Presenting Information Closer to Mobile Crane Operators’ Line of Sight: Designing and Evaluating Visualisation Concepts Based on Transparent Displays

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Figure 1: The left image shows an example of supportive system inside a mobile crane [6]. The right image illustrates that mobile crane operators often look at areas that are far away from the location where the supportive system is placed [2].

ABSTRACT

We have investigated safety information visualisation for mobile cranes operators utilising transparent displays, where the information can be presented closer to operators’ line of sight with minimum obstruction on operators’ view. The intention of the design is to help operators in acquiring supportive information provided by the machine without requiring them to divert their attention far from operational areas. We started the design process by reviewing mobile crane safety guidelines to determine which information that operators need to perform safe operations. Using the findings from the safety guidelines review, we conducted a design workshop to generate design ideas and visualisation concepts, and to delineate their appearances and behaviour based on the capability of transparent displays. We transformed the results of the workshop to a low-fidelity prototype, and then interviewed six mobile crane operators to obtain their feedback on the proposed concepts. The results of the study indicate that, as information will be presented closer to operators’ line of sight, we need to be selective on what kind of information and how much information that should be presented to operators. However, all the operators appreciated having information presented closer to their line of sight, as an approach that has the potential to improve safety in their operations.

Index Terms:  Human-centered computing—Visualization—Visualization application domains—Information visualization; Human-centered computing—Visualization—Visualization design

1 INTRODUCTION

The mobile crane is one type of heavy machinery commonly found in the construction site due to its vital role of lifting and distributing materials. Unlike tower cranes that require some preparations before they can be used, mobile cranes can be mobilised and utilised more quickly. However, mobile cranes are complex machines, as operating them requires extensive training and full concentration [9, 10].

When lifting a load, mobile cranes require wide work space in three dimensions. Operators must be cautious to prevent both the boom and the load from hitting other objects, such as structures, machines, or people. At the same time, operators must also avoid the machine from tipping over, since the machine’s centre of balance is constantly changing depending on many factors, such as height and weight of the lifted load, ground’s surface, and wind [18].

The complex mobile crane operation leads to operators’ cognitive workload continuously high [10]. Repetitive tasks and long working hours also make operators vulnerable to fatigue and distraction, which could lower their ability to mitigate upcoming hazards. 43% of crane-related accidents between 2004 and 2010 were caused by operators [11]. In addition, mobile cranes are also considered the most dangerous machine in the construction sector, as they contributed to about 70% of all crane-related accidents [17]. Crane-related accidents can cause tremendous losses in property and life of both workers and non-workers [11, 18]. The most common crane-related accidents are electrocution due to contacts with power lines, struck by the lifted load, struck by crane parts, or a collapsing crane [17].

To assist operators, modern mobile cranes are equipped with head-down display supportive systems (see the left image in Figure 1). For example, Load Moment Indicator (LMI) systems that indicate if the maximum load capacity is approached or exceeded [18]. However, the presence of head-down displays could obstruct operators’ view, and thus the information is displayed away from operators’ line of sight.
sight (see the right image in Figure 1). Furthermore, many LMI systems only present numerical information that does not support operators’ contextual awareness, and thus consequently requires extra cognitive effort to interpret the meaning of the information [8]. In this case, the benefit of having supportive information is nullified by both information placement and information visualisation.

We hypothesise that information presented near the line of sight would benefit mobile crane operators. For example, information displayed on the windshield would allow operators to acquire the supportive information without diverting their attention from operational areas. However, this approach has its own challenges. With information presented near operators’ line of sight, there is a potential risk to distract operators from their work. Therefore, the information needs to be presented cautiously, where the right information is presented at the right time, the right place, and the right intensity [9]. This approach will enable operators to perform their work, while maintaining awareness of both the machine and its surroundings.

