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Using Eye Tracking in the Research of Human Behaviour in Engineering Design

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***Abstract*—The application of eye tracking technologies becomes more and more relevant in the research of human behaviour. Due to advances in the usability of eye tracking systems, the reduction of its costs and improvements in its accuracy and precision, the number of users grows constantly. Today, eye tracking is already well-established in neuroscience, psychology, industrial engineering and human factors, marketing/advertising and computer science. The results within these research fields show the very high potential of eye tracking to gain new insights in the thinking and acting processes of human beings. In engineering design research the usage of eye tracking is still at its beginning. This paper presents the basic idea to learn from the disciplines that are more experienced in eye tracking experiments and to transfer successfully applied approaches to engineering design research. Based on this idea two eye tracking studies from engineering design are presented. The first one investigates visual strategies of novice and experienced design engineers, the second considers the behaviour of engineers while analysing a physical technical system. The results of both studies show that the data gained by eye tracking experiments provides an adequate basis to better understand human behaviour in design processes and thus might allow a human-centred improvement and development of engineering design methods and tools.**

***Keywords*—human behaviour, eye tracking, engineering design, visual strategies, research methodology**

I. Introduction

The main task of engineers is to apply their scientific and engineering knowledge to the solution of technical problems, and then to optimise those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations [1]. In order to define and communicate designed solutions they are often represented graphically in the form of hand sketches, technical drawings and virtual or physical models. These representations store engineering information and transfer it primary by visual perception. Due to this especially complex representations (e.g. sectional system drawings) that are characterized by a high information content and a high information density require cognitive performances, which can be researched by analysing the visual behaviour of engineering designers. In the last years several experiments in cognitive science, human-computer interaction and marketing research impressively showed that eye tracking is a powerful research method to gain deeper insights in the visual behaviour of humans [2].

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Eye tracking research has a long history that started more than 250 years ago [3]. The first essays on eye movement surveys are reaching back to the 18th century. Based on experiments that have been conducted on single vision with two eyes, vision and eye movements were integrated to determine the first principles of visual direction. Since then a lot of research was spend on the development of eye movement measuring methods and eye tracking devices.

Ever since there have been two different basic technological approaches: the sensor-based and the visual/video-based. Both approaches have different advantages and disadvantages and both are still applied. Nowadays the video-based eye tracking technology has become dominant [4]. Video-based eye tracking systems measure the eye movement (relative to a calibration) and project the calculated gaze onto the record of the test person's field of view, which is also called the 'stimulus'. In eye tracking analysis the stimulus usually is a picture, a sequence of pictures, a movie or a scene video that is simultaneously recorded by a camera integrated in the eye tracking system. Thus, eye tracking analysis bases on the combined interpretation of eye movement data and the stimulus data.

Video-based systems can be basically subdivided into remote systems and head mounted systems. A remote system is able to determine the gaze relative to a picture or an video presented on a stationary screen, whereas a head mounted system (e.g. eye tracking glasses) is recording the gaze path relative to the dynamic field of view of the test person.

Due to recent technological advances present eye tracking systems are highly user-friendly, i.e. they support the researcher by automatic calibration as well as by different options of data analysis and result visualisation. In contrast to well established research methods like interviews, document analysis and protocol studies eye tracking provides the opportunity to collect data (1) directly from the test person's view and (2) directly while solving an engineering problem.

This paper proceeds as follows. Section 2 gives a brief overview of eye tracking experiments recently conducted in other disciplines and discusses the transferability of the applied research approaches to research human behaviour in the context of analysing product representations and product applications. In section 3 two eye tracking studies from engineering design are presented. The first one investigates visual strategies of novice and experienced design engineers, the second considers the behaviour of engineers while analysing a physical technical system. The key results of both studies are briefly presented and discussed in regard to insights in the thinking and acting processes of engineering designers. Section 4 concludes and gives an outlook to future research activities.

