Designing User Interface Elements for Remotely Operated Rubber-tired Gantry Cranes

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***Abstract*— The graphical user interfaces (GUIs) for operating heavy machinery, such as cranes, vary significantly even for the same type of machines depending on machine manufacturers or third-party suppliers who develop the GUIs. This situation leads to diverse GUIs, which require operators to train themselves every time they use GUIs from different machine manufacturers or third-party suppliers. Using significantly different GUIs may also increase the risk of human error, since the GUIs may have different rules or mechanisms that operators should follow. To improve the design consistency across different machine manufacturers and third-party suppliers, there is a need for a design system that crane manufacturers and third-party suppliers can use when developing their own GUIs. This paper presents the process of designing user interface elements for operating remote rubber-tired gantry (RTG) cranes, which will be offered as part of OpenCrane Design System.**

***Index Terms*— graphical user interface, crane, design system, remote operation, human-centered design**

I. Introduction

Modern heavy machinery, including cranes, is increasingly equipped with digital systems that allow operators to monitor and control their machines through graphical user interfaces (GUIs) [1]. However, the GUIs for operating heavy machinery could vary significantly even for the same type of machines depending on machine manufacturers or third-party suppliers that develop the GUIs [2]. This situation leads to diverse GUIs, which require operators to train themselves every time they use GUIs from different crane manufacturers or third-party suppliers. Using significantly different GUIs may also increase the risk of human error, since the GUIs may have different rules or mechanisms that crane operators should follow [3]. To improve the design consistency across different machine manufacturers and third-party suppliers, there is a need for a design system that others can use when building their GUIs [4].

This paper presents the process of developing OpenCrane Design System, which is a design system that will offer open-source user interface (UI) elements for operating cranes. The motivation behind developing the design system is to improve design consistency by offering UI elements that different crane manufacturers and third-party suppliers can use to develop their own GUIs. Since cranes are available in many types, sizes, and different operational modes, this paper focuses on designing UI elements for operating remote rubber-tired gantry (RTG) cranes, which are also known as yard cranes (see Figure 1 for an example). RTG cranes are used for moving containers between trucks and the port's storage yard. Although it is still common to find RTG cranes that are controlled by operators who work from inside the cabin, there are newer RTG cranes that can be controlled remotely by operators working from a control room [5]. The shift from on-site operation to remote operation has been driven by higher demand for better safety and productivity, as operators are not exposed to accidents that may happen around their cranes and they can also control any cranes within the port from the same control room [6].

Fig. 1. Remote RTG cranes used at a port.

Since operators are separated from their cranes, they have to rely on the video stream and the GUIs shown on their monitors to observe the remote environment and control the cranes remotely [6]. Because of that, it is important to consider the match between the visual design and the context of use, while designing the UI elements. A good match between the visual design of the UI elements and the context of use is important since operators would not need to put extra cognitive effort to interpret the presented information while performing the required task [7]. This would enable operators to process the presented information and respond to hazardous situations that may occur [8]. To address the requirement of designing UI elements that match

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the contextual needs of operators of remote RTG cranes, we have defined the following research questions:

1) Which UI elements should be made available in the design system?
2) How should the UI elements be designed to correctly represent different operations of remote RTG cranes?
3) How do crane operators perceive and understand the UI elements that have been designed?

The rest of the paper is divided into five sections. Section II presents previous studies that investigate the design of GUIs for operating remote cranes. Section III describes the different activities that we carried out to address the research questions mentioned above. We conducted a field study at a port that employed remote RTG cranes and analyzed online videos uploaded by crane manufacturers to determine what UI elements should be made available in the design system. We then conducted three design workshops to generate UI elements that represent different operations of remote RTG cranes. At last, we evaluated the generated UI elements by involving nine crane operators. Section IV presents the UI elements that we generated from the design workshops and the results of the evaluation. Section V presents the reflection after designing and evaluating the UI elements, while Section VI concludes the study in this paper.

II. Related Work

As mentioned in Section I, operators must rely on the video stream and the GUIs shown on their monitors to control their cranes remotely. Considering this need, there are prior studies that investigate how the GUIs for operating cranes remotely should be designed. The proposed GUIs vary significantly among the studies depending on the type of cranes to be operated remotely and the fidelity level of the prototype (see Sitompul [9] for the complete review).

