An Empirical Study of Assembly Error Detection Using an Augmented Vision System

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Abstract. Within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" of RWTH Aachen University a numerical control unit and its ergonomic human-machine interface are developed for a robotized production unit. In order to cope with novel systems, the human operator will have to meet new challenges regarding the work requirements. Therefore, a first prototype of an augmented vision system to assist the human operator is developed dealing with the task of error detection and identification in an assembly object. Laboratory tests have been performed to find a preferable solution to display information.

Keywords: Augmented Reality, Assembly.

1 Introduction

Within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" of RWTH Aachen University a numerical control for a robotized production unit cell and an ergonomic human-machine interface are designed and developed.

Based on a representation of the target state (e.g. 3D-assembly object) the numerical control unit itself works out an assembly plan and performs according to it. During the execution, a critical error or mistake can occur that is only qualitatively able to be detected, meaning it is not possible to detect and identify the error. It is only possible to pass information to the skilled worker that an error has occurred. In that case (e.g. mistakes in the plan of the assembly process, mistakes in the implementation of the control programs of the elements of the production plant, unforeseen failure of a machine of the production plant), the error must be identified by the skilled worker in order to be able to correct it. A first prototype of an assistance system is developed dealing with the task of error detection in an assembly object (incorrect construction/composition of the assembly object). More precisely in this case, a prototype of an augmented vision system was developed and implemented with the focus on the presentation of the assembly information. The aim of using this system is to place the human operator in a position to detect the construction errors in a fast and adequate way. Due to this reason, laboratory tests are being performed to find a preferable

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ergonomic solution to display information. The augmented reality technology in the form of a head mounted display (HMD) has been used for the laboratory tests, so that additional synthetic assembly information or unit information can be displayed in the natural field of view of the human operator next to the real assembly object.

2 Method

Based on the common techniques for designing written assembly instructions from the domain of the technical writing [1], different modes of visual presentation were designed and developed. In general, assembly instructions are synthesized of different information objects: exploded views of parts to be assembled, textual or graphical step-by-step instructions of the assembly procedure, wiring diagrams, schematics, rules, shipment, assembly tools etc. [1], [4], [5]. Regarding the assistance system to detect assembly errors, the exploded views and graphical step-by-step instructions are considered [8]. The parts were modeled as 3D solids and were displayed in 3D stereo.

2.1 Experimental Design

The experimental design distinguishes three factors (each with two levels) representing different modes of presentation (and interaction) of synthetic assembly information, see Fig. 1: the so-called augmented vision mode (factor AVM), the a priori presentation of the goal state of the completely assembled LEGO model (factor APP), and the mode for interactively composing and decomposing the LEGO model during the error detection and identification process (factor DCM).

A full factorial design with repeated measures was used in the laboratory study and therefore eight experimental (2 x 2 x 2) conditions were distinguished.

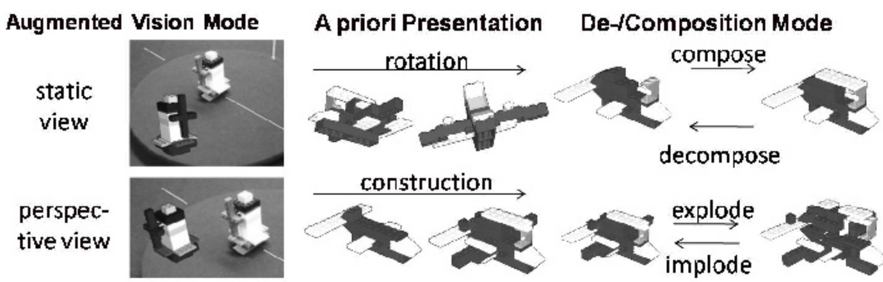

Fig. 1. Factors and factor levels in the laboratory study

Augmented Vision Mode (AVM):

1. Perspective View: The virtual LEGO model is aligned with the position and orientation of the real object in the field of view and is positioned to its left at a distance of 4 cm. A motion of the real model or a head movement leads to the redrawing of the virtual model, so that the perspectives accord.

2. Static View: In this case the virtual LEGO model is fixed to a position relative to the screen coordinates of the HMD. In the experiments the virtual object was displayed under an inclination angle of 20 degrees to its vertical axis in the third quadrant of the binocular screens.

A Priori Presentation (APP):

1. Rotation: the completely assembled virtual LEGO model rotates once on a predefined rotation axis with an inclination angle of 20 degrees and an angular velocity of 3.2 seconds for 360 degrees.
2. Construction: the virtual model is composed step-by-step by the single bricks with a cycle time of 1.2 seconds per element.