II. Eye Tracking in the Research of Human Behavior

Eye tracking is a technology that nowadays is quite well establish in different fields of research. Duchowski [2] gives a broad overview of present and upcoming areas of eye tracking applications. These are: Neuroscience (e.g. attentional neuroscience), psychology (e.g. reading, visual search, information processing), industrial engineering and human factors (e.g. aviation, driving, visual inspection), marketing and advertising (e.g. print advertising, web usability) and computer science (e.g. selective systems, collaborative systems, gaze-contingent displays). One of the most relevant application field for eye tracking is market research testing website usability. Here by eye tracking application the individual customer behaviour can be observed. This application field shows the potential of this technology to gain insight of visual behaviour and cognition. Exactly this is a central aspect in engineering design: for the engineer, who is designing the product and as well as for the customer, who will use the product. Beside the usability aspects of visual search are highly relevant for engineering design research.

A. *Analysing Product Representations*

Product representations are explicit descriptions of the product including a selection of its characteristics and properties. In addition to textual representations in engineering design especially functional and geometrical representations are of particular importance. Here, product models illustrate hierarchical and structural interdependencies of single elements or subsystems. Furthermore sketches, technical drawings and 3D-CAD-models are built up to document and to communicate the product's embodiment [5]. These product representations are characterized by both high information content and high information density. The information contained in the respective product representations has to be perceived and processed primary visually. Thus, the application of eye tracking seems to be most suitable for the analysis of product representation and the identification of correlations of visual behaviour and cognition.

In the context of functional and geometrical representations eye tracking analysis already is successfully applied in different other fields of research. Bednarik [6] for example analysed the visual attention strategies of programmers debugging software code that is displayed in multiple representations. Rosengrant et al. [7] applied eye tracking in order to record the gaze path in the evaluation of electrical circuits represented in simple 2D-drawings. The findings of both studies indicate that the duration as well as the order of eye fixations is related to the test subject's understanding of the respective representations.

Another field of research increasingly uses eye tracking analysis is cartography. Swienty et al. [8] investigating eye movements in order to enhance the visualization of relevant geographical information by focusing on utility and usability issues of designing geographical information representations. In this context they name challenges that are well known in product representations. These are for example the growing amount of available data at various levels of detail or the diversified applications of that data. Corresponding to the challenges the applied research designs are transferable as well. The basic idea is that in the representations of both fields of research (1) similar tasks (e.g. search for locations or search for flows) can be assigned, (2) similar segmentations of the test subjects (e.g. culture, sex or age) can be defined and (3) similar measurement readings (fixation count, fixation duration, time to first fixation) can be recorded and statistically evaluated.

B. *Analysing Product Applications*

In contrast to the section above, which focuses on the measurement of the designer's eye movement, this section discusses the benefits of analysing the user's gaze during product application. Here, eye tracking analysis can be purposefully applied to support engineering design regarding the evaluation of usability and customer acceptance aspects. In fact an essential part of product validation already considers the observation and survey of customers realistically applying physical prototypes or final products. On one hand the testing of physical prototypes can reveal weaknesses of a product's design that should be necessarily eliminated before the market launch. On the other hand the analysis of products in market can lead to the identification of new customer needs that have to be satisfied by the next product generation. In both cases the testing aims the gathering of information about the user's perception of the product in its application.

Badni [9] states that one of most common methods used for product evaluation tests is the 'think aloud technique'. He further describes that verbalizing own actions and thoughts during the product application causes additional cognitive efforts that negatively affects the test results. In order to overcome this problem he suggests the application of eye tracking allowing the user to review physical products in a more natural way. The visual appearance of a product plays a significant role in determining consumer response. However, the judgment on whether a product is attractive or not, does not only include consideration of whether the product looks good, but also whether it appears functional and says the right things about the owner. Against this background Kukkonen [10] conducted an eye tracking study to analyse the appearance and apparent usability of different mobile phone designs. His findings indicate that eye tracking analysis seems to be especially useful in the evaluation of single design aspects and thus can assist a designer in exactly those design stages focusing on these aspects.

Another prominent eye tracking study comes from aviation research. Anders [11] recorded the monitoring behaviour of professional pilots under realistic flight conditions in an A330 full flight simulator. The measurements of eye movement revealed that during the flight pilots especially pay attention to the primary flight display whereas shortly before landing their attention shifts to the runway outside the airplane. Thus, attention shifts indicates a change in the way a product is applied. This concept of attention shift is most suitable to also investigate in more dynamic product applications.

