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EYE TRACKING, A METHOD FOR ENGINEERING DESIGN RESEARCH ON ENGINEERS' BEHAVIOR WHILE ANALYZING TECHNICAL SYSTEMS

Sven MATTHIESEN (1), Mirko MEBOLDT (2), Anne RUCKPAUL (1), Moritz MUSSGNUG (2)
1: Karlsruhe Institute of Technology, Germany; 2: Eidgenössische Technische Hochschule Zürich, Switzerland

ABSTRACT
The analysis of technical systems is a central activity in design processes. Engineers need to understand the functions of a system in order to gain inputs for further development. In using design research methods in the area of acquiring functional understanding, data is usually gathered through interviews or observations. Since vision is tightly related to cognition, eye tracking may provide deeper insights into the analyzing behavior of humans. This paper investigates the applicability of different eye tracking technologies for research into function recognition. Pilot studies were conducted to show the practicability of the proposed technologies. In addition to that, the paper introduces relevant analysis methods for raw gaze data. The results suggest that remote and head mounted eye trackers are well suited to observing the behavior of engineers who are analyzing a technical system in different representation forms. Based on these findings, the authors propose the use of eye tracking technologies in qualitative and quantitative empirical studies of how engineers build up understanding of technical systems.

Keywords: eye tracking technology, functional understanding, design cognition, human behavior in design, research methodology

Contact:
Prof. Dr. Ing. Sven Matthiesen
Karlsruhe Institute of Technology
IPEK - Institute of Product Engineering
Karlsruhe
76131
Germany
sven.matthiesen@kit.edu

1 INTRODUCTION

Analysis of technical systems is a fundamental competence of engineers, which is called up constantly during the design process. Eye tracking technology can be applied to detect which areas of an object an engineer is directing his/her focus and interest while building up a functional understanding. This technology records gaze data of participants, and thus enables access to insights about the thinking processes of engineers. This paper introduces eye tracking technology as a method for research on the behavior of engineers while analyzing product representations. First pilot experiments using eye trackers were conducted in order to detect if and how this technology can be used for empirical studies in this field of research.

Understanding, defining, developing and implementing functions are core activities of engineers. Thus, in many design methodologies (e.g. Pahl and Beitz (1996), Hubka and Eder (1996)) functions play an important role. Functions themselves, and how they are handled, are vitally important for engineers to solve problems. The overall aim of the authors is to research how engineers build up a functional understanding of technical systems in order to support these core activities. For reaching this aim, empirical studies have to be conducted to record the behavior of engineers during analysis.

Several empirical studies have been conducted in this field of research. Dylla (1991) concentrated on the thinking and acting of engineers during problem solving and designing. In collaboration with psychologists, team processes and the behavior of design teams in group work were observed successfully (Frankenberger, 1997).

In an empirical study that applied protocol analysis, Eckert et al. (2012) focused on the ability of engineers to identify functions, build up functional understanding, and express functional structures. Further findings on human behavior can be elicited by the application of eye-tracking technology in such studies. By tracking engineers' gaze directions while they build up functional understanding, deeper insights into their cognitive abilities can be gained.

After discussing the motivation of the application of eye-tracking technology in empirical studies, this paper presents the technology itself with different recording devices and functionalities. Initial pilot studies are introduced to present different experimental setups, and to explain and classify which analysis methods can be used to evaluate the eye tracking data recorded by different systems.

A summary of possible fields of application for eye tracking, including opportunities and challenges, is provided.

2 MOTIVATION

In order to understand how engineers behave during the analysis of technical systems, and how they build up a functional understanding, empirical studies have to be conducted which observe engineers during these activities. Several research and observation methods exist which support researchers to elicit knowledge of engineers. Ahmed (2007) gives an overview on research methodologies and research methods used for empirical studies in industrial settings. Table 1 shows which research methods should be applied in order to access the different kinds of information or knowledge. The table shows that only a few research methods support the exposure of implicit or tacit knowledge.

Table 1: Research methods mapped against information and knowledge (Ahmed, 2007)

Research method	Stored externally	Stored internally in human memory		
	Information	Explicit knowledge (which is not yet explicated)	Implicit knowledge	Tacit knowledge
Document analysis	x		x	
Interviews	x	x		
Discourse analysis	x	x	x	
Observations	x	x		
Participant observation	x	x		
Protocol analysis	x	x	x	x

However, these two types of knowledge are important and necessary for closer investigations of thinking processes of engineers. The visual sense highly influences the mental activities of humans. In reading studies (e.g. Rayner, 1998), the recording of gaze data is already established for research on cognitive abilities of humans. The application of eye tracking technology in empirical studies enables the detection of the visual information which engineers acquire during the analysis process, and provides a further possibility to elicit explicit, implicit and tacit knowledge.