Decompostion/Composition Mode (DCM):

1. Step-by-step: the user can interactively decompose or compose the virtual LEGO model in relation to the goal state step-by-step and self-paced using two keys on a tablet.
2. Exploded view: the user is able to interactively either explode or implode the virtual model using a different key on a tablet.

2.2 Apparatus

The LEGO models with the assembly errors to be detected were placed on a small turntable (Fig. 2, left). The position and orientation of the HMD and the small turntable were tracked by the infrared real time tracking system smARTtrack of A.R.T. GmbH. A binocular optical see-through Head Mounted Display (nVisorST by NVIS Inc.) was used to display the synthetic assembly information.

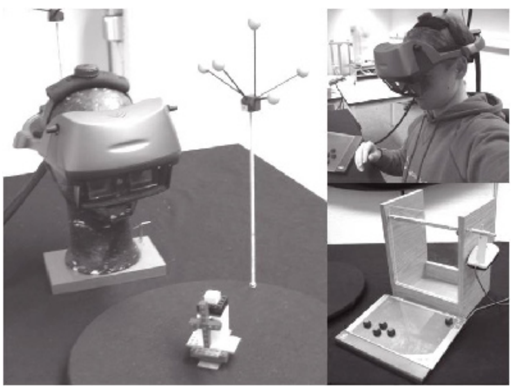

Fig. 2. Main components of the Augmented Vision System

A color marker pen was used by the subjects to mark the assembly error directly by hand on the corresponding LEGO brick. The pen was located behind a transparent lid (Fig. 2, top right). When grasping the pen behind the lid, a microswitch connected to the lid registered the point in time of error detection. The keys for manipulating the virtual LEGO models were mounted on a magnetic key tablet (Fig. 2, top right).

2.3 Procedure

The procedure was divided into two major phases:

1. **Pretests and training under experimental conditions:** First, the personal data were collected, e.g. age, profession, experiences with computers, experiences with virtual and augmented reality systems as well as assembly skills concerning LEGO models. Furthermore, a visual acuity test, a stereo vision test and a color test according to Ishiara are processed by means of a vision test device (Rodatest 302 by Vistec Vision Technologies). Third, the “dice test” of IST 2000-R (module: figural intelligence) [7] was carried out in order to quantify the imagination of spatial visualization. After completing the pretests, the subjects have some minutes to get familiar with the system.
2. **Data acquisition:** Each subject conducted eight trials. The procedure was as follows: Start of trial by the a priori presentation of the goal state of the LEGO model. The virtual assembly sequence was presented to the subjects without having the real object in their field of view. After the a priori presentation of the goal state, the real model with the assembly error was presented on the small turntable by the experimenter. It was possible to manipulate the corresponding virtual object with the keys on the tablet either by stepwise decomposing/composing it or by exploding/imploding it (factor DCM). The subjects could replay the a priori sequence at its full length in between without the possibility to abort the sequence or to further manipulate it. After the detection of the error, the erroneous brick had to be marked with the color marker pen and the difference had to be written down on an error identification sheet. It was possible that the subject could not find any difference between the real and the virtual LEGO model. In this case, it had to be indicated in the error identification sheet as well. Finally, in the post test the participant had to take the HMD off and had to fill in the cited questionnaire about visual fatigue. The total time-on-task was approximately two hours for each participant. The subjects were balanced in the experimental conditions.

2.4 Dependant Variables

The following four dependent variables were considered:

- Detection time: The detection time represents the time elapsed from the trial start until either an assembly error is detected and identified by the participant or the participant indicates the absence of an assembly error. The start and finish events were measured by the introduced apparatus. The detection time was limited to a maximum of 15 minutes.
- Quality of error detection in terms of frequency that the participant detected and identified the error correctly by marking the correct brick in the real model, frequency that the participant detected and identified the error incorrectly by marking an incorrect brick in the real model and frequency that the participant did not detect the error.

2.5 Subjects

A total of 24 subjects, 16 male and 8 female, participated in the laboratory study. All of them satisfied the requirements concerning stereo vision, color vision and emmetropia. Moreover, the imagination of spatial visualization was measured by the means of a "dice test" of IST 2000-R (module: figural intelligence) [7]. On average, the subjects allocated 13 of 20 dices correctly.

The age of the subjects was between 19 and 36 years (mean 26.8 years, SD 4.4). 37.5% of the subjects had prior experience with 3D computer games. The average weekly play time was approx. 4 hours. The average experience in assembling LEGO models was 3 (SD 1.4) on a scale ranging from 0 (low) to 5 (high). Eight persons stated problems in the past after working with electronic information displays.