2 RELATED WORK

Considering the current setting where mobile crane operators receive supportive information via head-down displays, one may suggest alternative approaches using auditory or tactile modalities. However, mobile cranes are noisy and generate internal vibration due to the working engine [3] and the swinging lifted load [5]. Similarly, auditory information is already used in mobile cranes to some extent [9]. Adding more information via haptic and auditory channels could be counterproductive due to less clarity for conveying information compared to visual information [7]. Prior research indicated that visual information is still used as the primary modality for presenting supportive information in heavy machinery, including both mobile cranes and fixed-position cranes (see Sitompul and Wallmyr [22] for the complete review). Proposed approaches for improving safety in operations using cranes also vary. For off-shore cranes, Kvalberg [13] proposed to use transparent displays that could be installed to the crane’s windshield for presenting the relative load capacity (see Figure 2a), which indicates how much weight a crane can lift depending on how far and high the load will be lifted [20]. For remotely controlled tower cranes, Chen et al. [4] proposed multi-displays where each display presents certain information, such as machine status, potential collision, and multiple views of the working environment (see Figure 2b). Fang et al. [10] proposed a tablet-like display in mobile cranes to show multiple views of the working environment, including the supportive information that indicate recommended lifting paths, potential collision, and excessive load (see the both images in Figure 2c).

Fang et al. [10] involved five mobile crane operators, and their study was also carried out using a real mobile crane. The studies of both Kvalberg [13] and Chen et al. [4] were limited to technical evaluations within controlled environments and no mobile crane operators were involved (see Figure 2a and Figure 2b). To evaluate the proposed system, Fang et al. [10] compared the performance of operators with and without the proposed system. The result showed that the operators have shorter response time and higher rate of correct responses when using the proposed system. In addition, the result from the Situation Present Assessment Method (SPAM) also indicated that the operators were able to maintain higher level of situation awareness by using the proposed system. Despite the positive results, the operators commented that the display was too small and it could also obstruct their view.

3 METHODS

Aligned with prior research, we hypothesise that information presented near the line of sight would benefit mobile crane operators, since they could acquire the supportive information without diverting their attention from operational areas. However, as the information will be presented near operators’ line of sight, the information needs to be presented cautiously to prevent counterproductive impacts on
the operators. For this paper, we have had the following research questions:

RQ1. What kind of information that mobile crane operators need to know in order to perform safe operations?

RQ2. How should the supportive information behave and look like with respect to the performed operation?

RQ3. How do mobile crane operators perceive the proposed visualisation approach?

3.1 Utilising Safety Guidelines as a Source of Information

To address RQ1 and figure out which information is important for operators to perform safe operations, we reviewed four different mobile cranes operation safety guidelines [14, 15, 19, 20]. This could also have been done by asking operators or domain experts. However, this alternative may be less efficient, because operators may have different operational styles or preferences, and thus having different requirements. Furthermore, we would have missed the international aspect covered by the guidelines from different parts of the world. Therefore, we used the safety guidelines as the starting point, as they are applicable to all operators regardless different operational styles or preferences. From the safety guidelines review, we have found that the guidelines are provided to prevent the following events:

1. Collisions that may occur between the mobile crane, its parts, or the lifted load; and nearby people, or structures at the working area. To prevent this from happening, operators should know what is around the machine and what the machine is about to do.

2. Loss of balance that could occur due to many factors, such as excessive load capacity, strong wind, or unstable ground. To avoid this event, operators should know the current state of the machine and never operate the machine beyond permitted conditions.

3.2 Generating Ideas Through a Design Workshop

To address RQ2, we used the findings from the safety guidelines for a design workshop, with three participating human-computer interaction (HCI) researchers, in order to generate ideas for the appearance and behaviour of the visualisation. Since the type of displays influences the form of information and how it can be presented, we firstly discussed which display is appropriate in mobile cranes. As mobile cranes have a large front windshield and operators look through it most of the time [5], we reasoned that using transparent displays, like what Kvalberg [13] has used, could be a good approach. However, using transparent displays also give us two main disadvantages [1, 16]. Firstly, they are limited in terms of colors, since only yellow and green are currently available. Secondly, they support static visualisation only, as the display can only present information that has been specified before the display is manufactured. See Figure 3 for a commercial example of transparent displays.

