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SDViz: A Context-Preserving Interactive Visualization System for Technical Diagrams

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Abstract

When performing daily maintenance and repair tasks, technicians require access to a variety of technical diagrams. As technicians trace components and diagrams from page-to-page, within and across manuals, the contextual information of the components they are analyzing can easily be lost. To overcome these issues, we have developed a Schematic Diagram Visualization System (SDViz) designed for maintaining and highlighting contextual information in technical documents, such as schematic and wiring diagrams. Our system incorporates various features to aid in the navigation and diagnosis of faults, as well as maintaining contextual information when tracing components/connections through multiple diagrams. System features include highlighting relationships between components and connectors, diagram annotation tools, the animation of flow through the system, a novel contextual blending method, and a variety of traditional focus+context visualization techniques. We have evaluated the usefulness of our system through a qualitative user study in which subjects utilized our system in diagnosing faults during a standard aircraft maintenance exercise.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques I.3.8 [Computer Graphics]: Applications—

1. Introduction

In electronic/mechanical maintenance and repair tasks, 2D technical documents, such as schematic and wiring diagrams, are used by technicians to guide their work. Typical tasks include component finding and circuit tracing in which technicians hypothesize and test what components along a circuit path are working. To facilitate these tasks, maintenance workers often print a variety of documents to annotate and highlight as they perform their analysis. Many of these documents contain multi-page spreads of complex wiring diagrams. Technicians will often need to find a component in a schematic diagram, search through the manual for the related wiring diagram, and then trace paths through the wiring diagram, while maintaining contextual information about where these wires and components may be in relation to the schematic diagram. As such, tracing paths from page-to-page and in-and-out of components can be tedious. Furthermore, the amount of documents needed can be cumbersome, and maintaining contextual information when switching between related diagrams is difficult. Meanwhile, over the last decade, as technical documents have grown in size, manufacturers have begun transferring them from the printed pages to electronic files. Unfortunately, given that many of these manuals consisted of multi-page fold-out diagrams, scrolling through pdfs and trying to maintain context amongst various components is not a viable option.

In light of these issues and after performing cognitive task analysis on a typical maintenance task, we have developed a novel visualization system to aid technicians in their analysis of schematic and wiring diagrams for maintenance tasks. Our system provides the following capabilities:

- **Context preservation**: preserving highlighting, working status, switch status, and spatial information

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- **Single diagram navigation**: jumping to a connected neighbor component, finding circuit breakers, overviewing a diagram
- **Inter-diagram navigation**: moving to the related diagram, transition by blending
- **Highlighting**: highlighting components and connections, marking working status of components, changing switch status
- **Distortion viewing**: magic lens, fisheye lens, relational lens
- **Animation**: flow animation
- **Searching**: keyword searching, tree-viewing file explorer
- **Zooming**: zoom in and out, marquee zoom

In the following section, we describe our system design and categorize the design principles.

2. System Design

Recent work by Barnard et al. [BRM06, BR06] noted that individuals use technical documents differently and develop their own mental models while interacting with systems. This work noted the need for task-oriented and user-adapted electronic technical documentation. Further, work by Heiser [HTAH03, HPA*04] detailed procedures on finding and instantiating design principles through cognitive experiments. Based on ideas from these works, we have designed the SDViz system by consulting with aviation repair technicians in order to develop an appropriate knowledge base of what user needs should be met. A routine tabletop maintenance exercise, used for training, was performed by three technicians of varying skill levels. A task analysis of the technicians' tasks was performed, and our system design was based on these results.

Our system could be further enhanced through the application of graph-based visualization tools (e.g., Tulip [Aub03]). A graph based framework for our system would provide various manipulation tools based on the graph properties. However, unlike other information, there exist specific notations for schematic and wiring diagram drawings. Furthermore, the details of components and connections between the components are often not consistent in technical diagrams. Thus, it is difficult to apply graph visualization techniques to schematic and wiring diagrams. Moreover, all the information for system maintenance is *system-oriented* and uses a hierarchical structure (e.g., system, subsystem, and component) to organize various documents in relation to each other. Technicians can search related diagrams using the hierarchy of the component or document identifications in the diagrams. As such, our work focuses on using this hierarchical structure. We provide the user with appropriate information, maintaining the layout and style of schematics and the conventions in these diagrams. We have chosen not to apply graph or network visualization techniques as many technicians are not familiar with them. However, such techniques are valuable and could be applied in future systems. For example, Van Ham [vH03] and Abello et al. [AvH04] described visualization techniques using matrix representations providing multi-level zooming to efficiently abstract information. Unfortunately, such matrix representation fails to provide appropriate views for some tasks like diagram visualization for actual maintenance.