So far, for uncovering implicit as well as tacit knowledge, protocol analysis is the appropriate research method. Eckert et al. (2012) used protocol analysis for studies on strategies for a functional analysis of an existing product. Audio and video data of the subjects and their behavior was recorded for eliciting implicit and tacit knowledge. Many findings on the understanding and handling of functions could be drawn. However, some noticeable issues could not be explored. For example subjects assigned different functions to the same part of the system. It could not be determined if the differing functional understanding was due to a lack of visual information gained by the subject or to misinterpretation. With additional recordings of gaze information even more conclusions could have been drawn out of the experiment data.

In the following, after explaining the technology of eye tracking systems, the paper introduces how this additional gaze information can be recorded and extracted.

3 EYE-TRACKING TECHNOLOGY

3.1 Application and technology

Eye tracking technology has become increasingly important over the last decade. Due to advancements in the usability of the systems, the reduction of costs and improvements in accuracy and precision, the number of users has grown constantly. Today, eye tracking technology is applied in many different domains. Neuroscience, psychology, industrial engineering and human factors, marketing/advertising and computer science are some of the largest application fields (Duchowski, 2002). According to Duchowski (2002) eye tracking applications can have either a diagnostic or an interactive role. In a diagnostic role, the systems record gaze data in an experiment in order to analyze the captured data in a subsequent step. Here, systems are used in both fundamental research (e.g. reading research (Rayner, 1998)) as well as applied usage (e.g. product development in automobile design evaluation (Wang et al., 2011)). In an interactive role, the systems are implemented in products and respond directly to the user`s gaze (e.g. eye laser treatment systems). From the technological point of view, video based eye tracking has recently become the dominant technology in use (Holmqvist, 2011). In order to calculate the direction of the gaze, they use both a video camera, which observes one or two eyes, and an infrared illumination light, which is directed to the eye(s) of the subject.

Using the eye-camera recording, gaze estimation is done by setting the calculated center point of the pupil in reference to the reflection point on the eye balls (corneal reflection), which is caused by the infrared illumination (Hansen and Ji, 2010).

Because of differences in the shapes of human eyes, calibration is necessary for each new subject. A defined gaze point on the stimulus (also known as scene; i.e. the object the subject looks at), on a screen or in the field is then calculated. In general, video based eye trackers used in the diagnostic role are divided into three different classes: 1. static eye tracker, 2. head mounted eye tracker, and 3. head tracker (Holmqvist, 2011).

1. Static eye trackers are installed in a fixed position and have a defined distance to the stimulus, which is presented in front of the participant, mostly on a screen. They are subdivided into two different subclasses. First, there are tower mounted eye trackers, where the head of the subject is positioned in order to avoid head movement during recording. Second, there are remote eye trackers, which record the subject from a distance, and which avoid direct contact between measuring equipment and subject. The camera and the illumination unit are normally placed below the stimulus.
2. Head mounted eye trackers are placed on the head of a subject. The tracking elements (illumination and camera) are fixed on a helmet or are directly included in glasses. With these systems the mobility of a subject is ensured and the gaze can be recorded in any environment.
3. The third class is specified as head trackers. These systems combine a head mounted eye tracker with a tracking of the head itself in space.

3.2 Eye movements and events

Human eye movements are characterized by events. The two main events are fixations and saccades (others include glissade, smooth pursuit, microsaccades, etc.). If the gaze is fixed on a local area, which is defined by a maximum gaze angle (typical max. angle 0.5 – 2.0°) for a certain minimum time (typical min. duration: 50 – 250ms), it is called fixation. In general during fixations, humans have their attention directed to the place where they look and are able to perceive information. Saccades are fast movements (typically between 30 – 100°/s) of the eyes from one fixation to another. During saccades humans perceive almost no information (Holmqvist, 2011). The raw data, which is recorded by video based eye trackers, consists of defined points in reference to a screen or a video section. Each sample records a new point. By using duration, dispersion and velocity constraints, the algorithms of the analysis software calculate events (e.g. fixations and saccades) out of the raw data. The accuracy of the system depends on the eye tracker itself and its calibration to the subject (angular deviation < 0.5°).

In order to analyze the attention of subjects to certain areas in the stimulus, the fixations can be assigned to areas of interest (AOI). AOIs (e.g. different machine elements in a technical drawing) can be created in any shape on the stimulus and have to be defined manually. Assigning fixations to AOIs, whether done automatically by software or manually, simplifies data analysis, especially in case a statistical analysis is requested.