We generated ideas for the visualisation that could help operators in preventing hazardous situations mentioned in Subsection 3.1. We then selected some of the generated concepts based on their suitability with transparent displays (see Figure 4). Eventually, we produced eight visualisation concepts that suit the appearance, characteristics, and capability of transparent displays:

1. Two concepts for proximity warning that indicates position, distance, and height of obstacles.

2. Two concepts that indicate the balance of the machine.

3. One concept for showing both wind speed and wind direction.

4. One concept for illustrating how much the lifted load swings.

5. One concept for presenting the relative load capacity, including the angle of the boom, the height of the hook to the ground, and the distance between the lifted load to the center of the machine.

6. A generic warning sign that tells operators to stop their current action.

The description for each visualisation concept is presented in Section 4, along with the feedback from the operators.

3.3 Obtaining Feedback from Mobile Crane Operators

To answer RQ3, we interviewed six mobile crane operators to validate the ease of use and possible benefits of the proposed visualisations for performing safe operations. After explaining both
motivation and procedure of the interviews, as well as obtaining informed consent from the operators, we collected some background information from the operators, such as age, experience as an operator, and different mobile cranes that they have used. In addition, we also asked if the operators have prior knowledge or experience on head-up displays. See Table 1 for some information about the operators that we have interviewed.

After that, we presented the visualisation concepts printed on papers, which illustrated how the visualisations look like in certain situations. We firstly explained what is the meaning of each component within the visualisation concepts. We also used some tools (see Figure 6) to demonstrate the meaning for the visualisation concepts. Once the operators confirmed that they understood the logic behind each visualisation concept, we continued with five tests which evaluated the operators’ understanding of the concepts for proximity warning, balance, wind speed, load swinging, and relative load capacity. We then presented different forms of the visualisation on papers to the operators. There were ten forms for each concept of proximity warning, eight forms for each concept that shows the machine’s balance, eight forms for wind speed, four forms for load swinging, and eight forms for relative load capacity. Some of the various forms are presented in Section 4. The test for proximity warning had increasing complexity, for example, starting from one obstacle and the same height to multiple obstacles with different heights. The operators were asked to use the provided tools, such as toys, coin, and pens (see Figure 6) and moved them according to the shown visualisation (see Figure 5). This method was useful for both us and the operators, since we could understand the operators’ way of thinking through their actions and the operators could show what they were thinking. Surprisingly, four operators had their own mobile crane replicas and we encouraged them to use their own instead. This process was repeated until all visualisation concepts were described and evaluated. The generic warning sign was not evaluated, since its meaning was too obvious for the operators.

Lastly, we provided a paper that has an image of the interior view of a mobile crane’s cabin. The operators were asked to place the visualisation concepts, which were printed on a transparent film and then cut into pieces, on the windshield according to their preferences (see Figure 7). They were also encouraged to exclude concepts that they considered less important. Eventually, the operators were asked
Figure 8: a. The distance between the machine and the obstacle is divided into three levels: near (1 radius), medium (2 radius), and far (3 radius). b. The meaning for each segment in the first concept of proximity warning. c. The meaning for each segment in the second concept of proximity warning.

to describe the reasons for their decisions.

4 Results

This section presents the description for each proposed visualisation concept, including the feedback that we have obtained from the operators.

4.1 Proximity Warning

Both concepts for the proximity warning were made based on the top view of the mobile crane, with three levels of distance: near, medium, and far (see Figure 8a). In this study, we used humans as the form of obstacles for simplification purposes, and also because humans are moving objects. In practice, the obstacle can also be other things, such as buildings, trees, or overhead power lines. The visualisations are always shown based on the direction where the cabin is facing.

In the first concept, there are two groups of segments and each group represents the presence of obstacle(s) on the left side or the right side of the cabin (see Figure 8b). The left segments will be turned on when there is an obstacle on the left side of the cabin, and vice versa. As the visualisation is split into two half circles, for obstacles that are exactly in the front or behind the machine, the same segment on both sides are turned on (see the bottom left image in Figure 9). The vertical segments show the position of the obstacle and its distance to the machine. The horizontal segments indicate three levels of altitude of the obstacle: lower, on the same level, or higher than the machine. The second concept is a similar to the previous concept, except that the visualisation is in the form of a complete circle and the center parts indicate the altitude of the obstacle (see Figure 8c). See the images in Figure 9 for some examples on how the visualisation will work in certain scenarios.