Other considerations in system design include the fact that our system deals with legacy data (e.g., pdf, CGM (Computer Graphics Metafile) format diagrams, and paper manuals), and generating the appropriate data from these various legacy data is also an important issue. This issue again leads us to choose a hierarchical tree structure (as opposed to other graph or network visualization schemes) based on SVG and XML specifications in order to store, as well as represent technical diagrams. This also allows our system to maintain the layout and style of diagrams without abstraction or rearrangement of components and links, and at the same time, we can take various manipulations based on the tree structure. Unfortunately, the data provided in the legacy formats do not yield themselves to effective automatic analysis (they are lacking needed information). Moreover, we cannot assume that a user would have all the necessary input to enable effective analysis across the large set of schematics and wiring diagrams available. Instead, our system enables users to effectively analyze circuits in diagrams visualized and highlight important components, focusing on their maintenance task at hand. Therefore, we focus only on the practical system design and integration as well as a system evaluation within the context of a realistic maintenance task.

2.1. Tabletop Exercise

The tabletop scenario consisted of a two fault error analysis design in which a lefthand side window heating unit in a Boeing 737 is found to be inoperable. The two faults included a short in the wiring leading from the power supply to the window heater, and a bent pin in the P5-9 component. During the tabletop exercise, the technicians diagnosed the issues using printed manuals. When measurements were needed (for example when a technician wanted to know if component x had power) the exercise leader would provide that information as they proceeded through their steps. As the technicians performed, they spoke outloud, detailing their actions. Notes were taken about the technicians' actions. Three technicians participated in this stage of knowledge gathering.

We noted that there were underlying actions taken by all technicians. First, the technicians searched the maintenance manual (MM) and schematic diagram manual (SDM) for keywords relating to the components under question. Second, the technicians utilized the wiring diagram manual (WDM) indexed from the keywords found in the MM and SDM. In the WDM, technicians traced the path from the window unit to the power source to determine what components may be contributing to the fault. While searching and identifying system components, subjects systematically checked the wiring continuity beginning with the circuit breaker, wire run, panel switch, and window connections, spending most of their time using the SDM.

2.2. Design Principles

From the task analysis, we derived the system needs as follows:

- Providing seamless visualization compared to legacy data
- Allowing users to find what they want in multi-diagrams
- Allowing users to highlight components and links
- Following the flow of electricity from source to sink components
- Preserving component context between diagrams
- Enabling users to easily move back and forth among related diagrams

The most important observation from the task analysis was that preserving context among related diagrams can enormously help technicians find desired information providing a starting point when they refer to related diagrams. Hence, we focus on preserving component context (e.g., highlighting, working status, switch status, and spatial information) in the visualization system for technical documents, particularly, technical diagrams.

3. SDViz: A Schematic Diagram Visualization System

Based on the design principles developed in our knowledge acquisition phase, we have developed a Schematic Diagram Visualization System (SDViz) to aid technicians in the navigation/diagnosis of faults and the traversal of multiple linked diagrams. Unlike general document visualization, we have chosen not to map the technical documents into multivariate space as such views are not familiar to technicians. Instead, our system provides a seamless transition from paper manuals to the visualization realm by adding tools and features that are intuitive to technicians and designed based on observations of technicians' work. System features include highlighting relationships between components/connectors and components/components, maintaining context between several related diagrams, animation of electrical flow through the system, component/sub-component annotation (marking a component working/not-working), and improving navigation and linking of diagrams through advanced blending and other novel visualization techniques.

In comparison to related work, Li et al. [LAS04] proposed an interactive image-based exploded view diagrams using 2D images. Further, Boose et al. [BSB03] migrated 2D illustrated part drawings to Class IV Interactive Electronic Technical Manual (IETM). In both work, technical diagram visualization reuses the legacy documents in a raster format without recreating diagram data. By contrast, Setlur and Chen [SC05] and Fredj et al. [FD06] used the 2D vector format in their technical document visualization systems. More recently, the PDF Schematic Tracing [PST] system was developed as commercial plug-in software allowing users to trace the connections in schematic diagrams in PDF format by highlighting the path components, and by providing hyperlinks between components and their descriptions. The PDF Schematic Tracing has the most similar purpose to our system in terms that it was developed to help maintenance personnel to look through many diagram manuals, and it provides navigation in technical diagrams without any modification of the layout and style of diagrams.