4 EXPERIMENTAL SETUP

To validate the applicability of eye tracking in the area of engineering design pilot experiments were carried out. The studies are to detect if and how video based eye tracking systems can be used to research the field of functional understanding of technical systems, on basis of different representations of technical products. On each experimental setup, two subjects are asked to acquaint themselves with the function of the presented technical object, and explain it, while the gaze direction is tracked. The aim of the experiments is not to influence or evaluate how the functional analysis is conducted. It aims on examining whereon the subjects gaze is placed when functions of the technical system are identified.

4.1 Objects

In order to research, how engineers build up a functional understanding of technical systems the selection of the product representations, more generally called objects, which are analyzed is essential. On the one hand the objects should be typical in the field of engineering and on the other hand they have to match to the eye tracker to get useful data. This study exemplifies four types of objects, which are highly relevant in the field of product development. The first object is a 2D sectional drawing presented on a screen whereas the second object is the same product representation, but as printed version. The 2D drawing still plays an important role in the field of engineering and is used as across departmental visualization of technical information (e.g. in product development, quality management and production). The third type of object is a 3D CAD model. It is one of the most important product representations in engineering design, because it is used during the whole product development process. To the fourth type belong physical objects, such as prototypes or existing products. They are highly relevant for validation or benchmarking. Beside the importance of physical objects within the development process, the customer's perspective on the final product is fundamental. In order to realize how the product works, the customer has to build up a functional understanding of the system, as well.

4.2 Experimental setup

Basically the experimental setup on the one hand should reproduce the natural working conditions of engineers, while analyzing the mentioned types of objects. On the other hand the data, which can be gained, have to be adequate for functional understanding research. Therefor two classes of eye trackers are qualified: (1) a remote eye tracker (Figure 1, left) is used for 2D drawing and 3D CAD model on the screen and (2) eye tracking glasses as head mounted eye tracker (Figure 1, right) are used for printed versions of 2D drawings and physical objects. On basis of these object to eye tracker combinations the four experimental setups are described, which are particularly suitable for investigations in functional understanding of technical systems.

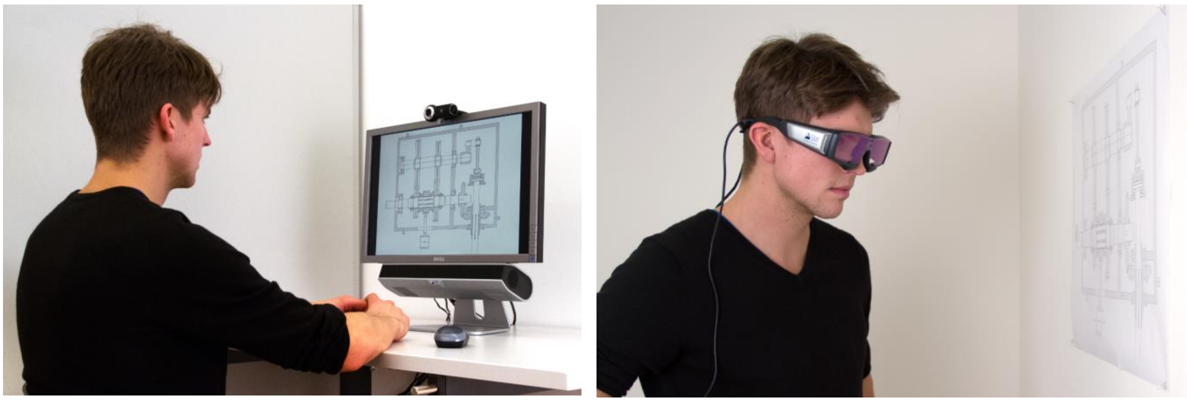

Figure 1. Subject, tracked by a remote system (left) and by head mounted glasses (right)

4.2.1 Experimental setup 1: Remote system

For both experimental setups with the remote system (2D drawing and 3D CAD model) the authors use a SMI RED 250 eye tracker in combination with a 22’’ stimuli screen (1680 x 1050 pixels). As illustrated on the left side of Figure 1, the subject is situated in front of the screen and uses a mouse to navigate and mark elements. The system is placed on a height adjustable table in order to be able to adapt the tracking system to different subjects. The remote unit is a binocular tracker with 250 Hz sampling frequency. In addition to that, a webcam, which is directed to the subject and records video and audio data, is installed. The gaze data of the remote system, the video and the audio data of the webcam are synchronized by software. In both experiments the minimum fixation duration for the event detection is adjusted on 80 ms. In the first setting the subject looks at a 2D sectional view of a technical system, illustrated on the left side of Figure 2. It is a static stimulus, which does not change over the experiment or the subjects.

