Gaze-based Interaction in Various Environments

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ABSTRACT
The analysis of cognitive processes during human-machine and human-human interaction requires various tracking technologies. The human gaze is a very important cue to gather information concerning the user's intentions, current mental state, etc. To get this data the framework consisting of a highly accurate head-mounted gaze tracker combined with a low latency head tracking method was developed. Its integration into various experimental environments forces an easy to use calibration method for multiple working areas and also the implementation of numerous interfaces. Therefore a calibration method by simply looking at known fixation points was integrated. Also, first results of a brief user study using the proposed framework are presented.

Categories and Subject Descriptors
H.1.2 [**User/Machine Systems**]: [Human factors, Human information processing]; H.5.2 [**User Interfaces**]: [Input devices and strategies, Interaction styles]; D.4.4 [**Communications Management**]: [Input/output, Network communication]; I.4.8 [**Scene Analysis**]: [Stereo, Tracking]; J.7 [**Computers in Other Systems**]: [Real time]; I.2.9 [**Robotics**]: [Operator interfaces]

General Terms
Human Factors, Measurement, Experimentation

Keywords
Gaze tracking, gaze-in-space, calibration, area-of-interest, stereo camera system

1. INTRODUCTION
The work described in this contribution was done within the project RealEYE in the CoTeSys cluster [5]. The analysis of cognitive processes during human-machine interaction is the main task of the Cognitive Factory in the CoTeSys cluster. Most scenarios here use various tracking technologies to get the information about the user's actions. The human gaze is also a very important cue, that gives us evidence about attention, intentions and the mental state of the user. Our aim is the integration of gaze tracking into various demonstrators.

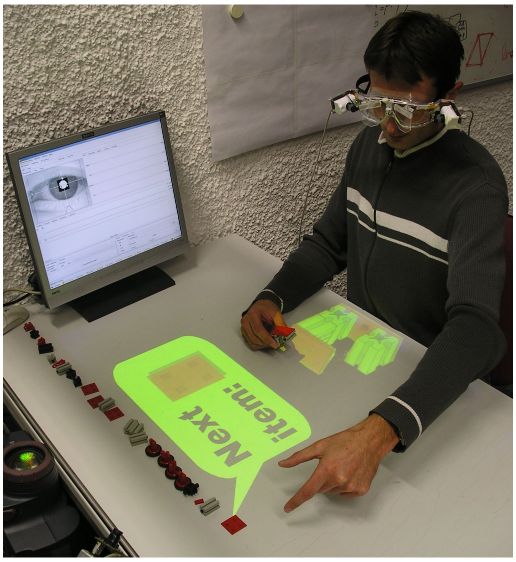

Figure 1: The user wears eye tracker goggles and fixates a target on the table. The eye tracker position in 3D space is determined by a stereo camera system. One of the two cameras of the stereo system can be seen in the lower left corner. The origin of 3D coordinate system is placed in the middle of the left camera. Three LEDs , which are placed on the eye tracker goggles determine the position and orientation of the head in 3D space.

Since the 70s of the last century, eye and gaze tracking systems have been widely used in various research fields, but mainly in the area of psychological studies. Here, the main focus was on the user's attentiveness, which means that the gaze tracking systems are used in a passive manner. Afterwards, from the early 80s till the 90s first approaches have been realized to operate computers by eye gaze – so called Command & Control applications. Since that time,

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there are eye tracking systems available that allow disabled persons to control a personal computer [15]. Nowadays, good-quality commercial eye trackers are getting more and more affordable (see section 2) and their usability advances continuously. Command & Control applications are still enhanced and new kinds of applications are developed. Today, also Attentive User Interfaces (AUI) are in the research focus. These incorporate the user's eye gaze to adapt at the user's current visual attention [11].

In our case, the gaze tracking should be integrated into different experimental setups and platforms. Fig. 1 shows the example of the integration into an experimental setup. Here the user has a working area, where he gets the information projected on a table by a beamer. By knowing the position of the point of gaze on the table, the information is displayed at the point the user is currently looking at.