In our system, we use two data for each diagram; SVG data converted from a legacy diagram, and the eXtensible Markup Language (XML) [Ext] data containing semantic information within the diagram. Hence, our system is intended to reuse legacy data (e.g., pdf, CGM, and paper diagram scanned as a bitmap) as well as to take advantage of 2D vector graphics by using SVG format. As such, our system builds on previous work, creating new techniques and providing a quantitative analysis of these techniques for technical document visualization. The following subsections will describe the data representation for context preserving information systems and key features of our system.

3.1. Data Generation

To relate documents from different sources, a structured data representation is required. Moreover, context preservation during document navigation and investigation requires semantic information to identify the focus component, the contextual components, and the connections. Setlur and Chen [SC05] identified, categorized and stored the characteristics of each object in the XML based data files in order to enhance key objects by maintaining the objects' size while zooming out. A higher level graphical structure semantic markup language (GraSSML) has been proposed to store the structure and semantics of diagrams [FD06].

All diagrams used in our system follow specifications such as IETM, SVG and SGML/XML, which enable the effective querying and displaying of diagrams along with providing resolution-independent visualization. Each diagram is converted to SVG format for graphics information, and then XML file is generated by our semantic editor, which is a very simple tool developed as a part of our entire system to authorize semantic information of a given technical diagram. This data generation step introduces the hierarchical structure and semantics of components and connectors in a diagram, and allows us to take advantage of searching information based on XML-tagged Document Instances (DI), which forms the basis for our context-preservation work.

3.2. Preserving Contextual Information

While troubleshooting, technicians need to use multiple diagrams, requiring a contextual shift as they move from high-level schematic diagrams to low-level wiring diagrams. For

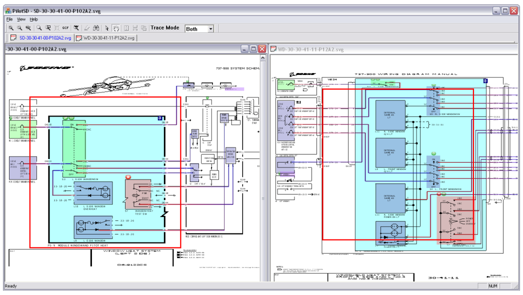


Figure 1: *Contextual information preserved between a schematic (left) and the related wiring (right) diagrams in our system.*

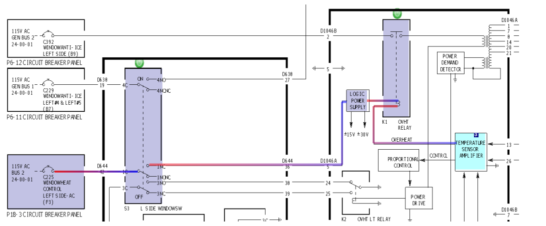


Figure 2: *Finding circuit breakers (leftmost highlighted component) connected to the focused component (rightmost highlighted component).*

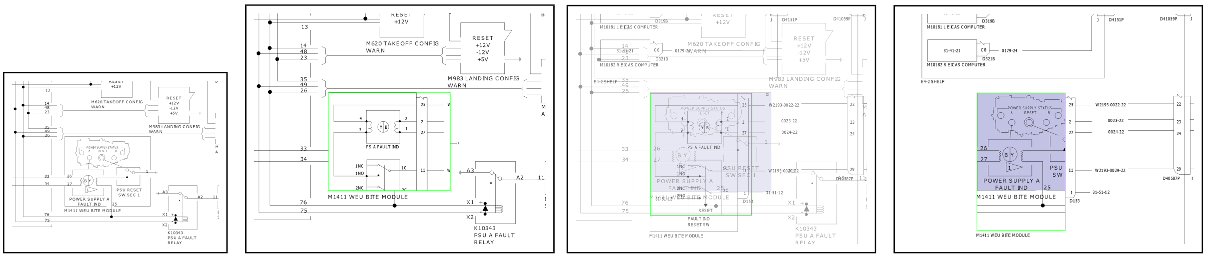
instance, any component in a schematic diagram may be the cause of a system fault. A technician would begin their analysis by finding their component of interest and then loading up a wiring diagram. Our system provides technicians with tools that help maintain context when shifting between documents by maintaining spatial coherency between components, component annotation, and highlighting information during a document shift. In the example of changing from the high-level schematic diagram to the detailed schematic diagram, preserving the contextual information of the component such as highlighting information, working status, etc., provides users with a seamless transition. Moreover, our system introduces a feature in which spatial information is maintained by blending the two documents gradually. By blending, we are able to more effectively allow users to perceive the related information between documents in comparison to switching back and forth between pages (although that option exists as well in our system). Figure 1 shows how contextual information is preserved between two related diagrams distorted with the rectangular fisheye lens. In Figure 1, the user's interactions (component's working status and a user-selected focus component) with the schematic diagram are preserved and visible in the related wiring diagram maintaining contextual information.