When there was only one obstacle, it was quite easy for the operators to understand the meaning of both concepts and pinpoint the location of the obstacle. However, for the first concept, the idea of turning on the same segments on both sides, when something is either in front of or behind the machine, were interpreted differently by the operators (see the images in Figure 10). The first concept was considered insufficient for all different scenarios, since if there are actually two different obstacles and have similar proximity on both sides, then the visualisation will be the same as what is used for showing the obstacle in front of or behind the machine. For the second concept, as the visualisation is formed in a complete circle, it does not have the same drawback as the first concept (see the bottom right image in Figure 9). The operators could easily pinpoint multiple obstacles using the second concept regardless of their proximity, and thus the operators preferred the second concept over the first one.

Figure 9: Some scenarios that illustrate how both concepts of proximity warning are used. The visualisations are always shown depending on the direction where the cabin is facing.

Figure 10: The first concept of proximity warning was understood differently by the operators when the obstacle is in the front or behind the cabin. However, this way of thinking was not wrong either, since if there are two obstacles where one is in the left side and the another one is on the right side of the cabin, the visualisation will then look exactly the same.
Furthermore, we also discovered that both concepts have another drawback for indicating multiple obstacles in different altitudes (see the images in Figure 11). In this case, it was not clear which obstacle is higher, on the same level, or lower than the machine. The operators also commented that it would be good if we can also show the indication of altitude directly in the segments that show the proximity of the obstacle. Despite this drawback, all the operators would like to have this kind of information on the windshield.

Figure 11: Both concepts are insufficient to visualize all different scenarios. In this case, although the operators were able to pinpoint both distance and position of the obstacles, the altitude of multiple obstacles could not be determined.

4.2 Balance-related Information

We have created two concepts which indicate the balance of the machine. The first concept is called ‘center of gravity’ and the second one is called ‘loads on outriggers’. These names also imply what kind of information being visualised.

The concept of center of gravity was also made based on the top view of the machine and it shows the current position of the center of gravity with respect to the center of the machine (see the left side images in Figure 12). When the center of gravity is near the center of the machine (the circle in the center), it shows that the machine is in a very stable position. To maintain the machine’s balance, operators should ensure that the center of gravity does not go beyond the outermost segments, as the risk of tipping over is higher. Each segment in this concept indicates the position of the center of gravity.

The concept of loads on outriggers depicts the load that four outriggers have. Depending on the direction of the cabin and how far the boom is extended, each outrigger may have different loads. In this concept, there are three rectangles next to each outrigger. These rectangles are used to indicate three levels of load on each outrigger: low, medium, and high. The right side images in Figure 12 illustrate how this concept in certain scenarios.

Both concepts could be understood easily by the operators and there was no issue with the concepts. Only one operator preferred to have the concept of center of gravity, while five operators rated loads on outriggers as the better concept. The main reason was due to the fact that modern cranes already have similar visualisation, thus they felt more familiar with it. However, only four out of six operators would like to have either concept presented in the cabin. The remaining two operators commented that this kind of information already exists on the head-down display, thus they felt that it is unnecessary to have it on the windshield as well.

4.3 Wind Speed and Wind Direction

In this concept, the arrows indicate the direction where the wind goes. In each direction, there are three arrows that indicate the force of the wind: low, medium, and strong. In the center, the segments indicate the estimated wind speed counted in kilometer per hour.

Figure 12: Some scenarios that depict the use of balance-related information based on the center of gravity (left) and load on outriggers (right). The red circle represents where the center of gravity is, with respect to the machine. For both concepts, the visualisations are shown based on the direction the front part of the machine, and not according to the cabin’s direction.

See the images in Figure 13 for some scenarios that illustrate the use of this concept.