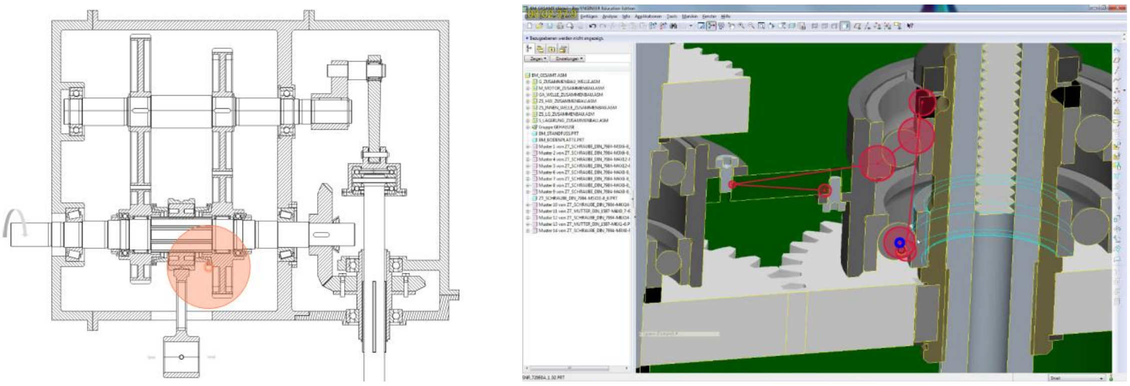

Figure 2. 2D sectional drawing with the actual fixation marked with an orange circle (left) and 3D CAD assembly with a scan path in red circles and lines (right)

In the second setting an assembly of a simplified drilling machine is shown to the subject by 3D CAD software (Figure 2, right). Each subject is allowed to navigate individually in the program in order to understand the function of the object. Hence the view on the object changes permanently, which creates a dynamic stimulus.

4.2.2 Experimental setup 2: Head mounted system

In this experimental setup binocular SMI eye tracking glasses are used. In addition to the infrared illumination unit, the eye camera (30 Hz) and the scene camera the head mounted system includes a microphone, which allows recording a synchronized audio signal.

The object on the left in Figure 3 represents the same 2D sectional view used in the remote setting, but instead of showing it on a screen a printed version is pinned on a wall. In the second setting a real model of a clutch, prepared to serve as demonstration, is analyzed by the subjects. Both settings have a dynamic stimulus because the movement of the subject’s head changes the view on the stimulus permanently. The two experiments point out that the use of head mounted tracker gives a high mobility to the subjects. They are able to handle it in the desired orientation or disassemble it, in order to get different views on the technical object, which is important to understand the function of a technical system.

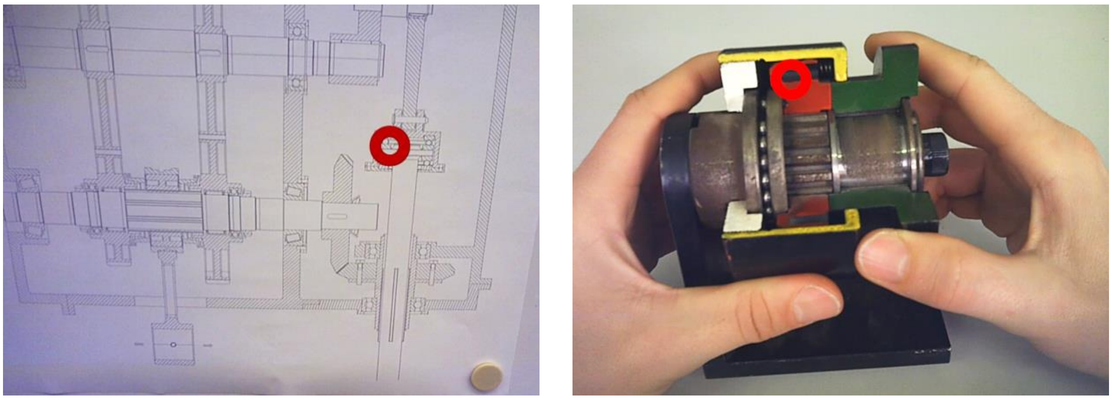

Figure 3. 2D sectional drawing (left) and demonstration model of a clutch (right) both with point of gaze marked with a red circle