3.3. Navigation

Single diagram navigation For navigating within a given diagram, we consider common methods used in maintenance and repair using technical diagrams. Since most components are connected to other components through wire connections, we provide the capability to center any of the connected components by selecting the component's name from a popup menu. In many maintenance tasks dealing with large diagrams, this jumping by selecting a component name can be useful to navigate within a diagram without tracing wire connections. Additionally, the quick identification of special components, such as circuit breakers, can be essential in helping technicians find the fault while navigating in a diagram. Hence, we have designed a method to find all components of a specified type that are connected to a focus component. For a graph representing the relationship of wire connections between components generated with the connection information of a diagram, we apply a breadth first search, and paths from the focused component to the circuit breakers are displayed. For example, when a component has been selected by a user, all wire connections and neighbor components are highlighted on the backward path from the focused component to the circuit breakers. Figure 2 shows an example of using this feature for the focused component, highlighting circuit breaker components at the leftmost end on the highlighted wire connections.

Inter-diagram navigation In complex electrical and mechanical systems, most diagrams are inter-related to other diagrams. For instance, each schematic diagram is associated with the related schematic and wiring diagrams. Hence, moving to the related diagrams without explicitly searching will be essential for maintenance tasks. For such inter-diagram navigation, preserving the contextual information is indispensable because it enables users to keep their focus while switching diagrams. To preserve contextual information, all components are assigned an unique identifier so that user interactions can be applied to all components in related diagrams. In maintaining highlighting information between diagrams, the schematic diagrams are often simpler than wiring diagrams. Therefore, the parent component including any focused component in a wiring diagram may be solely highlighted in a schematic diagram, or children components within the focused component in a schematic diagram may be highlighted together in a wiring diagram. In those cases, the hierarchical information is used to find appropriate components in the related diagrams to apply the changes by users' interaction.

The speed of the diagram switching is another consideration of a visualization system for technical diagrams. We propose *Transition by blending*, a method to show the related diagram within the view of the current diagram by blending the diagrams under user-controlled speed. Figure 3 shows the example of procedures using the Transition by blending for a focused component from a schematic to a wiring diagram. While diagrams are blended, the highlighting as well as spatial context of a focused component are maintained to provide a user with consistent contextual information. In



(a) (b) (c) (d)

Figure 3: *Transition by blending from a schematic diagram to a related wiring diagram preserving spatial information of a selected component. (a) Schematic diagram, (b) initial view of Transition by blending combined with our Relational lens, (c) 60% blending, and (d) final transition to the related wiring diagram.*

Figure 3(b) and 3(c), the size of the focused component in a schematic diagram is smaller than that of the component in the related wiring diagram. Hence, the green rectangle is enlarged more and more while being blended with the wiring diagram. The green rectangle in Figure 3(b) indicates our *Relational lens* which we describe in subsection 3.5.

3.4. Highlighting

Highlighting enhances the information relevant to the user's task and immediately draws the user's attention by using colors or marks. We highlight the names of components, the focused component, neighbor components connected to the focused component, and wire connections between highlighted components in various colors and with marks indicating the status of a component. Figure 4 shows several components and connections highlighted. The highlighting of each component is blended with that of a parent component. For use in highlighting, the relationship between components can be generated from the connection information in XML data, since each diagram includes XML data for the semantic information. Unlike components, connections have a directional property, such as a source or a sink. Hence, we interpolate colors of the end points of each connection from a source (red) to a sink (blue) to present the directional cue.