A few years before remote RTG cranes were available commercially, Kim [10] proposed a GUI designed for operating a remote RTG crane. The GUI consisted of two video camera views: (1) the cabin view and (2) the spreader view, buttons to operate the remote RTG crane, and some UI elements that indicate different states of the RTG crane. The GUI was designed to operate a virtual RTG crane, but the study does not report any user evaluation. Therefore, it is unclear to what extent the proposed GUI could be reused for operating real remote RTG cranes.

Singhose et al. [11] proposed three different GUIs that can be respectively used for remote operation of an all-terrain crane, a bridge crane, and a tower crane. However, the proposed GUIs were not designed for real operation. Instead, they were only meant to be used for educational purposes, in which students can learn about crane-related concepts by operating mini replicas of the cranes. The study also does not report any user evaluation, and thus it is unclear how the proposed GUIs could be reused for operating real cranes remotely.

Karvonen et al. [12] proposed a GUI for operating a virtual RTG crane remotely. The proposed GUI consisted of two camera setups (2-camera view and 4-camera view) and some UI elements that indicate various states of the virtual RTG crane. They involved six crane operators to evaluate the proposed GUI, but the evaluation only focused on which of the two camera setups was the most suitable one. The results suggest that the 2-camera view was preferable by the crane operators, as the video size from the 4-camera view was considered too small. Although the study offered insights into how camera views should be organized, the study did not evaluate the suitability of the other UI elements that exist in the proposed GUI.

Chen et al. [13] conducted a study that compared two GUIs for operating a tower crane prototype remotely. The first GUI consisted of multiple camera views only, while the second GUI consisted of multiple camera views and UI elements that indicate various states of the tower crane prototype. They evaluated both GUIs by involving 30 non-operator participants. The results suggested that the participants encountered fewer unsafe situations when they were using the GUI with multiple camera views plus UI elements that indicate various states of the tower crane prototype. Although the results of this study indicated that the participants worked more safely with the GUI that had the UI elements, this study does not describe how the individual UI elements contributed to the safer performance.

Finally, Yu et al. [14] proposed a GUI that consisted of four camera views, buttons to remotely control a bridge crane prototype, and four icons that can be clicked to change the input techniques. However, the study focused on comparing the effectiveness of the different input techniques by involving 21 non-operator participants and 11 crane operators. Therefore, it is also unclear how the proposed GUI could be reused for operating remote bridge cranes.

Although the number of related work is very limited, the review of related work suggests there is high diversity and low consistency in the design of GUIs for operating cranes remotely. This can increase the risk of human error, since the GUIs may have different rules or mechanisms that crane operators should follow to perform their work [3]. In addition, none of the reviewed studies specifically investigate the suitability of the individual UI elements in their proposed GUIs with the task that crane operators have to perform. Although the previous studies are all published and other people could reuse or take inspiration from the proposed GUIs, it is difficult to know which part of the UI elements that should or should not be adapted. Considering a single crane-related accident could cause serious damage to life, property, and the environment [15], it is also important to have UI elements that have been properly evaluated with respect to the task that operators have to perform [16]. Therefore, there is a need for a design system that offers UI elements that (1) crane manufacturers and third-party suppliers can use when developing their GUIs and (2) have been evaluated with respect to the task that operators have to perform.