The low latency gaze tracking system is required in various human-machine interaction use cases, e.g., in cars or airplanes for adjusting of the user interfaces and also in scenarios with interaction between humans robot and other production machinery. To get the gaze data on the experimental platforms with two or more working areas (e.g., table, monitor plane) (see Fig 7) there is a remote gaze tracking system required, that able to track the gaze in extreme head positions ($\pm 30-40°$) and also provide accurate data if the user acts far (standing more than 100 cm away) from the tracking system. To get the accurate gaze projections, the position and orientation of the working area should be known. In view of the different experimental setups, the quick and precise method for calibration of one or more working areas per setup should be developed. Computing clusters gaze projection points on the working area, we will be able to define user's regions of interest and to analyze its scan path. The working area (e.g., table, monitor plane) – the so-called Area-of-Interest (AOI) – is the central interaction area. Here, the user operates the technical system.

For a seamless integration of the remote gaze tracking system into cognitive systems, solutions for the following three tasks are needed amongst others:

- low latency gaze tracking in 3D space
- calibration of areas of interest
- interfaces for integration into various experimental setups

2. GAZE TRACKING

There are a lot of commercial remote gaze tracking systems available. There are numerous manufacturers of eye trackers for head mounted setups (Chronos Vision, SMI, ASL, SR Research, OpenEyes, GN Otometrics), for remote setups (Arrington Research, Cambridge Research, SR Research, ASL, Tobii), as well as for remote setups in vehicle cockpits (Smart Eye, Seeing Machines). The EyeLink remote eyetracking system works with a very small latency at 500 Hz. The gaze direction is detected with the accuracy of 0.315° while the allowed head movement is limiteted by ± 25 mm horizontally or vertically. The ASL eyetracker measure the gaze direction at 60 Hz with the accuracy of 0.5°. The user is able to act at maximal distance of 100 cm. The range for horizontal and vertical head movements is limited by 30 cm.

The integration of eye tracking into novel concepts that support a seamless human-machine interaction requires gaze data with a constant low latency. Also, flexible interfaces and open source software modules for the planed integration into control frameworks of robots and properties like tracking from the large distance and during high range on head rotations are required. None of the commercially eye trackers has the ability to fulfill all these requirements.

Due to applicable characteristics we decided to develop the first prototype for remote gaze tracking based on the baseline system for gaze-in-head measurements *EyeSeeCam* (see Fig. 2, www.eyeseecam.org). This system has been already successfully used in applications and experimental setups like the gaze driven head mounted camera [19]. Since the system computes the gaze direction in the head coordinate system, we extended the *EyeSeeCam* to be used as a head-free gaze tracker that calculates not only eye-in-head but also gaze-in-space. To get the highly accurate pupil data for the remote system we also plan to integrate eyetracking into a moveable vision system. That demands the use of small light weight pivotable cameras. The results achieved in our lab by developing the head mounted gaze driven camera [19] can be used for this aim.

Figure 2: EyeSeeCam head-mounted mobile eye tracking system.

2.1 Head tracking with remote stereo cameras

To calculate the position and the orientation of the head mounted system, 3 infrared LEDs – one LED in the middle and two laterally – were attached to the eye tracker goggles of Fig. 3B. The LED positions in 3D space are calculated by using a stereo-camera system, that is placed in front of the user (e.g., on a computer monitor). The stereo cameras run synchronously to the head-mounted eye tracker cameras, and consists of two digital cameras operating at 120 frames per second. The cameras are equipped with infrared filters. Consequently, only blobs from the infrared illumination remain. To distinguish between the LEDs and their reflexions on the user's skin and eyetracker goggles, the parameters shape, size, and intensity of each blob are evaluated. Noise is dynamically suppressed by flooring the minimal intensity relative to the current histogram, and a spatial filtering of the blob area. For more accuracy a non-linear lens distortion correction was used [10]. The position of the LEDs is computed from the centers of the remaining blobs in the image.