Annotations, placing comments on the diagrams which are meaningful to users, are another method to highlight diagrams. Marshall [Mar97] studied where students made marks in their text book and defined the form and function of these annotations. The annotations were placed either within text or in marginal or blank space, and were categorized into two categories: telegraphic (e.g., underlining, stars, and circles) and explicit one (e.g., brief notes and short phrases). In the SDViz system, we support annotations by placing special marks (switch off/on, component working/not-working), which are then used to provide a symbolic note when performing maintenance tasks across multiple diagrams. These special marks are preserved in all related diagrams as contextual information in our system by managing each component's unique identifier.

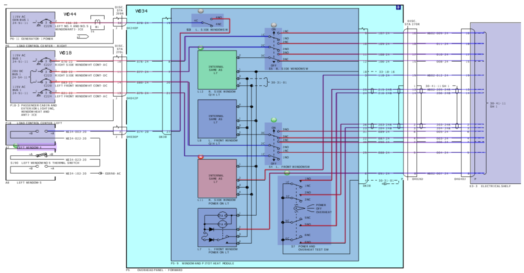
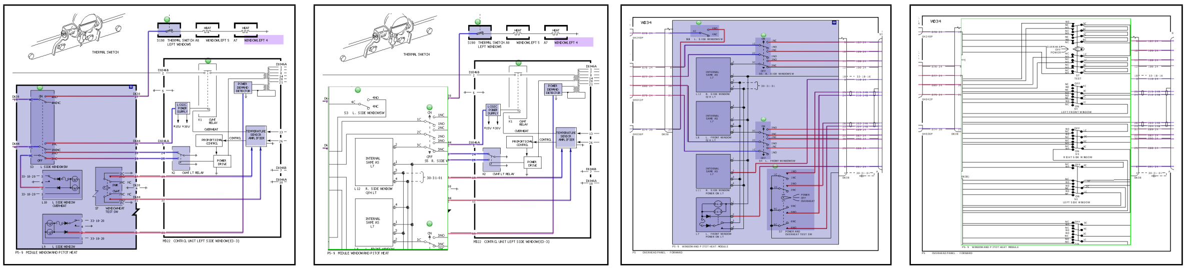


Figure 4: *Highlighting components and connections in various colors (green: marked as working status, red: marked as not-working status, cyan: locked focusing, purple: highlighted as a neighbor) and with different marks (switch on/off, working/not-working status).*

3.5. Distortion Viewing

Unlike general documents, distortion viewing for technical diagrams is less preferred by maintenance personnel because it changes the structural view of contents within the diagrams. Despite this limitation, a few distortion viewing techniques can be effective for the visualization of relatively large diagrams on a computer display and can enhance a user's area of interest within the context of a diagram. Furthermore, Baudisch et al. [BGBS02] showed that focus+context visualization reduced the time to perform tasks by evaluating focus+context, overview+detail, and pan+zoom interfaces for large detailed data. Hence, we provide the magic lens and the rectangular fisheye lens. The magic lens uses a fixed-size magnifying area occluding neighbor regions, whereas the rectangular fisheye lens [Rau99, RJS01] distorts neighbor regions around a user-defined area providing contextual information unoccluded. Our system also incorporates work by Gutwin [Gut02] in which focus-targeting is improved by accounting for the users' activity (speed of mouse movements) to modulate the rate of distortion while supporting navigation and inspection.

In addition, we propose the *Relational lens* that uses a fixed-size lens defined by the boundary of a focused com-



(a) (b) (c) (d)

Figure 5: *Relational lens applied to the focused component in (a) a schematic diagram and (c) a wiring diagram to see more detail wiring information. (b) The wiring information shown through the Relational lens in a schematic diagram, and (d) more detail wiring information shown through the Relational lens in a wiring diagram.*

