Comparing Three Task Guidance Interfaces for Wire Harness Assembly

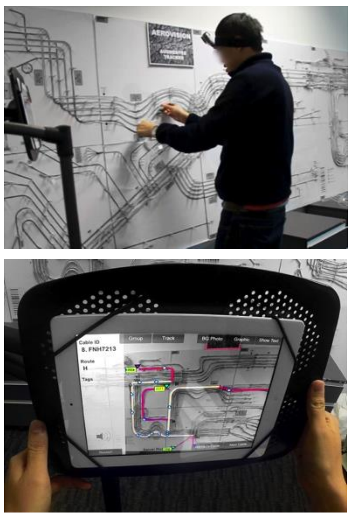

Figure 1: The wire routing setup and visual display.

In this paper, images of the formboards have been converted to black and white dues to commercial restrictions.

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Abstract

In this paper, we describe a user study that compared the design of three visual interfaces (i.e. *Text*, *AR* and a *2D Schematic* view) to support the wire harness assembly of electrical wires in modern aircraft. Displayed on a portable iPad, 18 participants were instructed to route three sets of wires on a commercial aerospace formboard. Through video analysis, the results identified significant differences in the mapping time, and number of visual references made in viewing information on the three interfaces. In particular, a lack of graphical information in the *Text*, and camera alignment issues in the *AR* conditions demonstrated noticeable limitations in interaction. We briefly discuss these findings.

Author Keywords

Augmented reality; wire assembly; aircraft; user study; visual interface.

ACM Classification Keywords

H.5 Information Interfaces and Presentation (e.g., HCI): H.5.1 Multimedia Information Systems.

Introduction

Modern aircraft contain complex electrical wiring systems, which can consist of hundreds of kilometers of wires [8]. In operational facilities, custom-made

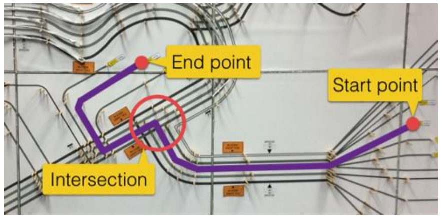

Figure 2: Example of a formboard. Operators route from a start to end point/s, sequencing information at intersections.

Task level	Start/ end points	No. of inter-sections	Approx wire length
Easy	1, 1	1	230 cm
Medium	2, 1	3	330 cm
Difficult	4, 1	4	530 cm

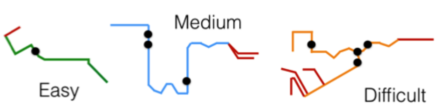

Table 1: Wire routing tasks. Tasks levels incrementally increased in the number of start points, intersection crossings and wire length per level.

boards, called *formboards* are used to assemble complex wire structures. This can be labor intensive, with high financial costs if unidentified human errors occur before wire structures are installed into the aircraft. Moreover, few known digital technologies are available to support the formboard routing process, as tasks rely heavily on the skill and acquired knowledge of the operator. This indicates new opportunities for investigating technical solutions in this domain area.

Related work

Dating back over 15 years, the work of Siewiorek et al. [7] explored speech interaction to support the external inspection of aircraft, while Ockerman and Pritchett [5] evaluated variations in an electronic checklist using a head-mounted display for pre-flight inspection. In both cases, while improvements were identified in using the technology, interaction issues were reported in terms of inaccurate speech recognition [7], and problems with the visual display impeding the inspection process [5].

More recently, growing commercial interest has been raised in the use of wearables to support the design, maintenance and repair of modern aircraft [e.g. 2]. This includes creative solutions that aim to transform manufacturing processes in the aerospace industry [1].

In the context of wire harness assembly, the inventive work of Mizell [4] explored the use of head-mounted displays to augment the assembly of wire bundles for factory operators. However, despite its novelty, the technical implementation from a pilot project was reportedly impeded by limitations in user interface design, and low user acceptance of wearing head-mounted displays on the factory floor.

Alternatively, Lewerenz and Willers [3] have investigated the use of a large projection-based jigboard display for wire assembly. However, while an interesting concept, to our knowledge there is a lack of publically available literature evaluating the effectiveness of this approach.

In comparison to these works, in this paper we were motivated to explore a low-cost solution that could be easily implemented in a shop floor environment. The design of the study is based on regular meetings between the aircraft manufacturer and research team as part of a two year project. The main contribution of this paper is to report on the evaluation of three user interfaces with 18 participants, in which we compare their efficacy in completing a small set of wire routing tasks.