In the next step the 3D coordinates of the LEDs are computed by using the intrinsic and extrinsic parameters of the stereo camera system and the 2D positions of the blobs in every single camera image (Fig. 3C).

2.2 Computation of gaze-in-space data

The computation of the gaze-in-space is conducted in two steps. The first step of gaze detection is done by two eyetracking cameras placed on both sides of the head mounted goggles. The image processing algorithms detect the position of the pupil (Fig. 3A) and compute the user's gaze direction measured in the eye tracker coordinate system COS_G [6].

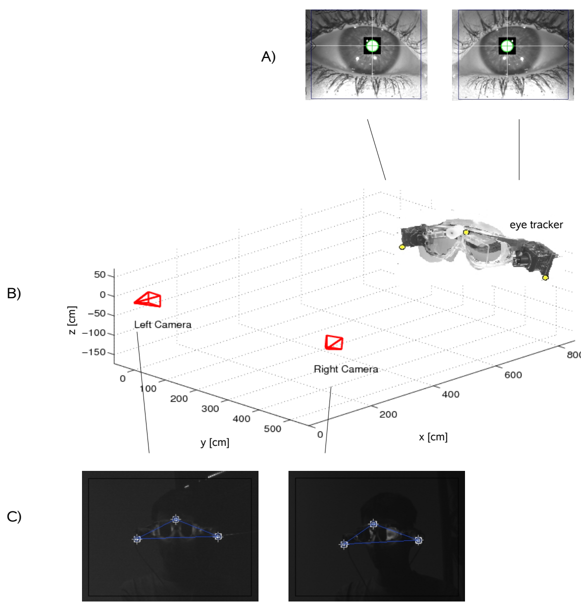

Figure 3: A) Images of the left and right eyetracking camera show results of image processing algorithms detecting the position of the pupil. B) Head tracker with 3D-coordinates system COS_W. The origin of 3D coordinate system is placed in the middle of the left camera. Three LEDs , which are placed on the eye tracker goggles determine the position and orientation of head in 3D space. C) Infra-red light images of the left and right head-tracking camera with three marked LED blobs.

In the second step the position of the head in 3D space is computed as described below (see section 2.1). After the gaze-in-head direction and the orientation and position of the head in 3D space are computed, this data is transformed into the gaze direction vector in 3D space.

2.3 Calibration of Gaze Tracking Framework

The full system calibration procedure consists of two different calibration sub-procedures: the stereo camera system calibration and the user gaze-calibration. First, the stereo camera system needs to be calibrated once at system setup. The automatic calibration procedure of the stereo camera system is implemented using the OpenCV library. The intrinsic and extrinsic parameters are calculated automatically by showing a chessboard pattern of known dimensions at different angles and positions to both cameras. Due to the quick calibration procedure both cameras can be freely positioned in any experimental setup. The obtained coordinate system of the calibration procedure is further used as world coordinate system COS_W with the origin placed in the middle of the left camera (see Fig. 3B). Second, the head mounted eye tracker should be calibrated by the 15 sec long calibration procedure. This should be done for each user at the beginning of the experiment. During this calibration the user is instructed to make subsequent eye fixations in five defined gaze directions. For this purpose, a small five-ray laser was attached on the goggles as close as possible to the subject's eyes [19].