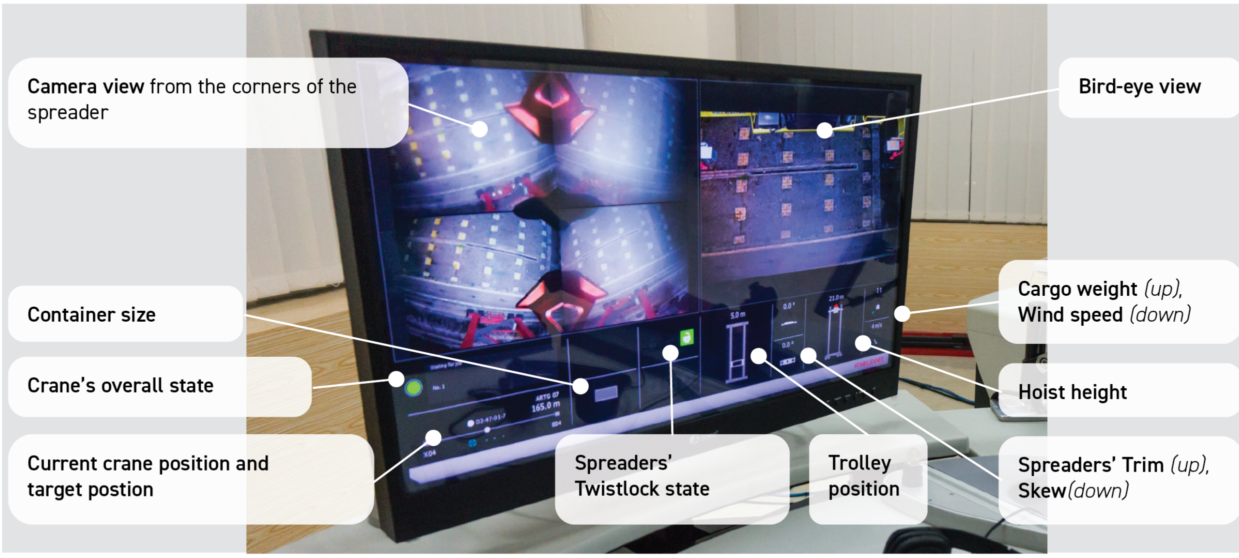


Fig. 2. An example of how we inspected every UI element that exists in the GUI used for operating remote RTG cranes.

III. Methods

This section presents the process of designing the UI elements for operating remote RTG cranes.

A. Creating a List of UI Elements to be Made Available in the Design System

One of the early phases in developing a design system is to make a list of UI elements that should be included in the design system [17]. Having a list of UI elements is essential since we would know which UI elements to be designed later. We reviewed existing GUIs for operating remote RTG cranes to determine which UI elements to include in the design system. This was done by (1) conducting a field study at a port that employed remote RTG cranes and (2) analyzing online videos uploaded by crane manufacturers that partially or fully show their GUIs. These two activities are relevant to find the answer to the first research question "Which UI elements should be made available in the design system?" mentioned in Section I.

1) Conducting Field Study at a Port: We conducted a field study at a port that employed remote RTG cranes to directly see an example of GUIs for operating remote RTG cranes. During the field study, we took photos of the monitors to capture the variations of the GUI. After that, we manually analyzed the photos by inspecting every UI element shown on the monitor (see Figure 2 for an example of this activity). We also asked the crane operators if there were UI elements shown on the GUI, which we could not easily understand.

2) Analyzing Online Videos Uploaded by Crane Manufacturers: After conducting the field study, we realized that our samples of existing GUIs were still limited, as the remote RTG cranes used at that port were produced by one manufacturer only. To ensure our list of UI elements was not biased towards this crane manufacturer, we decided to analyze online videos uploaded on YouTube by three manufacturers of remote RTG cranes[1][2][3]. Out of 863 videos that these three manufacturers have uploaded when we conducted this study, there were only 11 videos where the GUIs for operating remote RTG cranes were fully or partially visible in the videos.

The analysis process started by watching the 11 videos and taking screenshots whenever the GUIs were visible in the videos. We then manually analyzed the screenshots by inspecting every UI element that was visible in the videos, which was quite similar to what we did when analyzing the photos taken from the field study (see Figure 2). This approach allowed us to expand our samples of existing GUIs by covering three manufacturers of remote RTG cranes. The combined results from conducting a field study and analyzing online videos uploaded by crane manufacturers generated a list of UI elements to be included in the design system.

B. Generating UI Elements through Three Design Workshops

After creating the list of UI elements for the design system, the next phase was to generate design ideas to visualize those UI elements. We conducted three design workshops, where each workshop was dedicated to different activities. Conducing the design workshops was relevant to find the answer to the second research question "How should the UI elements be designed to correctly represent different operations of remote RTG cranes?" mentioned in Section I.

1) First Design Workshop: The first design workshop was conducted separately by the authors, where each of us tried to generate design ideas for every UI element in our list. We decided to conduct the first design workshop separately to give freedom to each of us to generate any possible design ideas without getting influenced by each other.

[1] www.youtube.com/c/abbmarineandports/videos
[2] www.youtube.com/user/KalmarGlobal/videos
[3] www.youtube.com/c/konecranes/videos

2) Second Design Workshop: Several days after the first design workshop, we conducted the second design workshop, where we met and combined the design ideas that we created individually. We also discussed the suitability of the generated design ideas to represent every UI element in our list. We then selected some of the design ideas that we deemed more suitable and further refined them into UI elements made in Figma [4].