5 ANALYSIS

The analysis of the measured raw data depends strongly on the kind of stimulus, which is observed by the subject. Basically, a stimulus can be either static or dynamic. A static stimulus shows the same view for a certain time. In this study, the 2D drawing used together with the remote system, pertains to the group of static stimuli. A dynamic stimulus can be subdivided into repeatable dynamic and individual dynamic. A repeatable dynamic stimulus shows always the same sequence for all subjects, e.g. a video, whereas an individual dynamic stimulus changes for each subject, because the subject navigate the stimulus individually during the recording. The study presented in this paper investigates three experiments with individual dynamic stimuli: The printed 2D drawing and the physical model of a clutch tracked by the head mounted glasses and the 3D CAD model of a drilling machine tracked by the remote system. In the following important analysis methods for investigations in functional understanding processes of technical systems are introduced and classified on basis of Figure 4. Further analysis methods are presented e.g. by Holmqvist (2011), however this paper concentrates on only the most important methods in context of the research field.

5.1 Static stimulus

As illustrated in Figure 4 the analysis of static stimuli can be done on three levels. On the first level, the direct output of the measurement, the raw data, is used. The gaze point, which is created by the eye tracker in every sample, can be visualized on the stimulus. By showing not only the actual point but also a certain history of raw data points, a first impression of where the subject looks, can be given. However, raw data analysis comprises a high amount of measuring points and hence needs to be simplified.

Level 2 analysis contains methods on basis of fixations, which are calculated out of the raw data by the event detection algorithms as described in chapter 3. Basically the actual fixation can be visualized as seen on the left side of Figure 2, where the circle diameter shows the fixation duration. The visual attention of a subject (fixations) can be assigned to specific components of the technical systems.

By watching the actual fixations along the timeline, the gaze direction at a certain time as well as an overview of the recording can be read out. In order to evaluate the course of action of a subject analyzing a technical system a scan path can be generated.

As illustrated on the left side in Figure 5 (also the right side of Figure 2) scan paths visualize fixations (circles) and saccades (lines). They show not only the actual fixation, but also a certain history of the recording, here in both illustrations approx. 4 s. Scan paths are qualified to analyze in which patterns engineers build up functional understanding of technical objects. If an overview of a longer recording or the illustration of gaze directions of several subjects is required, scan paths become confusing, because of the high amount of visualizations on the stimulus. In this case heat maps are more qualified. Fixation location and duration are used to calculate a representation for certain or complete duration of the experiment (Figure 5, right). Areas, which are observed the longest, are colored in red. In differently colored gradation steps, the relevance of the other areas is visualized. This kind of illustration is relevant to get a fast overview on areas of special interests of the participants. In addition to that, mouse clicks on certain points in the stimuli can be located and visualized (rhombs in Figure 5, right). The pilot experiments indicated that engineers usually look mainly on one side of symmetrically parts in a sectional view. But if one part is unknown, it is observed for a longer period and the gaze goes on both sides of the symmetrical axis.