2.4 Software framework and interfaces

The developed new software components are integrated into the *EyeSeeCam* framework, which offers most diverse control and analysis tools (e.g., graphical visualization of eye position, gaze direction, saccade distribution, etc.). The framework can be used as additional item in the complex experiment setup and also as central module. The structure of the framework is shown in Fig. 4. The newly implemented components are:

- head tracker
- Area-of-Interest calibration
- various interfaces

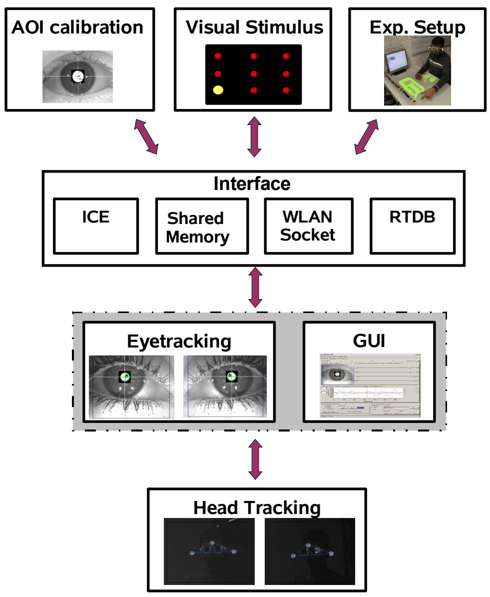

Figure 4: Structure of the framework. The dotted line marks the base functionality of the eyetracking system. For the integration into cognitive systems there are few additional components developed: head tracker, AOI calibration and various interfaces.

Flexible interfaces have been implemented that ensure seamless integration with other components. The gaze direction in 3D space is delivered to requesting devices by a socket- and shared memory-based interface, an ICE [1] and Real-Time-Database (RTDB) interface [22] and a D/A converter (USB-DUX). Thus, communication with remote and local experiment setup components (e.g., hand tracker, visual stimulation, user interface) is enabled. This setup was already used in first evaluations and conceptual system implementations (e.g., [18, 9]).

3. AREAS-OF-INTEREST

Various experimental setups require not only the gaze direction data, but also the 3D position of the fixated point on an Areas-of-Interest. Using the calibration data, the intersection point with the predefined (calibrated) plane can be computed. In our scenario, an AOI describes an interactive area in the human working environment (see Fig 7). Here, the user can interact with several displayed graphical user interfaces (GUI), hardware control elements (e.g., buttons, knobs, joystick, etc.), or supply racks in manufacturing scenarios.

3.1 Calibration of Areas-of-Interest

In order to detect and analyze human fixations of AOIs, their exact position and orientation in the corresponding world coordinate system COS_W have to be determined. Our COS_W is defined by the stereo camera system used to track the eye tracking goggles.

To approximate the coordinates of the single AOI_i, we decided to use an approach that works without manually measured references, but with tracked gaze points delivered by the gaze tracker. Therefore, the user has to fixate nine calibration points $P_{j,i}$ (see Fig. 6) of every AOI_i that are displayed at known positions on the screen (pixel coordinates). This measurement is repeated from different points of view to obtain different lines of sight at every single point. During the calibration process, the AOI handler records the line of sight data

$$\mathbf{gaze}_{3D} = b_{gaze} + \mathbf{v}_{gaze} \tag{1}$$

Where b_{gaze} is the basis point of the computed gaze vector $\mathbf{v}_{gaze}$. Together, these values describe the current line of sight of the user in 3D. Afterwards, these data are analyzed to determine the position of the calibration point in world coordinates. To compute the exact position of the needed points, at least two data sets (see equation 1) for each point are needed.

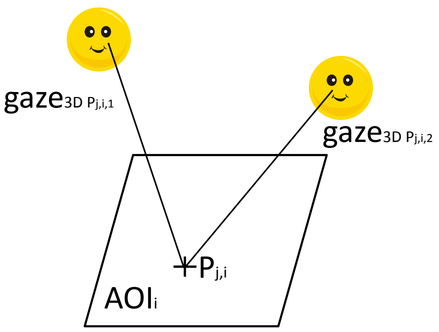

Figure 5: The user, represented by a smiley-head, had to fixate one point displayed on the plane AOI_i from two different viewing positions. $P_{j,i}$ is the computed intersection point of two lines of sight.