3) Third Design Workshop: A couple of weeks after the second workshop, we conducted the third design workshop by involving three people who developed OpenBridge Design System [5], which is a design system for maritime navigational and ship systems [4]. The purpose of the third design workshop was to get feedback from the people who had experience in creating and maintaining a similar design system. During the third design workshop, we went through the UI elements generated from the second design workshop and received feedback on how well they fulfilled the criteria of consistency and scalability. In this context, consistency means to what extent the design of the icons and the UI elements followed the same visual style, while scalability means to what extent they could be modified into different sizes. We then improved our UI elements based on the feedback that we received from the third design workshop.

C. Evaluating the Generated UI Elements by Involving Crane Operators

As the outcome of the design workshops described in Section III-B, we generated three groups of UI elements that could be relevant for operating remote RTG cranes. Following the human-centered design approach [16], [18], it is important to involve end users to evaluate the design solutions in order to determine to what extent the solutions are suitable for the end user and the task to be performed. Evaluating the UI elements with crane operators was also relevant to find the answer to the third research question ”How do crane operators perceive and understand the UI elements that have been designed?” mentioned in Section I.

To evaluate the UI elements, we involved nine participants who worked as operators of remote RTG cranes. The operators were aged between 20 years old and 31 years old with between one and three years of experience as operators of remote RTG cranes. The evaluation consisted of two activities and the entire evaluation lasted up to two hours. The protocol of the evaluation was reviewed and approved by Norwegian Agency for Shared Services in Education and Research (No. 782630). The operators provided their written informed consent before participating in the evaluation. Each participant received a gift card worth around USD 15 as the token of gratitude for taking part in the evaluation.

1) Asking the Operators to Describe the Meaning of the UI Elements: In this activity, we printed the UI elements that we generated through the design workshops (see the top-row images in Figure 4) and provided the papers to the operators. Without giving any prior explanation, we asked the operators to verbally describe what they thought about the meaning of every UI element shown on the papers (see the middle-row images in Figure 4). This activity allowed us to determine to what extent the designed UI elements could be understood by the operators before receiving any prior instruction or training.

2) Evaluating the Operators' Understanding on the UI Elements: We also conducted a short evaluation, which required the operators to move the given toys (see Figure 3) based on the UI elements that they saw on paper. We conducted this evaluation to ensure we did not misinterpret the verbal description given by the operators in the previous activity (see Section III-C.1) and to determine whether the operators fully understood the meaning of the UI elements. This method has also been used for evaluating low-fidelity UI prototypes in the context of mobile cranes [19] and excavators [20].

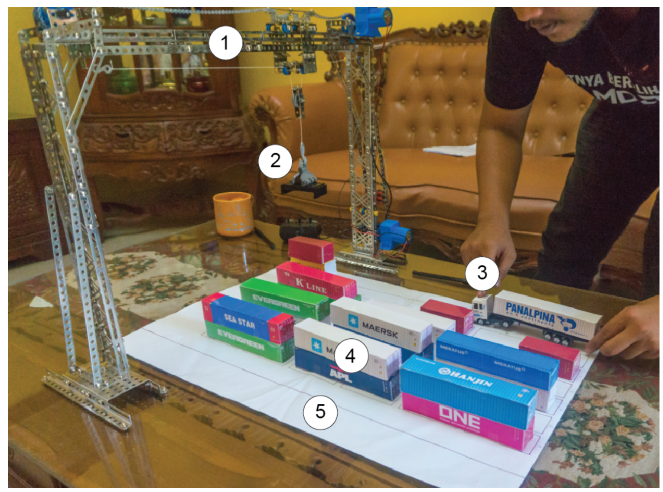


Fig. 3. The toys that we used in the evaluation phase. The toys consist of (1) an RTG crane replica that can be moved using a wired joystick, (2) a spreader replica, (3) a truck replica, (4) multiple container replicas, and (5) a white paper that represents the area of the storage yard.

The evaluation started by providing the operators with a print that showed one out of the three groups of UI elements (see the top-row images in Figure 4) at a time. We then asked the operators to move the given toys according to the values shown on the printed UI elements (see the bottom-row images in Figure 4 for the examples of this activity). After the operators finished moving the toys to the designated positions, we changed the values shown on the printed UI elements and asked the operators to move the toys again according to the new values. For each group of UI elements, we changed the values shown on the paper four times. We decided to limit the test to four times for each group of UI elements, as it was already apparent whether the operators correctly understood the meaning of the UI elements after doing it four times. Once we finished the first group of UI elements, we continued with the second group and followed the same test procedure. The test ended after all three groups of UI elements have been evaluated four times.

