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Where are the robots? In-feed embedded techniques for visualizing robot team member locations

Stela H. Seo James E. Young Pourang Irani
Computer Science
University of Manitoba
{stela.seo, young, irani}@cs.umanitoba.ca

***Abstract*—We present a set of mini-map alternatives for indicating the relative locations of robot team members in a teleoperation interface, and evaluation results showing that these can perform as well as mini-maps while being less intrusive. Teleoperation operators often work with a team of robots to improve task effectiveness. Maintaining awareness of where robot team members are, relative to oneself, is important for team effectiveness, such as for deciding which robot may help with a task, may be best suited to investigate a point of interest, or to determine where one should move next. We explore the use of established interface techniques from mobile computing for supporting teleoperators in maintaining peripheral awareness of robot team members' relative locations. We evaluate the nontrivial adoption of these techniques to teleoperation, comparing to an overview mini-map base case. Our results indicate that in-feed embedded indicators perform comparatively well to mini-maps, while being less obtrusive, indicating that they are a viable alternative for teleoperation interfaces.**

Keywords—Teleoperation; Embedded Indicator; Robot Team Location; Group Awareness; Human-Robot Interaction

I. INTRODUCTION

Teleoperated robots are rapidly expanding into a range of applications including urban search and rescue (USAR), exploration (e.g., in remote or dangerous places), or industrial inspection. Developing improved interfaces for supporting operators' efficiency and effectiveness, while reducing cognitive demand, is an ongoing research challenge [1], [2].

Teleoperation robots, such as for search and rescue, are increasingly working in teams [3]–[5]; multiple robots can cover more area, have heterogeneous capabilities, and can coordinate (e.g., by offering views from different perspectives) to complete tasks more efficiently than a single robot. When controlling a robot in a team, maintaining peripheral awareness of the other robots' locations is important for efficient and successful team coordination. For example, knowing which robot to call for assistance, which robot to send into an area, or where to go oneself.

A common solution to this problem is to include a top-down map (e.g., [4], [6], [7], often called a mini map): even when environmental data is not available, it is useful to include the other robots' locations (e.g., [6]). However, such maps have limitations. It consumes screen real estate when beside the video, or obstruct the video if overlain on it, even if translucent; this is undesirable as the video feed is a main source of critical information in teleoperation [8], [9]. In addition, map reading requires a mental perspective shift, mentally localizing on the map and translating to one's own view. Maintaining team robot awareness requires ongoing map reading, dividing operator attention, potentially impacting task performance. We explore alternatives to mini maps that aim to mitigate some of these issues.

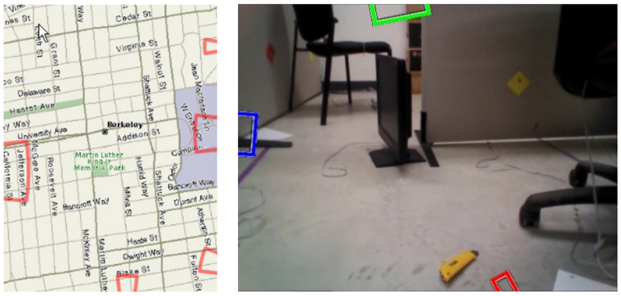


Fig. 1. (left) Wedge [10] in mobile HCI literature shows off-screen objects. (right) We adapted and built in-feed embedded indicator in first-person teleoperation view, showing robot locations of robot team members.

Mobile interface design, with highly constrained screen sizes, has developed solutions to the problem of indicating off-screen objects (Fig. 1). For example, when using a phone to search for a local hotel, minimal visual overlays have been designed to indicate off-screen targets [10]–[12]. However, important task differences in teleoperation makes the application of these techniques non-trivial. While existing work integrates the indicators into a person's primary task, with the indicators being static [12]–[14], teleoperators must monitor indicators in addition to their primary task (e.g., searching). Further, the indicators would constantly move and shift as the robots move and turn. These indicators also use a top-down mapping, overlain on top-view maps, while teleoperators typically work in first-person view. As such, it is not immediately clear if these techniques are suitable for use in teleoperation.

We implemented three in-feed embedded indicators from the mobile map-use literature [10]–[12], and conducted a study to explore their use in teleoperation. Our results indicate that the in-feed indicators perform comparably to mini-maps, for helping operators to maintain peripheral awareness of the other robots' locations, while being less obtrusive, taking less screen real estate, and requiring fewer perspective changes.

II. RELATED WORK

Research improving teleoperation interfaces for robot teams has included how to work with large numbers of robots [3], [15], effectively provide commands to teams [5], [16], [17], design visual interface [5]–[7], [15], or provide increased amounts of state or sensor data effectively [17], [5], [18]. This also includes interfaces for controlling multiple robots from a single, meta interface [18], and controlling a single robot at a time, as part of a larger team [17], [3]. We follow this theme by investigating how to support operator awareness of other robots' locations.