Basing on the equated two lines of sight, aligned to the point $P_{j,i}$

$$\mathbf{gaze}_{3DP_{j,i,1}} = b_{gaze,1} + \mathbf{v}_{gaze,1} \tag{2}$$

$$\mathbf{gaze}_{3DP_{j,i,2}} = b_{gaze,2} + \mathbf{v}_{gaze,2} \tag{3}$$

we can compute the corresponding gaze point by solving the following equations.

$$\mathbf{v}_{gaze,1} * \alpha + b_{gaze,1} = \mathbf{v}_{gaze,2} * \beta + b_{gaze,2} \tag{4}$$

$$\mathbf{v}_{gaze,1} * \alpha - \mathbf{v}_{gaze,2} * \beta = b_{gaze,2} - b_{gaze,1} \tag{5}$$

Which can be written as follows

$$\mathbf{A} * \mathbf{l} = \mathbf{b} \tag{6}$$

The values for α and β are computed by solving the following equation

$$\mathbf{l} = \mathbf{A}^+ * \mathbf{b} \tag{7}$$

where $\mathbf{A}^+$ is the pseudo inverse of $\mathbf{A}$, with

$$\mathbf{A} = \left[\mathbf{v}_{gaze,1} - \mathbf{v}_{gaze,2}\right] \tag{8}$$

$$\mathbf{l} = [\alpha\beta]^T \tag{9}$$

$$\mathbf{b} = b_{gaze,2} - b_{gaze,1} \tag{10}$$

If the lines of sight do not intersect, e.g., because of too noisy data, we cannot compute the gaze point exactly, but have to determine an approximation of it. Therefore, we compute the center of the connection line $\mathbf{P}_{j,i}$ (see Eq. 11) of the nearest neighbors ($\mathbf{P}_{I,1}$ and $\mathbf{P}_{I,2}$ in Eq. 13) of the lines of sight from

$$\mathbf{P}_{j,i} = \mathbf{P}_{I,1} + 1/2 * (\mathbf{P}_{I,2} - \mathbf{P}_{I,1}) \tag{11}$$

where

$$\mathbf{P}_{I,1} = \mathbf{v}_{gaze,1} * \beta + b_{gaze,1} \tag{12}$$

$$\mathbf{P}_{I,2} = \mathbf{v}_{gaze,2} * \alpha + b_{gaze,2} \tag{13}$$

As a result from these equations, we obtain the 3D data in COS_W from the needed point $P_{j,i}$. From three or more calibration points we obtain the corresponding plane. During examination, only the intersection point of the line of sight, and the computed AOI-plane has to be determined to evaluate the user's current gaze point. This is done by the AOI handler described below.

3.1.1 Noise Suppression

In order to damp affecting noise from our sensor unit, we use the following computation steps to decrease the negative effects from noisy data. In the first step, we record 50 lines of sight per calibration point with a fixed head position. From these 50 lines we approximate a representative line of sight using the *Principle Components Analysis (PCA)*. Afterwards, the head position has to be changed. From this new position, we also record 50 lines of sight, and calculate a second representative. Thus, we can reconstruct the 3D coordinates of each calibration point by intersecting the two representatives for each calibration point using the method described above.

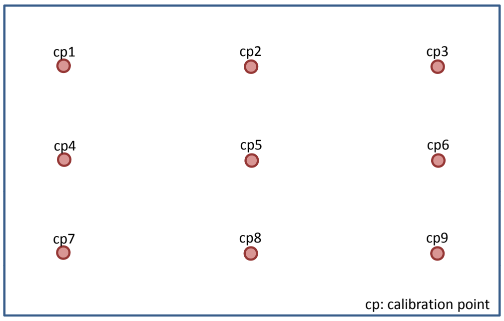

Figure 6: Pattern used for the calibration of each AOI. The pattern is displayed on the particular screen.

In a second step, the corresponding plane is computed from the nine calibration points. Here, we also use the PCA to approximate the plane. Afterwards, the nine calibration points are projected on the approximated plane. From the projected points $cp_1 \cdots cp_9$ we compute the direction vectors of the display coordinate system (x direction: cp_1 and cp_3, y direction: cp_1 and cp_7). Where cp_1 is the origin of the calibrated plane.