[4] www.figma.com
[5] www.openbridge.no

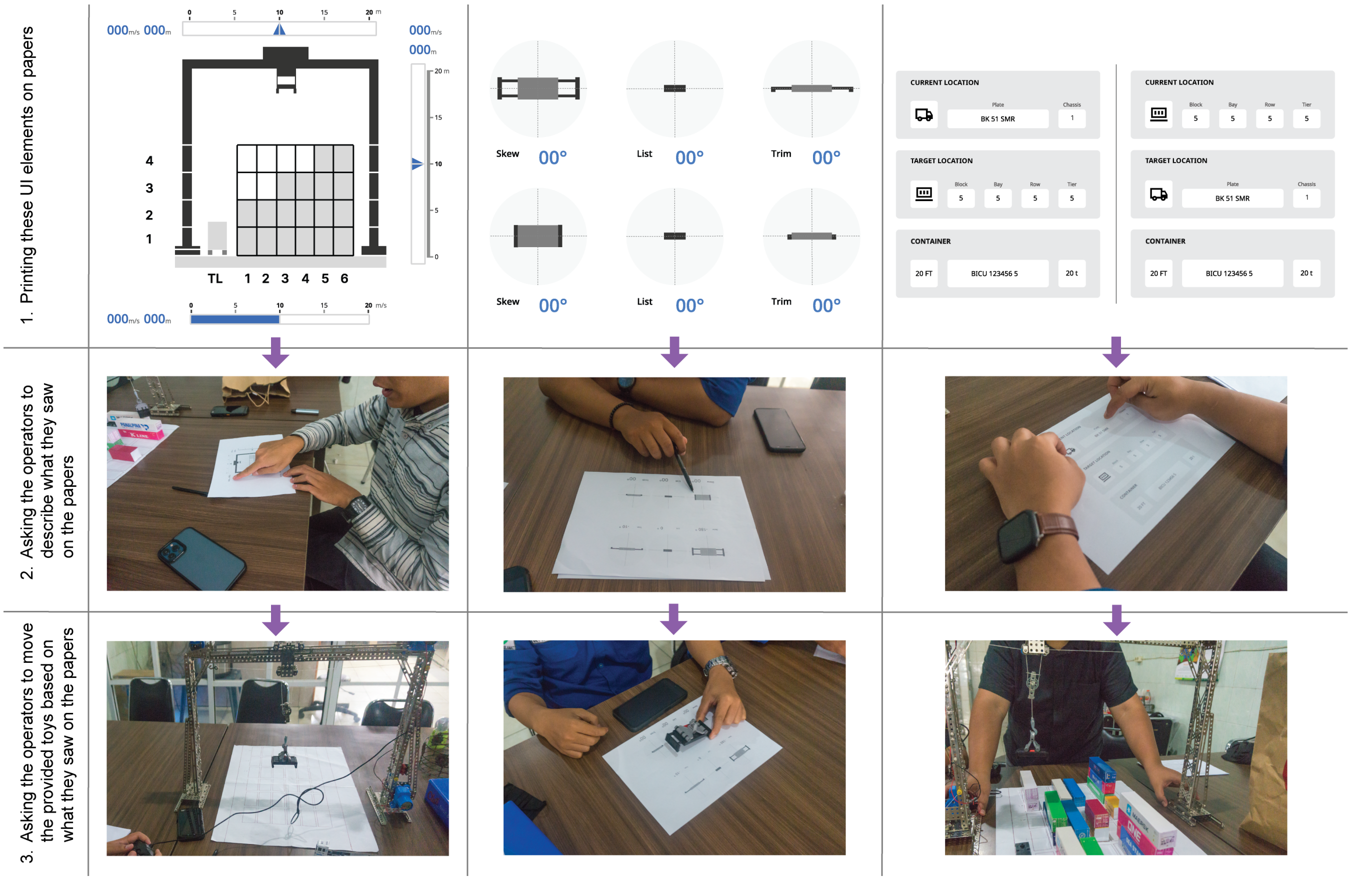


Fig. 4. The images that show how we evaluated the proposed UI elements. The top-row images show three groups of UI elements that were printed on paper. The middle-row images show the operators verbally described the meaning of the printed UI elements. The bottom-row images show how the operators moved the given toys based on the printed UI elements.