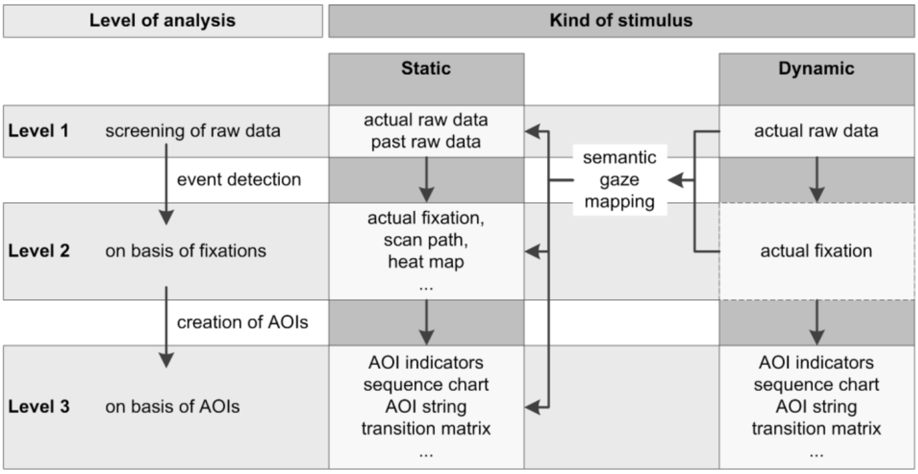

Figure 4. Classification of eye tracking analysis methods

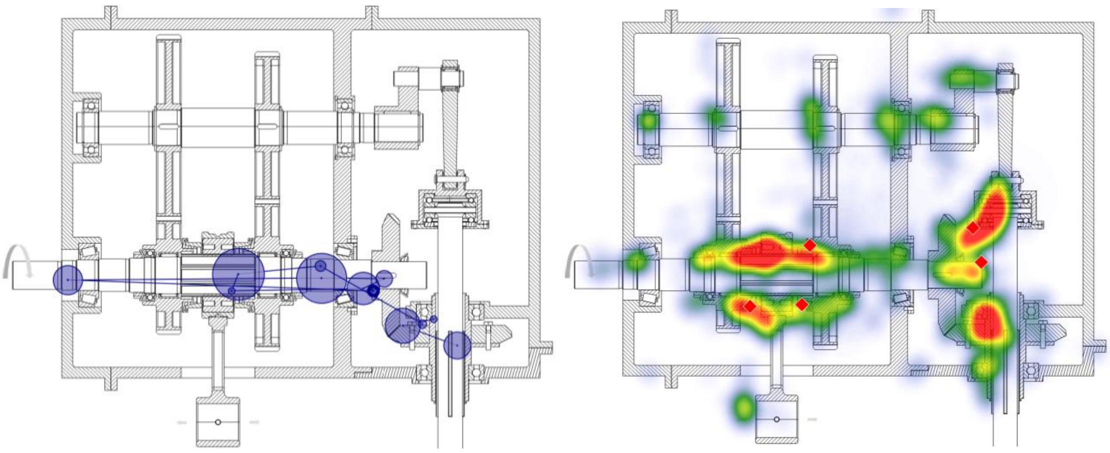

Figure 5. Scan path (left) and heat map (right) on a 2D sectional drawing

The third level of analysis can be done on basis of areas of interest (AOIs). In general there are two options to create AOIs, automatically or manually. On the left side of Figure 6 gridded AOIs, which can be generated automatically by software, are presented. The stimulus is divided into cells by a grid. In each cell the information (e.g. amount of fixations) is added. On the right side, manually created AOIs are shown exemplarily. Here, AOIs can be generated in every possible 2D shape. For each component of the technical drawing an AOI can be defined.

Thereby, the special characteristic of sectional drawings, having components that appear in two areas in the stimulus (e.g. bearing 1), has to be considered. Overlapping AOIs, which allow defining one of the two overlapping AOIs as dominant, can be used. For example, axis 2 can overlie bearing 1 and set as dominant, so that all gaze points between the two cross sections of the bearing belong to axis 1 and the gaze data on both sides of the bearing are directed to one “bearing 1 AOI”. On basis of AOIs, regardless if they are gridded or manually created, different analyzing methods can be applied. Basically, AOI indicators such as entry time, dwell time (accumulation of fixation durations), first fixation, fixation count, revisits, etc. can be displayed for each AOI. In addition to that, sequence charts (Figure 7) are important for research concerning technical objects. By mapping the AOIs, which represents for example components in a technical drawing (y-axis) over the time (x-axis), the sequence chart visualizes the order and the duration of AOIs. Hence, it is possible to detect patterns how engineers “read” technical objects in order to understand their functionality.

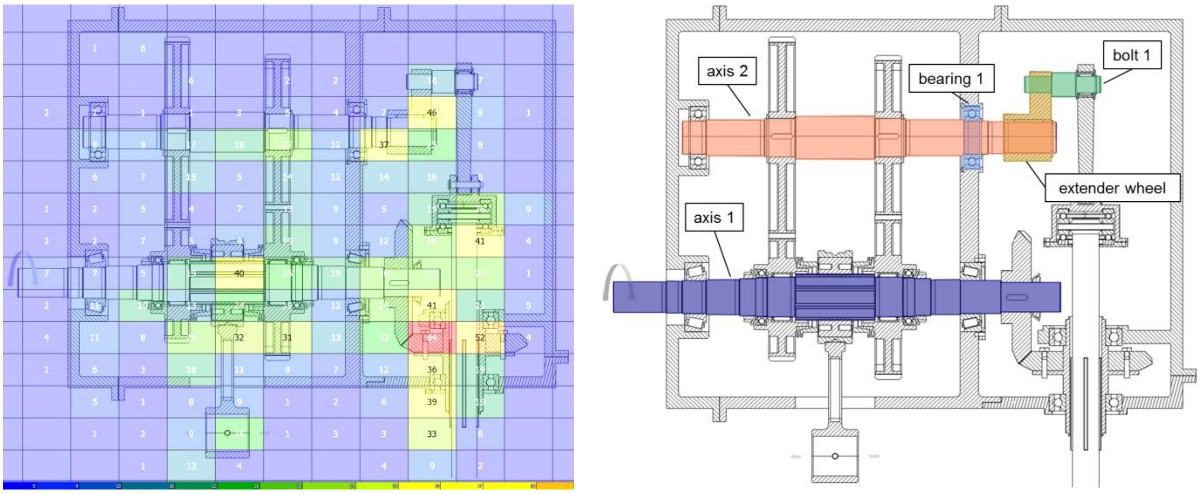

Figure 6. Gridded areas of interest (left) and manually created areas of interest (right)