III. Eye Tracking Experiments in Engineering Design Research

A. Visual Strategies of Novice and Experienced Engineering Designers

In engineering design several studies had been made to understand the differences between how novice and experienced designers approach design tasks. As a central finding Ahmed et al. [12] describe that novice designers tend to use a particular pattern of trial and error whereas experienced designers use particular design strategies. One essential part of these design strategies are visual analysing strategies.

At ETH Zurich the Product Development Group (pd|z) recently started investigating visual strategies of novice and experienced designers by eye tracking application [13].

The first study was conducted with novice and experienced mechanical engineers (n=8) to gain additional insights in their visual strategies when analysing a complex sectional drawing. The drawing selected for this eye tracking study represents an advanced gear box that is able to transform simple rotatory motion into a combined motion of forwards or backwards rotation and translation (cf. figure 1). Although the sectional drawing is accurately work out in detail it includes one essential functional design error, which the test persons of this experiment were assigned to find and mark as quick as possible.

All test persons were familiar with the single elements of a gear box as well as their corresponding 2D representation in sectional drawings. Within the experiment each test person was situated in front of the stimuli screen and used a mouse to navigate and mark elements. While searching the sectional drawing for the functional design error the eye tracking system recorded the test persons' eye movement in relation to the stimulus, i.e. in relation to the sectional drawing.

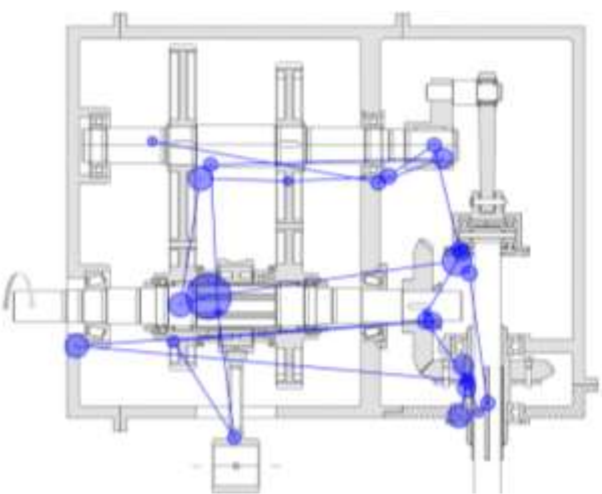

Figure 1. 2D sectional drawing of a gear box (stimulus) and gaze path of test person searching for a functional error (fixations and saccades)

Figure 1 also shows the qualitatively visualization of a test person's eye movement. The single circles represent gaze fixation. Fixations are events that happen when the eye remains still over a period of time. Fixations indicate the attention of the test person to the specific location on the stimulus. The circles' diameter represents the fixation duration and thus the intensity of attention. In addition to fixations in figure 1 also saccades are illustrated. Saccades describe the eye movement from one fixation to another. These eye movements are very fast, but also extremely accurate. During a saccade human beings are almost blind. Nevertheless saccades provide additional insights in the relations of fixations. By measuring the number and the order of saccades gaze transitions as well as whole scan paths can be recorded and analysed.

The test persons' task was to recognize that the represented gear drive is not able to work, because in operation it would immediately come to a physical collision of the upper shaft and the bearing box (right side of the drawing). This error was selected, because it causes a non-fulfilment of the overall function. In addition the identification of the errors requires an understanding of the function and the ability to imaging the sequences of operation, which are not explicitly represented in the sectional drawing.

Based on eye tracking analysis, including the evaluation of fixation locations, fixation duration and scan paths, Lohmeyer et al. [13] hypothesized the following visual strategies:

- Overview strategy: Experienced designers at first try to get an overview of the technical system, whereas novice designers tend to directly start with an detailed search without recognizing the system's overall function.
- Alignment strategy: Experienced designers align their search with the load flow. They start at the input shaft and check the design of bearings, joints and gears along the way to the output shaft, whereas the attention of novice designers often shifts causeless between different locations.
- Prioritization strategy: Experienced designers are able to prioritize their search criteria. They first check the basic functions of all subsystem, whereas novice designers tend to concentrate on one subsystem and additionally check all secondary criteria (e.g. sealing and lubrication).
- Pattern strategy: Experienced designers are using scan path pattern to check recurring parts or assembly (e.g. bearing arrangements), whereas novice designers vary in the way they analyse similar components of the system.
- Internalization strategy: Experienced designers seems to be able to imaging the dynamic behaviour of moveable parts. Thus, in contrast to novice designers they also check states of the system's operation that are not explicitly represented in the drawing.