The formboard process

In a commercial context, *formboards* are used to assemble complex wire structures for wire harness builds. This can consist of hundreds of individual wires that are grouped together into specific wire bundles. Factory operators identify these bundles by referring to wire tags, and a wire list document. The formboards are then visually used to identify their assembly points, the way code route they directionally follow, where they branch out, and are finally terminated for plug and connector fittings (see Figure 2). At intersections, routed wires are expected to follow a specific sequence by going under or over previously assembled wires. Once complete, these wire bundles are removed and installed onto the designated aircraft. The structural variation of aircraft models and their parts mean that formboards are custom-made in their design.

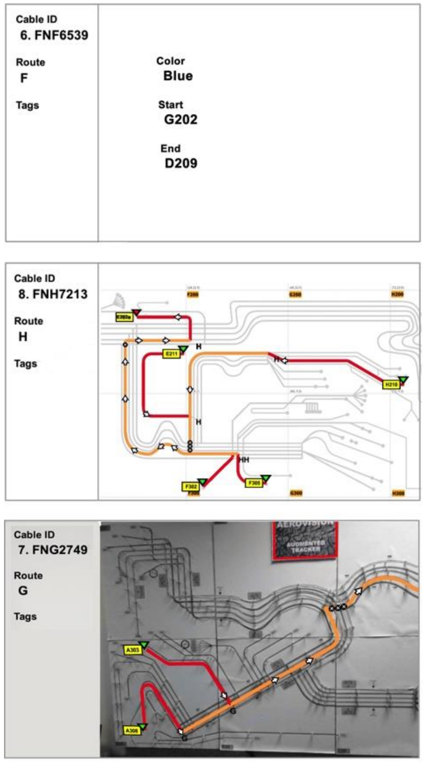

Figure 3: The user interfaces.*Top* Text, *middle* Schematic, and *bottom* AR interface.

User Study

Using a between-subjects design, three user interfaces were developed to compare the visual display of wire route information. Specifically, we wanted to understand how variations in the visual representation of information might affect task performance and user interaction.

User interfaces

The visual interfaces were designed to reduce the uncertainty in route planning (see Figure 3). In the graphical versions, this was accomplished by sequentially displaying wire routes in a similar order to a wire list. Visual features in the display included highlighting wire intersections and directional turns. The visual color and ratio of the wire routes were designed to correspond to those on the formboard. As part of our system design, a software module was developed to extract the route information from a 2D formboard drawing, while a rendering module was used to display the routes in the user interface.

Our early pilot testing found a number of interaction issues using commercial AR glasses, including poor visibility and physical discomfort [6]. In a wire harness setting, these are issues that can be further challenged by the need to wear safety glasses for eye protection. Subsequently, in this study we focused on using a portable tablet to display the user interfaces.

The prototype user interfaces were developed on the Unity 3D platform, with Vuforia extension for augmented reality support. For each interface, visual information consisted of *start* and *end points*, *route color* and a *route ID*, while on-screen buttons allowed the users to toggle between route sequences. Specifically, the three interfaces consisted of:

- *Text*: routing information was represented in a text list with no graphical features. This became the baseline condition.
- *Schematic*: information was represented in a 2D graphical format, with a background display of the wire routes replicating the appearance of the formboard drawing. Users were able to pan and resize the routing information.
- *AR (Augmented Reality)*: Using an inbuilt iPad camera, augmented information was front-projected over a live view of the formboard. AR markers were placed at two meter intervals at the top of the formboard for calibration. The graphical features were identical to the Schematic view.

Participants and equipment

In total, we recruited 18 participants (ranging from 21 to 39 years old) from the research institute. None of the participants had known color vision deficiencies, or previous experience with wire routing assembly. Participants were randomly assigned to one of three interface conditions (each n = 6).

For equipment, the wire routing tasks were completed on a 4.8 x 1.2 meters aerospace formboard. To support hands-free interaction, an adjustable tablet stand was used to position the iPad, while a GoPro HD camera was mounted to the head of each participant to get a first-person perspective of the routing tasks (see Figure 1). A second back-up video camera was positioned at the side of the formboard.