ponent. The main goal of the Relational lens is to display information from related diagrams by overlaying the related information on a focused component while intrinsically preserving the spatial context. For example, the Relational lens overlays the detail view of the related wiring diagram on a focused component within a schematic diagram or the overview of the related schematic diagram on a focused component within a wiring diagram. Figure 5 shows an example using the Relational lens on the schematic and wiring diagrams to see more detailed wiring information of a focused component. The outmost components highlighted in Figure 5(a) and 5(c) show components to which the Relational lens is applied resulting in Figure 5(b) and 5(d), respectively. The Relational lens is toggled by user interaction, and applied to the component focused by mouse over or highlighted by double clicking. What users see through the Relational lens is information for the same component from a related diagram. It can be from any related SDM (abstracted information) or WDM (detailed information). In Figure 5(b) and 5(d), the green rectangles show the boundary of the Relational lens applied to a focused component in SDM and WDM, respectively. The part of a diagram inside each green rectangle is taken from a corresponding related WDM. A similar concept, called semantic zooming, was introduced by Frisch et al. [FDB08] by visualizing overview and details based on focus+context technique for a focused node within a UML diagram. However, it differs from our Relational lens in terms that our system visualizes the different level of details as well as all contextual information (i.e., highlighting, switch status, working/not-working status) occurred dynamically by user interaction. From our observations, the matching the different scales of the same component in related diagrams can result in a distorted aspect ratio, confusing the users. Hence, the information from the related diagram through the Relational lens is displayed at the same scale as the current diagram. As shown in Figure 3, the Relational lens can also be used with the Transition by blending.

3.6. Flow Animation

Based on our task analysis, we found that most technicians follow the flow of electricity during troubleshooting operations. Furthermore, work by Robertson et al. [RFF*08] has demonstrated the effectiveness of animation in illustrating data trends. As such, we allow users to view flow animations using a texture mapping technique on connections to show system functions and flow. In technical diagrams, sources and sinks can be identified as technicians usually think. We had a senior student in Aviation Technology at Purdue University identify sources, sinks, and flow directions in diagrams we used, before we generate XML data for semantic information from the diagrams. Hence, our XML data contains the information about sources and sinks resulting in the flow of electricity highlighted from the source to sink component. The flow animation is affected by both the switches and working status of components. Therefore, flow animation can also be utilized as the method for single diagram navigation providing a dynamic visualization. Figure 6 shows an example of our flow animation. The electricity flows from the selected component (leftmost highlighted component) to the components connected to the selected one. The upper flow of electricity is stopped, whereas the lower flow passes through the switch due to the switch status (upper switch is on, and lower switch is off).

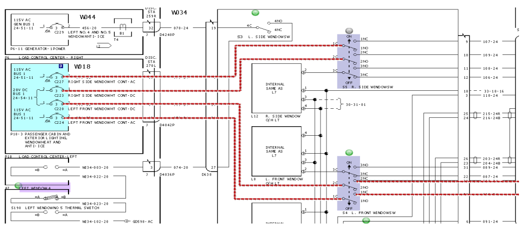
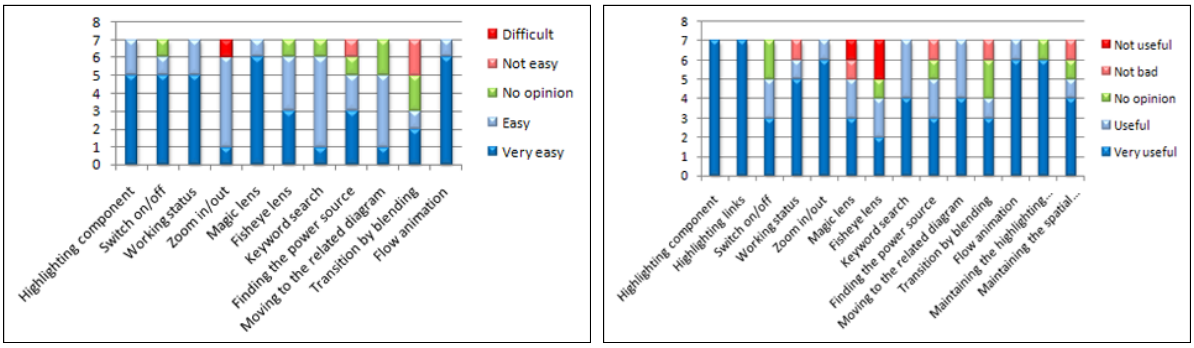


Figure 6: *Flow animation mapped with an arrow texture animated along the flow direction.*



(a) (b)

Figure 7: *Results from the field study by 7 senior students in the school of Aviation Technology at Purdue University. (a) Usability for each function, and (b) usefulness for each feature from the field study.*

4. Qualitative Field Study

In order to evaluate the effectiveness of SDViz, a qualitative field study was conducted with 10 college seniors from the school of Aviation Technology at Purdue University.