B. *Engineers' Behavior while Analysing Technical Systems*

The analysis of eye tracking data strongly depends on the kind of stimulus observed by the test person. Basically a stimulus can either be static or dynamic. Static stimuli remain unchanged for a certain period of time. Typical examples are pictures or drawings (e.g. the sectional drawing that was used in the experiment presented above). Dynamic stimuli changes or are changed continuously. Dynamic stimuli can be further subdivided into repeatable dynamic and individual dynamic stimuli. Repeatable dynamic stimuli are always shown in the same way to all test persons (e.g. a given video) whereas individual dynamic stimuli change differently depending on the behaviour of the individual test person (e.g. the recorded scene video).

The permanent change of view makes raw data, which is related to a position on the screen, irrelevant, because the view keeps moving underneath the marked raw data points. In order to deal with this effect and to still identify fixations and attention shifts, before the start of an experiment so called areas of interest (AOIs) should be defined. These AOIs are directly connected to clearly defined areas of the stimulus. Due to this a clear assignment of fixation that is not affected by turning the stimulus becomes possibly.

The definition of AOIs is closely connected to the research question and the corresponding research design. In this context Holmqvist et al. [13] distinguish between three basic AOI events: (1) the AOI hit, i.e. there is at least one fixation inside of the AOI, (2) the AOI dwell, i.e. there are two or more sequenced fixations inside the same AOI for a certain period of time and (3) the AOI transition, i.e. there are two or more sequenced fixations across different AOIs in a certain order.

In the field of engineering design Matthiesen et al. [14] conducted an eye tracking experiment, which investigates human behaviour in the process of analysing the function of a technical system. The dynamic stimulus was a physical three-dimensional model of a clutch (cf. figure 2), which during the experiment was allowed to be touched and turned by the test persons. The AOIs of the clutch model were defined according to the red, green and grey coloured areas illustrated in figure 2.

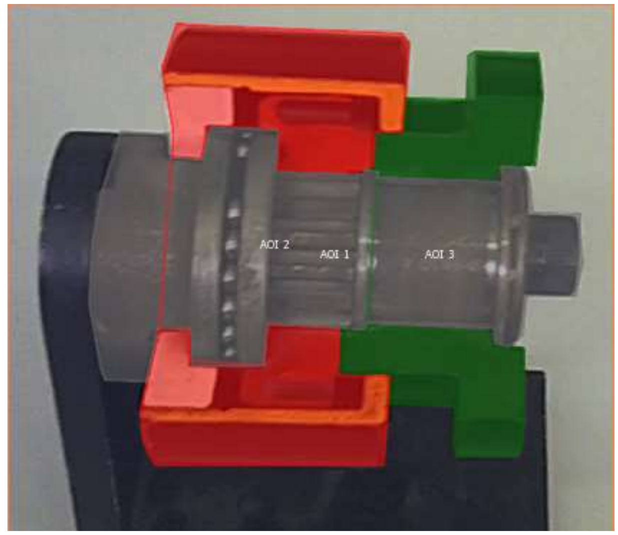

Figure 2. Physical three-dimensional model of a clutch (stimulus) and definition of three areas of interest (AOIs)

The experiment was conducted by application of binocular eye tracking glasses (i.e. a head mounted system). The test person was an engineering designer and the test time was limited to six minutes. The order of fixations were finally visualized by a sequence chart (cf. figure 3):

- The chart shows that in the first half of the experiment the test person gave its attention primary to AOI 1. This indicates that the test person assumes to extract relevant information from the clutch parts in this area to understand the system's function.
- In the second half an attention shift is recognizable. Here the test person especially focused the clutch parts within the AOI 2. In addition to this the chart shows that the gaze alternates more often between AOI 1 und AOI 2. This indicates that the test persons tries to understand the function of the interfaces, which in in this case was a shaft-hub-joint.
- AOI 3 was of less interest to the test person. This indicates an inferior role of this element in regard to function of the clutch. Nevertheless, the test person sometimes checked the interfaces to this area.