IV. Results

As shown in the top-row images in Figure 4, the UI elements that we generated from the design workshops can be grouped into three depending on what operations of remote RTG cranes that they represent. This section also provides the answers to the three research questions mentioned in Section I.

A. UI Elements that Represent Trolley, Gantry, and Hoist Operations and the Situation in a Particular Bay in the Storage Yard

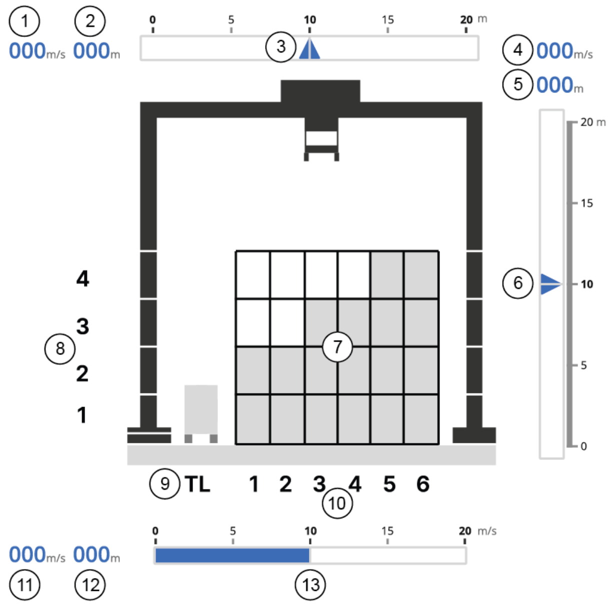
The first group of UI elements that we generated from the design workshops is the UI elements that represent trolley, gantry, and hoist operations, as well as the situation in a particular bay in the storage yard (see Figure 5). Based on the first activity, where we asked the operators to verbally describe what they saw (see Section III-C.1), all the operators were able to guess and describe the meaning of these UI elements according to the designers' intended meaning shown in the right side of Figure 5. The only exception to this was the UI elements for indicating gantry location and speed (see No. 11, 12, and 13 in Figure 5), since the operators had difficulties in interpreting the meaning of these UI elements, as indicated in the quote below:

> The numbers here (while pointing to the top UI elements) indicate where the trolley is currently located and its speed. The numbers here (while pointing to the UI elements on the right side) are the height of the spreader from the ground or what we usually called as hoist and the hoist speed. These ones (while pointing to the bottom UI elements), I cannot guess the meaning of these numbers [P2].

Only two out of nine operators were able to guess the meaning of the UI elements shown with No. 11, 12, and 13 in Figure 5 as gantry location and speed. Those two operators were able to do so by ruling out what kind of information that they have not guessed yet and not because of the design of the UI elements, as expressed in the following quote:

> If these numbers (while pointing to the top UI elements) are about trolley and these numbers (while pointing to the UI elements on the rigt side) are about hoist, then the ones in the bottom should be about gantry. Yes, I think these (while ponting to the bottom UI elements) actually mean the gantry location and its speed [P3].

To address this issue, one of the operators suggested to remove the bottom UI elements (see No. 11, 12, and 13



The intended meaning of every UI element in this figure

1. Trolley speed
2. Trolley location
3. Indicator the trolley location with respect to the beam
4. Hoist speed
5. Hoist height
6. Indicator how high the spreader is from the ground
7. The containers that exist in this particular bay
8. The numbers that indicate the height of the stack in the storage yard
9. Truck lane
10. The numbers that indicate the rows in the storage yard
11. Gantry speed
12. Gantry location
13. The bar that indicates the gantry speed

Fig. 5. The left image shows the UI elements that represent information about trolley, hoist, and gantry operations, as well as the situation in this particular bay. Each UI element is numbered between from 1 to 13. The meaning of each UI element can be seen on the right side of this figure.

in Figure 5), since it is difficult to visualize trolley, hoist, and gantry operations simultaneously in one 2D image, as expressed in the following quote:

> If we see the crane from this perspective, it does not make sense to have this bar (pointing to the bottom UI elements) as gantry speed. Here, it makes sense to present information about trolley horizontally and information about hoist vertically because they move in that way from this perspective. But not for gantry, since the crane is supposed to move either farther from us or closer to us [P9].

