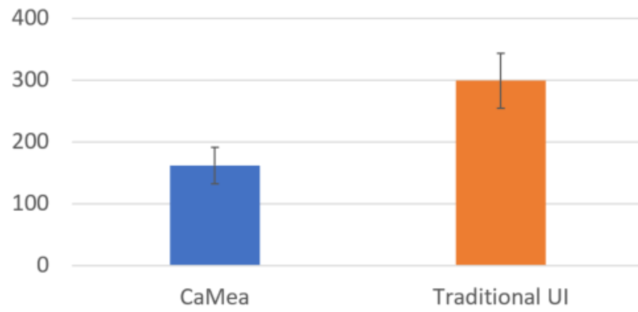

Figure 6: The average TCT (in sec) of CaMea compared to a traditional interface. The error bars depict the standard error.

4 CONCLUSION AND FUTURE WORK

In this paper, we proposed CaMea: A graphical user interface to support users in the measurement of workpieces in a computer numerically controlled (CNC) milling machine. We presented a prototype implementation and reported promising early user feedback that indicates a faster performance and enhanced user experience compared to traditional systems.

In the future, we plan to evaluate our system in a larger-scale study in the wild with potential end users. Further, we plan to explore possibilities for more automated measurement systems that require less or even no user involvement at all.

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