2.6 Hypotheses

The following null hypotheses were formulated:

- Detection Time: The augmented vision mode (H_{01}), the a priori presentation of synthetic assembly information (H_{02}) and the decomposition/composition mode of the virtual model (H_{03}) do not significantly influence the detection time.
- Frequency of error detection: The augmented vision mode (H_{04}), the a priori presentation of synthetic assembly information (H_{05}) and the decomposition/composition mode of the virtual model (H_{06}) do not significantly influence the frequency of correctly detected and identified errors.

2.7 Correlation

The detection time is not correlated with the imagination of spatial visualization (H_{07}), and the LEGO-assembly experience (H_{08}).

The frequency of error detection is not correlated with the imagination of spatial visualization (H_{09}), and the LEGO-assembly experience (H_{10}).

A three-way analysis of variance (ANOVA) with repeated measures was calculated to test the hypotheses H_{01} - H_{03} (significance level α=0.05). The means and the 95% confidence intervals of the detection times under the different experimental conditions are shown in Fig. 3.

In order to investigate the correlation, tests according to Pearson (H_{07}) and Spearman-Rho (H_{08} - H_{10}) were calculated to test the hypotheses (significance level α=0.05).

3 Results

3.1 Detection Time

The augmented vision mode (AVM) significantly influenced the detection time ($F(1,22)=8.088$, $p=0.009$), so that null hypothesis H_{01} was rejected. On the other hand, neither the a priori presentation of synthetic assembly information (factor APP) nor

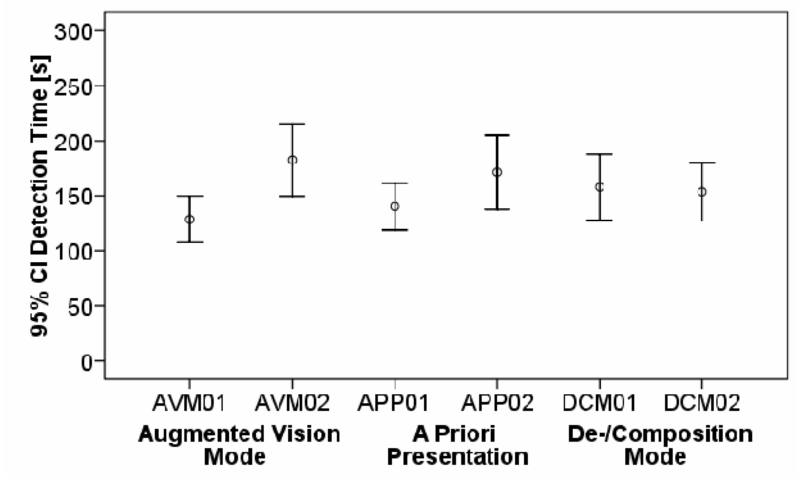

Fig. 3. Detection times [s] under the experimental conditions

the de-/composition mode (factor DCM) had significant effects on the detection time and the null hypotheses H_{02} and H_{03} were not rejected. According to Fig. 3 the average detection time under the static view condition of the augmented vision mode was on average 42.5% longer than under the perspective view condition.

Using the static view mode (instead of the perspective view mode), the users frequently had to process a mental rotation of the virtual LEGO model under consideration during the error search, which is a straining and time consuming operation. Since the classic works of SHEPARD & METZLER (1971) [10] it is known that the reaction time of a subject to decide if two items match or not is proportional to the rotation angle between them and our data confirms these findings. The reaction time also increased with the complexity level of the presented object [3]. The perspective view mode allowed a recognition-primed comparison between the goal and the given assembly state without the need to allocate significant cognitive resources for mental rotations or translations.

3.2 Frequency of Error Detection

According to Fig. 4, when comparing both augmented vision modes, the perspective view mode lead on average to a 19% higher frequency of correctly detected and identified errors than the static view mode. A rotating LEGO model for the a priori presentation of the product structure enabled the users to detect and identify 16% more errors correctly than under the alternative step-by-step construction. The frequency difference between step-by-step decomposition/composition and the exploded view was considerably smaller with 6% for correctly detected and identified errors. However, these frequency differences are not significant and therefore the null hypotheses H_{04}, H_{05} and H_{06} could not be rejected.