Figure 13: The arrows in the left side images and the wind icon in the right side images represent both wind direction and wind force. The wind direction is always shown depending on where the cabin is facing. The numbers in the middle indicate the estimated wind speed.

The operators could easily comprehend the meaning of the concept, since modern mobile cranes already display something similar. Regarding the importance of having such information, the operators said that it depends on the weather. In a clear weather, this information is not needed, as the operators already know that the wind speed will be within acceptable limits. On the contrary, when
operating the machine in other weather conditions, this information becomes critical for performing safe operations. Nonetheless, only three operators who would like to have this information all the time.

4.4 Swinging of the Lifted Load
As the name implies, this concept indicates the swinging intensity of the lifted load. From the safety guidelines, we learned that the swinging could occur due to the wind, as well as the movement of the boom, and the swinging could affect the machine’s balance. This concept shows something like a pendulum. The center segment is turned on when the lifted load is not swinging. The next two segments are turned on when the lifted load is swinging a bit, while the outermost segments are turned when the swinging is high. See the images in Figure 14 to see how this concept works.

![Figure 14: The images that illustrate how the concept works. If there is no swinging, the center segment will be turned on, while other segments will be turned off. Farther segments indicate stronger swinging.](image)

The meaning of this concept was obvious for the operators. However, only two operators who would like to have this information on the windshield. The remaining operators commented that this information is not needed, as they could see the swinging and estimate how the swinging will affect the machine’s balance.

4.5 Relative load capacity
Since the relative load capacity constantly changes depending on various factors [20], this concept shows four types of information: (1) angle of the boom, (2) height between the hook and the ground, (3) distance between the lifted load to the center of the machine, and (4) ten rectangles that each represents 10% relative load capacity (see Figure 15). The relative load capacity for each mobile crane, including the maximum limit for each influencing factor is usually documented and operators are advised to refer to that before performing lifting operations [14]. Exceeding the limit will cause the machine to tip over. In this case, the operators should prevent all rectangles from being turned on. See the images in Figure 16 for some examples that illustrate how the this concept works.

![Figure 15: The meaning for each component in the concept for showing the relative load capacity.](image)

When this warning appears, operators should stop their current action. Although the meaning of this concept was obvious to the operators, only four out of six operators would like to have this warning shown on the windshield. The remaining two operators said that modern mobile cranes already have distracting auditory warning for imminent danger, thus the visual warning is no longer needed.

![Figure 16: The images that illustrate how the concept works. Both top and center images illustrate that, even though the machine is lifting the same object, the relative load capacity varies depending on the height of between the hook and the ground, as well as the distance between the lifted load and the center of the machine. The bottom image depicts that the relative load capacity is of course increasing if the load is heavier. Note that the numbers in Figure 16 are used for simplification purposes only in order to demonstrate the concept.](image)

4.6 Generic Warning Sign
The last concept was a generic warning sign that appears only when a collision or loss of balance is imminent to occur (see Figure 17).

![Figure 17: A generic warning that only appears when a hazardous situation is imminent to occur.](image)
4.7 Placement of the Information

As mentioned in Subsection 3.3, we also asked the operators to place where the information should be visualised on the windshield. In this activity, they were also allowed to include or exclude some of the visualisation concepts according to their preferences. Based on the placements that have been made by the operators, we can observe that there is a pattern on where the information should be presented (see the images in Figure 18). We can see that the operators would like the information to be visualized peripherally. They commented that the central area has to be clear from any obstruction, otherwise it is going to harm their operations. However, an exception was made by two operators who put the generic warning sign in the centre, since this position could attract their attention immediately. Regarding the placement of other visualisation concepts, we unfortunately could not get a firm indication from this study, as the operators’ preferences are quite diverse.

5 Discussion

5.1 Reflection on the Method Used in This Study

Since the visualisation concepts are proposals, and thus do not exist in their intended forms, we need to reason about their validity on the basis of the method that we have used. Krippendorf [12] presents different levels of validity, in order of increasing strength, such as demonstrative validity, experimental validity, interpretative validity, methodological validity, and pragmatic validity. Due to the way this study was conducted, we are specifically discussing about demonstrative validity and methodological validity.