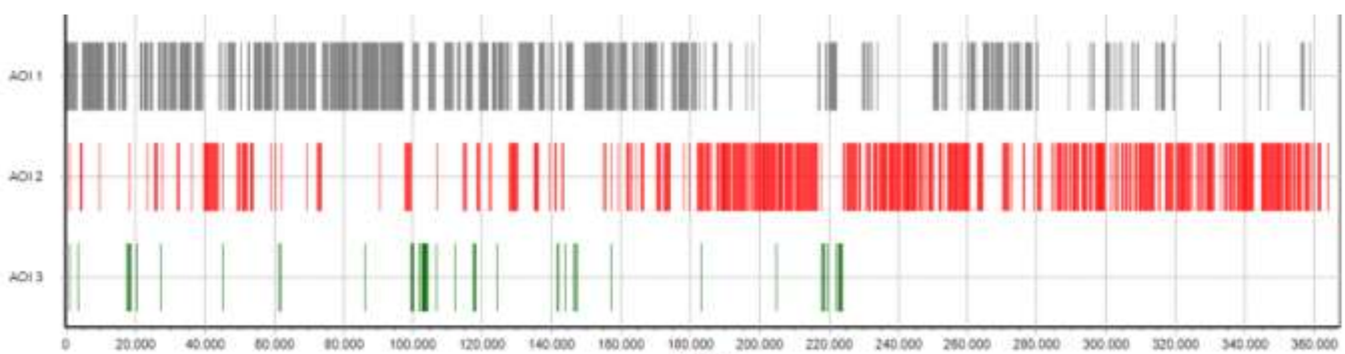

Figure 3. Sequence chart visualizing the fixations relating to the time and to the defined areas of interest (AOIs) [14]

IV. Conclusion and Outlook

Eye tracking technology became 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 grew constantly. Today, eye tracking technology is applied in many different disciplines. Neuroscience, psychology, industrial engineering and human factors, marketing/advertising and computer science are some of the largest application fields of eye tracking technologies. The results within these research fields have shown that eye tracking is a powerful tool to do research in the area of human factors and behaviour. Nevertheless up to now in engineering design research there only a small number of eye tracking studies with a small number of test persons were conducted.

This paper comes up with the basic idea to transfer successfully applied research approaches from other disciplines to engineering design. In eye tracking experiments (1) similar tasks (e.g. search for locations or search for flows) can be assigned, (2) similar segmentations of the test subjects (e.g. culture, sex or age) can be defined and (3) similar measurement readings (fixation count, fixation duration, time to first fixation) can be recorded and statistically evaluated. In order to improve the research on human behaviour in engineering design experiences from other research fields must be included. Experience exchange and mutual learning across disciplines need to be supported by interdisciplinary projects and conferences.

This paper further presents the results of two studies both showing that eye tracking is a useful method for investigating human behaviour in engineering design – especially in the context of product representations.

The first study considered the identification of visual strategies of novice and experienced engineering designers reading an 2D technical drawing. Here eye tracking analysis allowed the evaluation and comparison of the test persons' fixations and scan paths. The experiments indicate that there are considerable differences in the visual acting of the single test persons and that these differences depends on the individual level of experience. As a result five visual strategies were hypothesized. These strategies have to be further confirmed by additional experiments and probably need to be adapted or extended, before they can be trained in engineering design education.

The second study considered the behaviour of engineers while analysing a physical technical system. The experiment shows the challenges of working with dynamic stimuli. As a well-established approach to deal with these challenges the approach of areas of interest (AOIs) was presented und exemplarily applied. AOIs are relevant areas on the stimulus that are clearly defined before starting the experiment. Due to this fixations and scan paths can be referenced to the AOIs and this allows the gain of more accurate results. As a result of the experiment an AOI sequence chart was presented that provides first insight in the thinking and acting process of an engineer trying to understand the functions of a technical system.

As a next step additional research studies will be initiated according to the four following key aspects, in which eye tracking seems to be a central research method to understand the human behaviour: (1) analysing product representations, (2) analysing design engineering expertise, (3) analysing design creativity and (4) analysing product application. These results might help to improve the key issues of engineering design methodology and research: the usability and acceptance of design methodology itself.

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