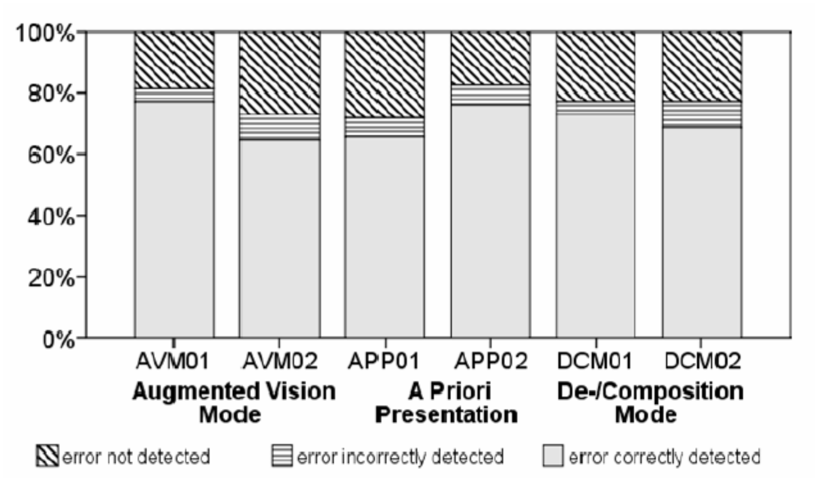

Fig. 4. Frequency of Error

3.3 Correlations

According to Fig. 5, on average, the subjects allocated 13 of 20 dices correctly (65%) regarding the imagination of spatial visualization. The average experience in assembling LEGO models was 3 (SD 1.4) on a scale ranging from 0 (low) to 5 (high).

The correlation between the experience in LEGO-assembly and error detection time (p=0.000) is significant. Hence, the null hypothesis H_{08} was rejected. The null hypotheses H_{07}, H_{09} and H_{10} were not rejected.

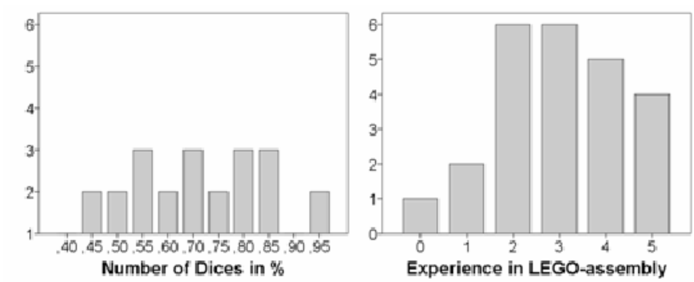

Fig. 5. Frequency of Number of Dices and Experience in LEGO-assembly

In Fig. 6 and Table 1, the weak negative correlation of the experience in LEGO-Assembly and error detection time (correlation coefficient = -0.261) is shown. The laboratory test confirms that a higher experience level leads to a lower detection time. Comparing the detection time of a subject with low experience and subjects with high experience, an average reduction of the detection time of 37.4% can be determined.

Table 1. Correlation Table

		Frequency of Error Detection	Error Detection Time
Experience in LEGO-Assembly	Correlation coefficient	0,014	-0,261*
	Significance level (2-sided)	0,851	0,000
Imagination of spatial visualization	Correlation coefficient	0.049	0.085
	Significance level (2-sided)	0.499	0.240

*) p<0.05 significant.

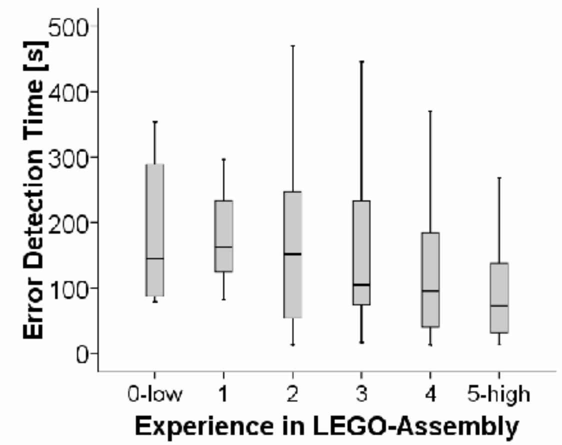

Fig. 6. Correlation between the error detection time and the experience in LEGO-assembly

Because of the fact, that the imagination of spatial visualization has no significant influence on the error detection and the error detection time, the assumption of a homogeny subject group can be confirmed. The differences in the detection time and in the frequency of error detection are due to the influence of the pre-knowledge of the subjects in the area of LEGO-assembly and to the influence of the investigated factors and factor levels (AVM, APP, DCM).

4 Future Work

Within this laboratory study of an augmented vision system, it was shown; that the influence of the augmented vision mode and the pre-knowledge in the area of the LEGO-assembly have significant influences on the error detection time.

Concerning future ergonomic studies of Augmented Vision Systems for self-optimizing assembly cells it is of special interest to analyze more complex work processes going beyond the admittedly simple assembly of LEGO bricks. Therefore, several products of medium complexity, e.g. a motorcycle carburetor, were already analyzed and it is planned to carry out similar laboratory study including also the robot motion. Due to the significant ageing of skilled operators in European manufacturing enterprises it is also of great interest to study age-related effects of visual perception and spatial visual memory when working with Augmented Vision Systems and to adapt the visualization and interaction modes to individual performance and workload.

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