4.1. Scenario

We reused the scenario performed in the knowledge acquisition phase. To reiterate, the scenario is that a window heater was malfunctioning in a Boeing 737 aircraft. No voltage is indicated when the left side window control switch is positioned to ON. No students in the field study participated in the knowledge acquisition phase, nor had they previously performed this task in their class. The subjects were asked to troubleshoot the problem using relevant maintenance, schematic, and wiring diagram manuals. Again, when measurements were needed, the exercise leader would provide this information.

4.2. Experimental Setup

Participants were given a pre-experiment questionnaire to evaluate their relative background knowledge and experience as well as were classified into two groups. Subjects in Group A used the full functionality of SDViz to perform the diagnoses. They were provided with tutorial videos and training prior to beginning. Furthermore, they could also consult the SDViz user manual at any time during troubleshooting. Subjects in Group B were given a basic pdf viewer with pan and zoom navigation controls to perform the diagnoses. Training was provided for those subjects unfamiliar with pdf navigation.

Upon completion of the scenario, subjects in Group A were given a post-experiment questionnaire to collect qualitative feedback for each functional component of SDViz. Subjects answered questions on the usability and usefulness of the SDViz capabilities, ranking them either from “difficult” to “very easy” or from “not useful” to “very useful” and were also asked to write any other comments they had about the system. Subjects also ranked the functions of SDViz based on their preference of use.

4.3. Qualitative Results

Figure 7 shows the results from our field study by the 7 subjects in Group A. The horizontal axis lists each function of our SDViz, and the vertical axis represents the number of subjects. In Figure 7(a), most subjects who used SDViz for the troubleshooting commented that most of functions were “very easy” or “easy” to use for the usability of our SDViz. Particularly, all subjects chose “very easy” or “easy” for the usability of the highlighting components, working status, magic lens, and flow animation. For the Transition by Blending, subjects agreed that it provided efficient context preservation keeping their focus, but two of them also answered it was “not easy” enough to use because they were not familiar with such an interface. Figure 7(b) shows the usefulness evaluation results for each SDViz feature. All participants who used SDViz for the troubleshooting agreed that highlighting, moving to the related diagram, and flow animation features were “very useful” or “useful.” In addition, 6 among 7 subjects chose “very useful” or “useful” for the working status and maintaining the highlighting features. Moreover, some of them proposed that it would be useful to highlight more than one component as focused components. Our analysis from consulting with repair technicians and our task analysis revealed that distortion viewing, using the magic lens and the fisheye lens, were not preferred by subjects. For each distortion method, 2 among 7 subjects answered “not useful.”

Although the purpose of the field study was to collect qualitative feedback, we also observed the troubleshooting time to complete the scenario for both groups. The participants who used a pdf viewer took 17-32 minutes to troubleshoot the component, spending most of their time finding related diagrams between various manuals, whereas participants using the SDViz system took 9-15 minutes to troubleshoot, thereby decreasing the task time by 46-52%.

5. Conclusion and Future Work

In SDViz, we applied various visualization techniques such as highlighting, locating a 2D viewpoint, distortion viewing, blending for transition, and animating for the exploration of technical diagrams in order to help users understand the diagrams as well as find the desired information effectively. Furthermore, we conducted a field study by students in the school of Aviation Technology at Purdue University to evaluate the capabilities of our system. Based on the results from our field study, we believe that our system can provide maintenance personnel with an effective and efficient visualization tool for maintenance, repair, and training tasks.

There are several issues to be considered as future work. First, we can consider improving the capability of interoperations between various units such as components, pages, diagrams, subsystems and systems. Such interoperations can help technicians understand the current trouble with a broad point of view about an entire system and cooperate with other technicians. Second, integration with multimedia data like 3D models, Macromedia Flash files, and video clips will make SDViz be more effective for maintenance tasks. Each component or subsystem can be displayed with 3D models providing users with a variety of interactive operations such as interactive viewpoints, internal 3D views, and assembly as well as on/off operations. Video clips can provide useful information to describe how to work with each component and subsystem. Third, more customized focus+context techniques need to be developed for dealing with the technical diagrams containing various complexities. Finally, using a touch screen device may also be considered to provide maintenance personnel with more intuitive interfaces.

6. Acknowledgement

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