Regarding demonstrative validity, we were able to show the meaning of the proposed visualization concepts and how they could possibly work in different situations through the printed concepts on papers, along with the tools that the operators could interact with. This arrangement enabled the operators not only to understand the meaning of the proposed visualisation concepts more easily, but also having ideas on how the proposed concepts would work in various scenarios. In addition, we were also able to discover what would make sense or would not make sense according to the operators’ way of thinking. For example, as what is presented in Subsection 4.1, we could discover that the proposed visualization concepts are inadequate for different situations.

With respect to methodological validity, we decided to evaluate the proposed visualisation concepts in the paper form, since modifications could be incorporated easily in early stages. Despite using a low-fidelity prototype and some other tools, we were able to discover to what extent the proposed visualisation could suit the operators’ needs and way of thinking in order to perform safe operations. Although the number of operators involved in this study is rather small, research on heavy machinery often involved small numbers of operators as the participants, either in observational studies [21] or experimental studies [22]. Our method was in contrast to what Kvalberg [13] and Chen et al. [4] have done, where the functional prototype has been developed, but there was no feedback from mobile crane operators. Needless to say, a prototype with higher fidelity that could be used in some operating scenarios is required to determine to what extent the proposed visualisation will benefit or hinder the operators.

5.2 Suggestions for the Proposed Visualisation Concepts

All the operators appreciated the effort of bringing the information closer to their line of sight. All of them agreed that this approach has the potential to improve safety in their operations, as they could acquire the information without diverting their attention from operational areas. Moreover, they also provided some comments on how the transparent display could be made to better suit their needs.

Firstly, the operators raised concerns on how much the transparent display will obstruct their view in practice. As mobile cranes could be used in any time of the day, they concerned that the brightness of the transparent display may be too much for their eyes when the operation is done in dark environments. On the contrary, having a bright display will be good in bright environments, thus the information can still be visible even though there is a direct sunlight. Therefore, besides automatic adoption to the ambient light intensity, it is should be possible to manually adjust the transparent display’s brightness.

Secondly, based on what is presented in Subsection 4.3, there were different opinions whether the information should be presented on the windshield or not. Although the information is important, the information may not need to be visualised all the time. The operators also commented that it would be beneficial if they could choose what kind of information that will appear on the windshield, depending on their work environments. However, this kind of modification is not possible yet with the current transparent display, as the visualization is fixed when the display is manufactured. However, if there are multiple transparent displays showing different kind of information, it is should be possible to manually decide which transparent display that should be turned on or turned off.

5.3 Limitation and Future Work

In this study, we used a low-fidelity prototype, which was printed on papers, and some other tools to show the proposed visualisation concepts and to test the operators’ understanding on the shown visualisation. With this arrangement, we were still able to convey the meaning of the proposed visualisation concepts to the operators, as well as to test their understanding with the help of the provided tools. Having said that, we are still limited in terms of the fidelity, and thus the result in this study is better to be considered as an indication.

In the future, we are planning to revise the proposed visualisation concepts according to the feedback from the operators that we have obtained. We are also planning to build a higher-fidelity prototype by building the actual transparent display that visualizes the proposed concepts. The prototype could then be used in future evaluations within controlled environments or real-world settings in order to
investigate the impact of having such visualisation on operators’ performance. Future evaluations could also be carried out to discover which placement of information that provides the optimum result for the operators.

6 Conclusion

In this paper, we have proposed and evaluated the visualisation concepts using transparent displays that could be used to assist mobile crane operators to perform safe operations. We started the design process by gathering information from few safety guidelines, generating ideas from a design workshop, and then obtaining feedback from the operators through interviews. The operators that we have interviewed appreciated this approach and the results from this study indicate what kind of information that operators need in order to perform safe operations, how we should visualise the information, and where to place the information. Nonetheless, more studies, such as evaluations with some scenarios using high-fidelity prototypes, will need to be conducted to determine both applicability and usefulness of this approach.

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