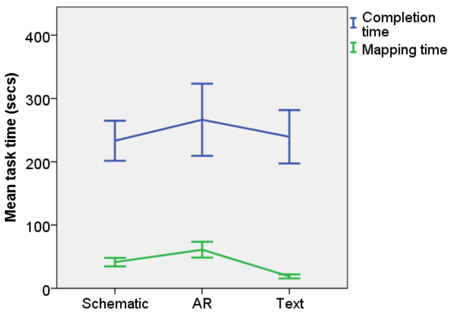

Figure 4: Mean task completion and mapping times for interfaces (95% CI).

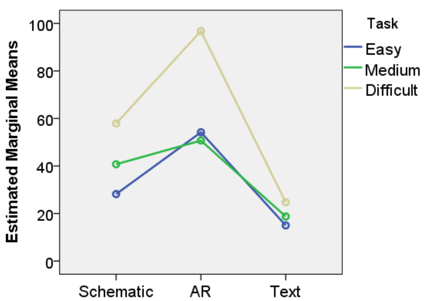

Figure 5: Mapping times for interfaces per task level (secs).

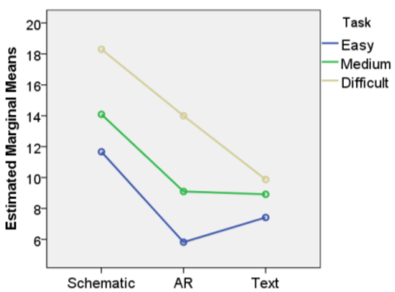

Figure 6: Number of visual references to interfaces per task level.

Procedure and data analysis

Each session lasted approximately 45-60 minutes and involved a single participant. Participants were first briefed on the interface features using a small set of PowerPoint slides. They were then required to route 3 separate wires on the formboard as part of a practice task. Once completed, for the experiment, each participant routed 6 wire tasks, across three task levels (see Table 1 for more details). Finally, a 10-15 minute interview was conducted to gather subjective feedback.

For data analysis, two independent coders reviewed the video recordings. This consisted of the following measurements:

- *Completion time*: the time required to complete each wire routing task.
- *Mapping time*: the time spent viewing the user interface for each wire routing task.
- *Visual reference*: the number of instances the user interface was referred to for each task.
- *Errors*: the type and number of ‘uncorrected’ errors made for each wire routing task.

Across the 18 participants, we collected data on 108 separate tasks, from which 17 were removed from the analysis due to either task incompletion or some intervention from the facilitator. For statistical analysis, a series of ANOVA’s compared the observational data, with post-hoc comparisons using a Bonferroni correction. A log transformation was performed on positively skewed data. Given the brevity of the paper, we focus on reporting the observational results.

Results

Completion and mapping times

On average, wire routing with the *AR* was 33 seconds, and *Text,* 6 seconds slower per task compared to the *Schematic* interface. Despite this, there was no significant difference in the **completion times** between the three conditions, $F(2, 88) = .56$, $p > .05$ (Figure 4).

In contrast, a significant difference was identified in the **mapping time** between the three interfaces, $F(2, 88) = 29.95$, $p < .001$, as post-hoc comparisons identified that participants took significantly longer to view information in the *AR*, compared to the other two conditions (p’s $< .01$).

Furthermore, with regards to mapping times, we identified a significant interaction between the interface type and task complexity, $F(4, 82) = 3.24$, $p < .05$. In particular, it was noted that the time spent viewing the *Text* interface did not greatly vary between the task levels, suggesting that task complexity only marginally altered participants viewing behavior (see Figure 5).

Visual references

The number of **visual references** to the interfaces was significantly different across conditions, $F(2, 88) = 8.33$, $p < .001$. Post-hoc comparisons identified a significantly higher number of visual references in the *Schematic* compared to the *AR* and *Text conditions* (p’s $< .01$). Moreover, although no interaction was identified between the interface type and task complexity, a noticeable trend was found with participants more likely to view the *Schematic* and *AR* interfaces the more difficult the task (see Figure 6).

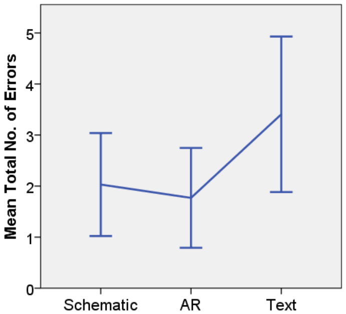

Figure 7: Mean number of combined errors per task (95% CI).