Other than the issue with the UI elements for indicating gantry location and speed mentioned above, all the operators had the same understanding as the designers with respect to the meaning of other UI elements shown in Figure 5. Based on the evaluation, where we asked the operators to move the given toys with respect to what they saw on paper, we observed that the operators moved the toys according to what we predicted. The operators also did not suggest any improvements on the other UI elements.

B. UI Elements that Represent the Spreader's Rotation

The second group of UI elements that we generated from the design workshops is the UI elements that represent the spreader's rotation from three different axes (see Figure 6). All the operators were able to correctly describe the meaning of these UI elements, as indicated in the quote below:

> This one (while pointing to the left) is for skew. Skew is used when the spreader rotates from the top view. This one (while pointing to the middle) is for list. List is used when the spreader tilts forward or backward. This one (while pointing to the right) is for trim. Trim is used when the spreader rotates from the side view. All these images are about the spreader, but the top images are used when the spreader is in the 40-feet mode and the bottom images are used when the spreader is in the 20-feet mode [P4].

Based on the evaluation, where we asked the operators to move the spreader replica according to what they saw on paper, we observed that the operators could correctly rotate the spreader replica according to what we predicted. Nonetheless, three out of nine operators suggested to modify these UI elements to improve their understandability, as indicated in the quote below:

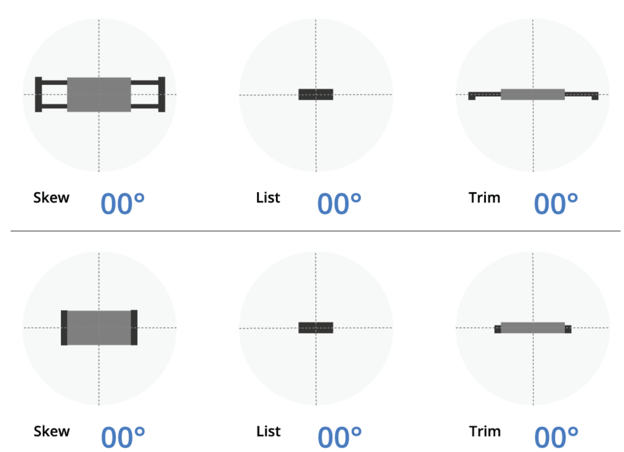


Fig. 6. The images that show the UI elements for indicating the spreader's rotation based on three different axes. The top images are used when the spreader is in the 40-foot mode, while the bottom images are used when the spreader is in the 20-foot mode.

> Based on what I see now, the spreader image seems static regardless of the numbers shown here (while pointing to the angle's value). I think it would be better if the skew is, for example, -10°, then the spreader image should also rotate according to this angle. The same also applies for list and trim. It would be better if the spreader image also changes following the angle's value [P8].

C. UI Elements that Indicate the Current and Destination of the Container

The third and last group of UI elements, which were generated from the design workshops, is the UI elements that indicate the current location and the destination of a container. The UI elements in this group are presented differently depending on whether the operation is about (1) moving a container from a truck to the storage yard or (2) moving a container from the storage yard to a truck (see Figure 7).

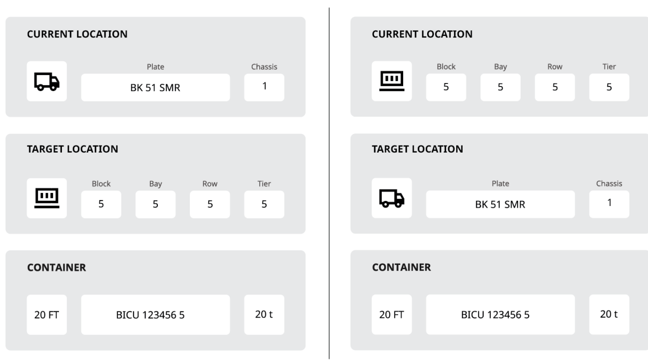


Fig. 7. The left images are shown when the operation is to move a container from a truck to the storage yard, while the right images are shown when the operation is to move a container from the storage yard to a truck.

When we provided the paper that showed the UI elements for an operation to move a container from a truck to the storage yard (see the left images in Figure 7), all the operators were able to correctly describe the meaning of the UI elements, as suggested in the quote below:

> On the top, there is a truck icon and its plate number. The chassis number is 1, which means the truck is carrying a 20-foot container. In the middle, there is information about which block, bay, row, and tier in the storage yard. In the bottom, there is information about the container. The container size is 20 feet, its number is BCU 123456 5, and its weight is 20 tons. Based on what I am seeing here, it seems like an operation to move the container from a truck to the storage yard [P6].