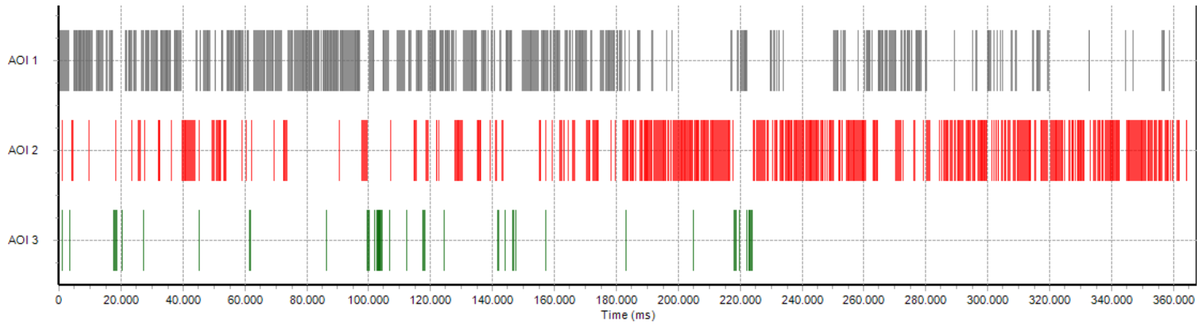

Figure 7. Exemplary sequence chart

The sequence of AOIs can also be visualized as string (e.g. AOI 3 – AOI 1 – AOI 2 – AOI 3 – AOI 2 – …). Even though in a string the duration information is lost, it has the advantage that different strings of individual subjects can be compared automatically. Especially for comparing "reading patterns", which are important for building up functional understanding, strings are qualified. Beside AOI sequences, a transition matrix is helpful. It visualizes the number of transitions from one AOI into another AOI (e.g. how often the subject looks at bearing 1 after watching axle 2). Hence, it can be found if a subject e.g. matches two components of a technical system more often than others.

5.2 Dynamic stimulus

The level 1 analysis of dynamic stimuli is equivalent to static stimuli, where the raw data and therefore the actual gaze direction of the participant is visualized in the scene video. In contrast to static stimuli, where the actual as well as the past raw data can be showed in one analysis, for dynamic stimuli it only makes sense to illustrate the actual gaze point. The permanent change of view makes the past raw data, which is related to a position on the screen, irrelevant, because the view keeps moving underneath the marked raw data points. On level 2, the actual fixation is shown. The fixations can be calculated on basis of the eye movements, but they cannot be illustrated as a stationary fixation in the recorded video. Due to the same reason scan path and heat map analyses are inapplicable for dynamic stimuli. However, in order to allow further analysis, semantic gaze mapping can be used (Figure 4). Thereby, the samples or the fixations have to be assigned manually to one or more reference views. The reference view can be any static picture, e.g. a capture of the recorded video or a list of components of the technical object. Now each sample or each fixation in the video can be mapped on the reference view manually. Hence, the dynamic stimulus is transformed to a static stimulus, which allows the application of the described analyses methods for static stimuli (level 1-3). It is important to know, that such a transformation is a simplification as well. Because of the manual assignment the gaze points can be falsified. In addition to that, one reference view is not always sufficient, so that two or more views are needed. This makes e.g. a broad scan path analysis impossible. Nevertheless, the semantic gaze mapping allows a deeper and easier analysis of the raw data of dynamic stimuli. Beside the semantic gaze mapping a level 3 analysis can be done directly on basis of the raw data of a dynamic stimulus. Thereby dynamic AOIs have to be animated in order to follow a certain element in the video and assigning all fixations to that element. The shape of a dynamic AOI has to be adapted to the relevant element at multiple frames of the video. This procedure is extensive and only useful for short sequences or repeatable dynamic stimuli. If the animation is completed, all the introduced 3 levels analysis of static stimuli can be done on basis of the raw data of the dynamic stimulus, as well.

6 RESULTS OF A PILOT EXPERIMENT

As described before, a pilot experiment was conducted with eye tracking glasses in combination with a physical model of a clutch as stimulus (see chapter 4.2.2). The clutch was prepared for demonstration purpose and the cut surfaces were colored differently for each part (Figure 8, left). As described in chapter 4 the subjects were asked to build up a functional understanding of the object at hand and think aloud while analyzing.