3.2 AOI handler

The Area-of-Interest handler combines the data delivered from the gaze tracker with the data obtained by the calibration of various AOIs. By analyzing the delivered gaze data and comparing it with the calibration data, it figures out which AOI the user is currently looking at. If the user fixates a displaying device (e.g., a computer monitor or a projected user interface, see Fig 7), the AOI handler provides exact data in display coordinates. Thus, an appropriate application is enabled to check which button or GUI element the user is looking at. E.g., this data can be used for enabling gaze driven interaction or the computation of the user's intention from look-ahead fixations [14]. If the user is looking at a non-displaying area, the corresponding environmental item is returned from the AOI handler (e.g., a calibrated hardware control element like a joystick).

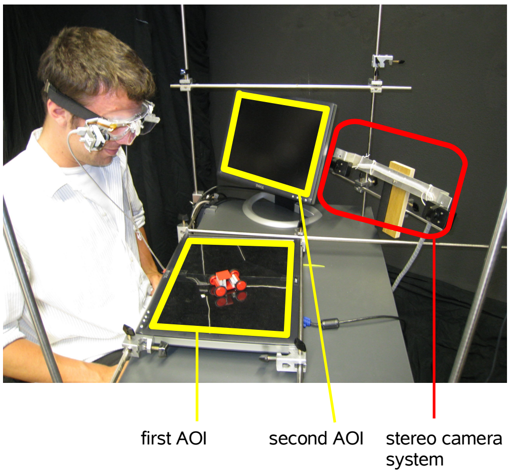

Figure 7: User wearing the eye tracker goggles sitting in front of the experimental setup with two AOIs. AOIs are marked with yellow lines. The red line marks the head tracking system (stereo camera rig).

4. EVALUATION

The first part of this section presents the measured accuracy and resolution of the gaze tracking system, and the accuracy of the developed AOI calibration method. The second part gives a short overview about first results of a brief user study using the described framework.

4.1 Resolution, accuracy, latency

To determine the accuracy of the developed AOI calibration method described above, the user was instructed to calibrate AOIs placed on 5 different known positions. The distance between the user and AOI was 65 cm. The user had to fixate three marked corners of one AOI from two different positions. Three intersection points of complement gaze vectors determine three corners of the AOI in 3D space. Using that three points, the position and orientation of the AOI was defined. The AOIs placed on 5 different known positions were detected with the accuracy of 0.61°.

In order to determine the precision of the gaze fixations on the calibrated AOI the user wearing the head mounted eye tracker had to fixate 9 points lying on one plane (see Fig 8). The distance between the user and AOI, was 65 cm. The accuracy of the fixation of the 9 points in 3D space was 0.458° and the resolution was 0.056°.

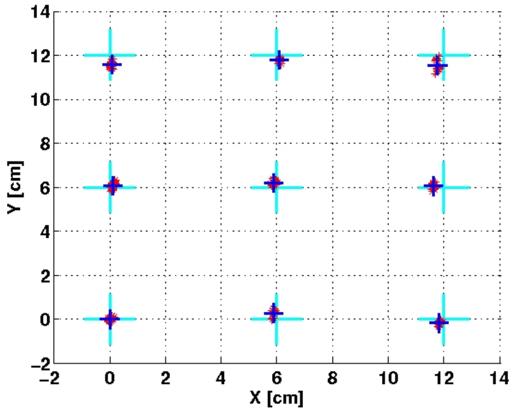

Figure 8: Measured data of the gaze fixations on the calibrated AOI. The light blue crosses mark the displayed calibration points on the AOI plane. The dark blue crosses mark the measured intersections of lines of gaze with the AOI.