When we presented another paper that showed the UI elements for an operation to move a container from the storage yard to a truck (see the right images in Figure 7), all the operators were also able to correctly describe the meaning of the UI elements, as indicated in the following quote:

> It is written target location here (while pointing to the middle image) and there is a truck icon here and its plate number. Then, it is an operation to move a container from the storage yard to a truck [P7].

Although all the operators were able to correctly guess the meaning of the UI elements in this group and they also moved the provided toys as what we predicted, there is still room for improvements. One of the operators suggested to change the order of the UI elements to make them much easier to understand, as expressed in the quote below:

> When the operation is to move a container from a truck to the storage yard, we will see the truck first, then the container, and finally the location in the storage yard. When the operation is to move a container from the storage yard to a truck, we will look at the location in the storage yard first, then the container, and finally the truck. I think the container information should always be in the middle, while the information about the truck and the storage yard can be either at the top or at the bottom depending on the operation [P9].

V. Discussion

As described in Section IV, the operators gave three suggestions on how the UI elements presented in this paper should be modified to improve their understandability. The UI elements that we generated from the design workshops have been designed by considering modifiability to a certain extent. Let us take the suggestion presented in Section IV-A, where one operator requested to remove the bottom UI elements in Figure 5. Removing these UI elements could be done without affecting the understandability of the remaining UI elements. If we look at the suggestion presented in Section IV-B, where three operators requested the spreader image to be rotated following the angle's value. This modification could also be done without affecting the design of the UI elements, since developers simply need to program so that the spreader images shown in Figure 6 would rotate following the angle's value. There is also a suggestion presented in Section IV-C, where one operator asked to change the order of the UI elements shown in Figure 7. Software developers could rearrange the UI elements shown in Figure 7 according to their needs without affecting the design of the UI elements.

As mentioned in Section I, the GUIs for operating heavy machinery, including cranes, could vary significantly depending on machine manufacturers and third-party suppliers that develop the GUI [2]. Having open-source UI elements that other people can use to develop their own GUIs could improve the design consistency of the GUIs across different machine manufacturers [4]. One may argue that the UI elements presented in this paper are adding more variation into the already-diverse GUIs for operating remote RTG cranes. Even if that is the case, we see at least two main reasons for reusing the UI elements presented in this paper. Firstly, as described in Section IV, the operators involved in the evaluation were able to correctly describe almost all the UI elements presented in this paper, even though they did not receive any prior instruction or training from us. This implies that almost all the UI elements were easy to understand and crane operators would not need to retrain themselves before using the UI elements presented in this paper. Secondly, through this paper, we have been transparent in the process of designing and evaluating the UI elements, and thus others could make informed decisions whether to reuse any of the UI elements.

In this study, we have designed and evaluated the UI elements that represent different operations of remote RTG cranes. The fact that we have evaluated the UI elements does not mean that the UI elements presented and discussed in Section IV are final. UI elements in a design system usually evolve over time [17], and thus we see the UI elements presented in this paper as the first draft rather than the final version. The crane operators, which we recruited to evaluate the UI elements, worked at the same port and had the same nationality as well. Therefore, it would also be interesting to replicate the evaluation presented in this paper with crane operators who work with remote RTG cranes from different crane manufacturers in different countries, so that we could determine to what extent the results presented in this paper remain applicable. In the near future, we also plan to publicly share these UI elements, so that a wider audience and different stakeholders could also have access to these UI elements. In that case, we expect to receive more feedback on these UI elements beyond what we already learned from this study.

VI. Conclusion

In this paper, we have presented the process of designing and evaluating UI elements for operating remote RTG cranes that others can reuse when developing their GUIs. The process started by conducting a field study at a port that used remote RTG cranes and analyzing online videos uploaded by manufactures of remote RTG cranes in order to create a list of UI elements that should be designed later. We then conducted three design workshops to generate design ideas for every UI element in our list. We finally evaluated the generated UI elements by involving nine participants who worked as operators of remote RTG cranes. The results suggest that the generated UI elements were easy to understand, since the operators were able to correctly describe the meaning of the UI elements without prior instruction or training and they also moved the provided toys as what we predicted. Nonetheless, since UI elements in a design system is expected to change over time, we consider the UI elements presented in this paper as the first draft rather than the final version.

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