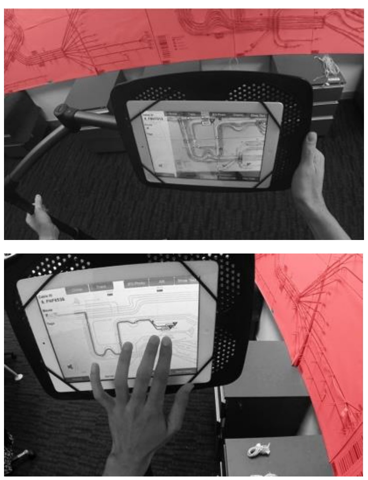

Figure 8: *Top*, illustration of the AR interface, *bottom*, the schematic interface. Variations in the distance of the displays to the formboards can be seen highlighted in red.

On the other hand, comparing the number of visual references with the previously reported mapping times, the results indicate that while participants looked at information in the *AR* interface for longer, they were less likely to repeatedly revert back to the display compare to the *Schematic* view.

Uncorrected errors
Routing errors consisted of three types: 1) failing to place a wire on a supporting board peg; 2) wiring on a wrong route; and 3) wiring in the wrong order at an intersection (i.e. routing over instead of under another wire bundle). Overall, no significant differences were identified between the types of errors made. Despite this, the average number of combined errors was noticeably higher in the *Text* compared to the *AR* and *Schematic* interfaces (see Figure 7).

Discussion

Our results demonstrate noticeable differences in the effectiveness of the user interfaces. For the *Text* condition, the lack of graphical cues, or what was commonly described as a 'color-coded map' meant participants were more reliant on using the formboard diagram. This can help explain why the number of visual references to the iPad interface remained consistently low between the different task levels.

Alternatively, the lack of a wide-angle lens on the iPad meant the device was often positioned further away from the formboard to get a global view of an augmented route in the *AR* condition. This often required individuals to step back from the formboard, disrupting and adding time to complete the physical tasks. On the other hand, the *Schematic* interface was commonly positioned to the side of the user, making it easier to quickly glance at, move, and track a route while physically wiring (see Figure 8). We believe these differences can help explain variations in the mapping times, and the number of visual references made between the two conditions.

For all the interfaces, the use of the route color and their directional shape on the formboard acted as useful landmarks. However, the reliance on this information posed problems when occluded by other pre-assembled wires. In particular, given the position of the iPad display to the formboard in the *AR* condition, participants reported that they were more likely to attempt to memorize information (by looking longer) until they reached a more complex stage of the wire routing task: *"I would try and remember as much of the route as I could, I go there, and then once I realize I have forgotten I just go back"*. This process was seen to be counterproductive and time consuming.

As such, a key challenge in designing augmented interfaces for wire assembly is the ability to accommodate for changing focal distances, and the different levels of visual inspection needed to examine on-board wiring. This raises further questions over the feasibility of exploring alternative mobile projection solutions – including their ability to be able to operate within a complex tooling environment.

In terms of the visual display, similar to our previous work [6], recommendations in the AR interface included considering approaches that enable the visibility of long route sequences at close proximity to the formboard. User suggestions included using a separate camera, or some means of 'freezing' the augmented image. Alternatively, for the 2D schematic view, to provide the means to alternate the viewing perspective (e.g. pseudo-3D) to identify the layer sequence of wires, such as at an intersection requiring a specific assembly order.

In addition, visual guidance appears most useful in aiding actions that require more cognitive processing, such as viewing beneath occluded wires, or assessing which start point provides the easiest routing approach. This raises further user-centered questions in how to optimize visual information based on the ability to track an operator's orientation, gaze or behavioral patterns over a given set of tasks.

CONCLUSION

This study presents an evaluation of three user interfaces for wire harness assembly in the aerospace industry. Overall, a lack of graphical information in the *Text*, and positional issues in the *AR* interface posed some guidance difficulties. These were more evident the more difficult the task. In contrast, the 2D *Schematic* view had the flexibility to enable users to quickly view information, while reducing the need to mentally visualize the wire routes. In this sense, the *Schematic* interface can be seen to be closest to a 'visual companion' in this study.

Importantly, the results demonstrate the value of using graphical representation over text-only information for wire assembly guidance, while we recognize the *AR* display could be greatly improved with better image alignment to the formboard. For next steps, we aim to validate the *AR* and *Schematic* interfaces in a wire harness factory setting with expert users. This will allow us to compare our results, and scale up the level of task complexity observed.

Acknowledgements

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