The latency of the whole system running at 120 Hz was 10 ms. The current system, based on combination of the high resolution head mounted eye tracker and the stereo camera-based head tracking system, allows a robust and low latency gaze-in-space detection both in short (50 cm) and in large (>150 cm) distances. During the measurements the user was capable of performing head rotations of $\pm 37°$ around a horizontal and $\pm 40°$ around a vertical axis. These system parameters depend on the geometry of the stereo camera head-tracker. If required, the alignment of the stereo rig can also be adjusted for the current experimental setup.

4.2 User Study

The following section gives a short overview of first results from a laboratory study. Ten persons (9 male, 1 female, age from 23 to 31 years) took part in the study.

4.2.1 Test Setup

The gaze tracking was integrated into a laboratory prototype of a manual assembly workbench of the Cognitive Factory (see Fig. 1), and is a mixture between a simple Command & Control (e.g., selection of buttons,), and an attentive user interface (e.g, gaze dependent integration of additional information). Here, the user has to accomplish several assembly tasks, i.e. in the presented study the assembly of a small toy car as shown in Fig. 9.

We set up a prototypical GUI which is displayed on a monitor on the working desk or projected on a table by a beamer. Here the user has a working area (AOI), where he gets information from the construction manual (see Fig. 10). These display the needed parts for every production step as well as the appropriate position where the user has to integrate them. In the lateral areas, the user finds the individual parts needed to complete the components. In the upper area, the user finds buttons to control the system via gaze. Here, he can skip through the manual. The buttons are activated using an adjustable dwell-time.

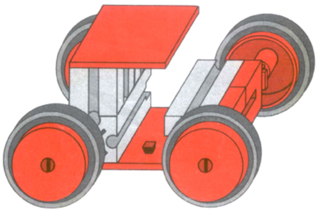

Figure 9: Completely assembled toy car.

If the user cannot find the parts needed to complete the production step, we can display an arrow (see Fig 10) that starts at the particular gaze point (see section 3.2), and points on the currently needed parts an th appropriate field in the GUI. The visualization of the arrow is triggered if the user cannot find the needed parts or the appropriate field or by the speech command *HELP*. The speech feature was realized as a wizard of oz input, as the test supervisor had to activate this functionality if the subject spoke the command. Also, additional information is presented depending on the user's current visual attention. Further information is presented in a text field that tells the user "to take *part X* from *field Y* to finish". This information is displayed depending on the particular working step at the current point the user looks at in the GUI. Thus, the user can easily access additional information without putting the part out of his hands. Also, the user operates the system without distraction from manually interacting with the manual, e.g., manually turning the construction manual.

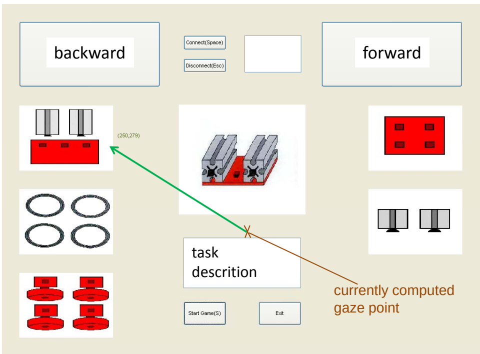

Figure 10: Graphic User Interface with additionally displayed arrow.

4.2.2 Results

The following sections present the results of our brief usability study.Therefore, we set up a general questionnaire to record general usability issues, and also used standardized questionnaires like SUS and a semantic differential. The general questionnaire was composed of several questions rated 5 fold Likert-scales (1 = very good/agree/etc., 5 = very bad/disagree/etc.).