After the event detection the data analysis continued with the semantic gaze mapping of fixations to a reference view (Figure 8, left and middle) according to the classification of analysis methods for a dynamic individual stimulus (Figure 4). Hence fixations can be assigned to different components of the technical system and the attention of the subjects on these parts can be analyzed. Three main AOIs were defined – red, green and grey (Figure 8, right) – and a sequence chart was deduced (Figure 7).

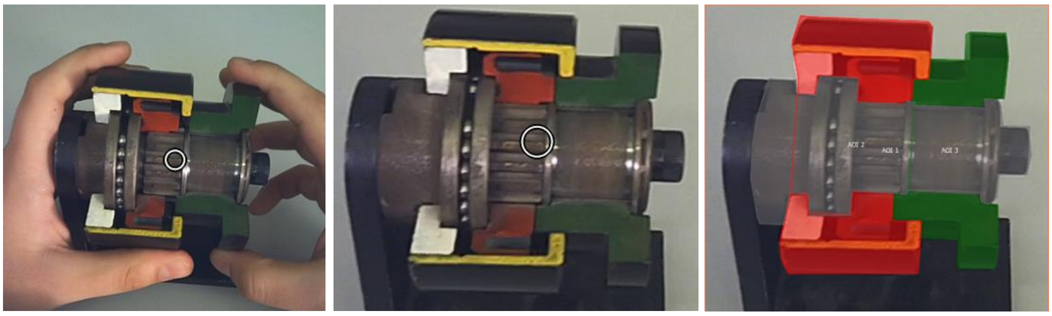

Figure 8. Raw data (left), assignment on reference view (middle) and defined AOIs (right)

From a first look at the sequence chart it can be inferred that the green AOI was not of great interest to the subject. Analyzing the additional audio and video recordings, this inference turns out to be valid. The subject recognized the presented object as a clutch after the first sights on the system and concentrated on the detailed parts of the object. After half the duration of the whole experiment the subject concentrated on the function of the red part and the shaft-hub-joint to the shaft of the physical model. In the sequence chart this fact is indicated by a concentration of red beams (Figure 7). In order to find out how the joint is realized the red and the grey AOI were compared several times. The transitions from the red AOI to the grey AOI can be identified in the sequence chart as well as in the transition matrix. It was first planned to apply AOIs for each part of the object. However, the accuracy of the recording was not high enough to subdivide the red AOI into smaller areas. This has to be considered for further experiments.

The subject often only looked at parts of the object without saying anything. Due to the fact that it is possible to screen the actual raw data of the eye movements on the monitor of the experimenter, it is possible to follow the gaze directions of the subjects live during the experiment. If desired, the experimenter is able to ask the participant specific questions according to the current gaze position. Thereby, the "looking without seeing" event, when participants fixate their gaze on the stimulus without receiving any information, can be detected.

In addition to the think aloud technique, where the subject is asked to speak during eye tracking, think after, where the subject tells his thoughts retrospectively, is relevant. Think after can even be done on basis of the gaze data, by asking the subject to comment his own raw data video. This approach provides a meaningful opportunity to gain further information on thinking processes of engineers.

7 CONCLUSION AND OUTLOOK

This paper shows that eye tracking is a useful method for empirical studies on the behavior of engineers while analyzing technical systems. Existing research methods for empirical studies primarily access documents as well as audio and video recordings of subjects. Eye tracking provides a

meaningful extension of those methods and can give further information how the subject understands the functions of a technical object. The different existing eye tracking systems are introduced whereas the use of remote and head mounted systems is proven to be qualified for research in the described field. Proposals on reasonable experimental setups are given. The analysis of recorded eye tracking data admits a high amount of possibilities, which are partially limited by the used eye tracking devices and the observed object. The paper deploys a classification of important analysis methods according to the applied experimental setups. This leads to an appropriate analysis by purposive selection of methods. Furthermore gaze data can provide information on different functional interpretation of objects by engineers caused by different visual focuses which cannot be accessed by audio and video data. The combination of gaze and audio data carries several advantages for research on building up functional understanding of technical systems. Misinterpretation of gaze data, e.g. “looking without seeing”, can be contained by comparing gaze directions with verbalizations.
Upon presenting that eye tracking is a useful extension to existing research methods further empirical studies on analysis of product representations by engineers will be conducted by the authors. The main goal is to elicit strategies engineers apply when building up a functional understanding of a technical systems. The comparison of two groups of subjects, experts and novices, can lead to gaining findings which can be introduced into education. Eye tracking can also be applied for further development of research methods.

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