GENERAL QUESTIONS The evaluation showed that all test persons rated the gaze driven interaction system as reasonable (average rating 2.3, scale 1 = very reasonable), practical (average rating 1.6, 1 = very practical) and usable (average rating 1.9, 1 = very usable). Furthermore, the test subjects indicated that they can subjectively interact with such a system quickly (average 1.7 rating, 1 = very fast) and especially intuitive (average 2.1, 1 = very intuitive). For most of the test persons it was easy to select a menu item/button via gaze (scale: 1 = very easy, 5 = very hard, average 3.6). By visualizing the currently computed gaze point on the GUI, the subjects had a sight to hit the buttons or active regions of the GUI. The subjects rated the visualization of the gaze point with an average of 2.1 when they were asked if they would need this visualization for correctly hitting the desired GUI element (1 = agree very much). However, the subjects rated the current matter of visualizing the gaze point not as satisfying since we visualized sensory ram data without smoothing fast eye movements like micro saccades. This resulted in a sometimes strongly jittered gaze point. Therefore, the integration of a smoothing filter like a median or a low pass filter figured out to be very useful for a future system revision.

The support in the form of a displayed arrow was rated as very helpful (average rating 1.4, 1 = very helpful), since it is a very intuitive way of directing the user's attention on the appropriate parts (willingly stated by eight participants). Furthermore, the attentiveness of the interface concerning the user's visual behavior was rated as very useful (average rating 1.4, 1 = very useful) and helpful (average rating 1.7, 1 = very helpful). This functionality was partly implemented as part of the running system, as it analyzed how long the user fixated the appropriate parts and the displayed end-stage of every production step. Also, the test supervisor observed the subject. Thus, the supervisor was able to trigger the additional help field.

SYSTEM USABILITY SCALE – SUS The SUS usability test was firstly introduced in [4] and captures the operability of a technical system. The SUS questionnaire is a simple 10 point scale analog to a Likert-scale, and is used to record a global impression of usability subjectively experienced by the user.

Analyzing the SUS data, a value from 0 to 100 can be achieved, whereas 100 is the best possible ranking. The evaluation of our recorded data showed an average of 74.4. Thus, the usability of the system can already be considered as satisfying. Also, most of the participants stated, that the system can be easily and clearly operated.

ATTRACTIVENESS To evaluate the attractiveness of the implemented interaction concepts we used the on line survey provided by [2], which evaluates both the recognized pragmatic quality as well as the hedonic quality of an interactive product.

Pragmatic Quality Here, the tested interaction system was clearly rated as very assistive, but there is still room for improvement regarding the usability. This is caused by the very simple interface we used for the test. Nevertheless, it is remarkable that the users felt assisted by the system.

Hedonic Quality Here, the tested interaction system was not clearly rated by the test persons. The users felt excited by the system, but the system only achieved medium values concerning hedonic qualities. Hence, there is still room for improvement regarding the hedonic aspects.

4.2.3 Summary of the Results

The short evaluation of the prototypical interaction system figured out, that gaze based interaction is an appropriate way to facilitate specific work steps in manual production tasks. However, to ensure an easy and intuitive usage of such a device, an adequate gaze tracker has to be integrated. Also, especially adapted displaying and interaction techniques have to be integrated.

5. FUTURE WORK

Future work will address an enhancement and further evaluation of the current system. Here, we want to figure out the benefits of a gaze directed system compared to an ordinary manually controlled system in various application areas of the Cognitive Factory. Also, the integration of a remote gaze tracker will be an important future work package. This will ensure an improved comfort for the user.

Future research will also address the implementation of a highly accurate and low latency remote eye tracker. Therefore, an approach that uses stereo reconstruction of pupil contours algorithm has proven useful for the implementation of a novel eye tracker without the need of calibration [13, 12]. Since this approach needs highly accurate pupil data, we will aim at the integration of pivotable cameras to allow a broad area for natural occurring head movements.

Based on precise and contact-less measured data containing relevant eye parameters, i.e. eyelid closure, iris and pupil size, and gaze direction, a humans vigilance and mental workload will be identified. Also, specific methods and algorithms for automated intention derivation from gaze data will be investigated. The idea is to distinguish between task-relevant and task-irrelevant gaze directions. Hence, important information cues for cognitive systems can be provided based on contact-less video based user monitoring.

6. ACKNOWLEDGMENTS

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