Teleoperation interfaces are typically built around remote video feeds, as a primary information [8], [9]. To maximize video size, and to support operator focus on the feed, graphics are commonly embedded into the video, as flat or augmented reality overlays [16], [19]. Others have developed virtual 3D worlds with camera feed and sensor data embedded into the environment [20]. We investigate similarly how robot team member locations can be embedded within a video feed.

For controlling or monitoring multiple robots or feeds, some use tiled or picture-in-picture views [5], [20], with other information (e.g., a map [14]) to support location awareness [6]. Instead, we provide peripheral awareness of team members when controlling one, and not whole-team overviews.

Providing locations of off-screen points of interest has also been explored in driving navigation aids, which particularly focus on a single static destination with minimal divided attention, eye movement, and visual obstruction [21]–[23]. This work motivates our approach of minimally obstructive in-feed embedded indicators. Unlike destination, however, we only need to inform coarse-grained location information. Thus, we placed them at the edge of the screen to use peripheral vision.

III. Off-screen Location Indicators

The problem of indicating off-screen items in an interface has been broadly studied in mobile interface literature, with a range of variants that target particular benefits and applications. Among them, we selected Halo [11], Wedge [10], and Arrows [12], as the current leading techniques. A prominent technique, EdgeRadar [24], is well-suited to moving robots. However, as with a mini-map, it consumes screen real estate. Furthermore, EdgeRadar assumes constant speeds of object, unlike the examined scenario of moving robots. For these reasons, it was not included in this study.

It is important to note that video game design has further extensive work on this problem, e.g., to indicate off-screen items or enemies in a dynamic and noisy environment. While the lack of empirical research on video game methods makes it difficult to build directly on this work, we note that our selection of techniques from the HCI literature (with empirical results) themselves build from video game design [10]–[12].

Halo represents off-screen objects by drawing a circle around each off-screen item with a diameter calculated to just overlap the intrusion on the view [11] (Fig. 2.A), such that halos are drawn at screen edges. The direction to the object is simply the direction from the screen center to the halo, and the distance is encoded in the curvature, where users can infer the circle center from the visible arc. A benefit is the encoded absolute location (distance and direction) in this fashion.

Wedge expands a triangle from each off-screen item so that the triangle base is visible on the edge of the viewport [10] (Fig. 2.B). Wedge uses the distance to the off-screen objects to calculate the length of the base, such that objects further away have a larger base (and larger on-screen presence). As the triangle is drawn from the off-screen object, the location of the wedge and the angle of the base indicate to the user the direction to the object. This indicates the distance to the object as an observer can imagine where the triangle legs converge. Wedge was specifically designed to overcome clutter concerns with Halo [10].

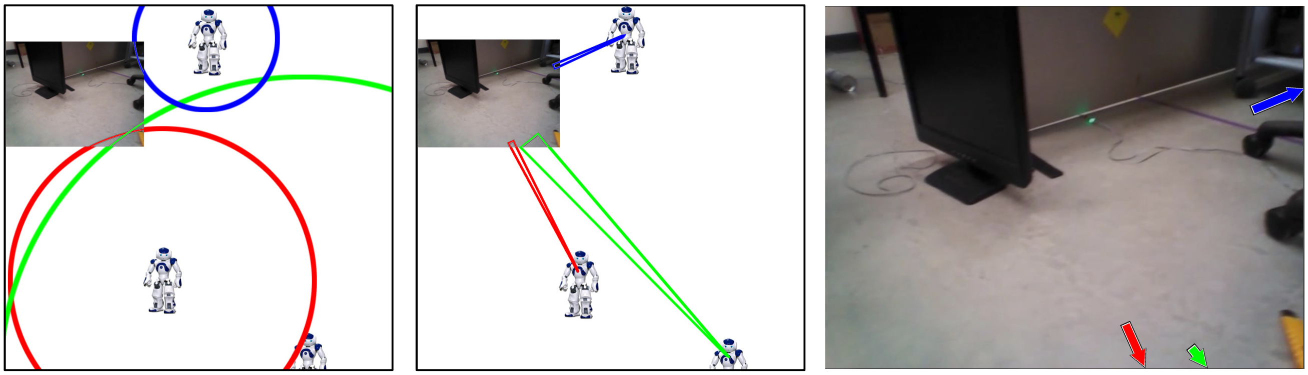
Arrow (also called stretched-arrow [12]) places arrows on the edge of the viewport that point toward the off-screen object; the arrow is placed along the line from the screen center to the object, matching its direction. The distance to the object is encoded in the arrow tail length, with the tail shorter the further away an object is [12] (Fig. 2.C). Arrow tail lengths are relative – they are linearly scaled between a pre-configured largest and shortest, based on the robot distances.

Our mini-map implementation has all three robots positioned relative to the main robot, represented by a black ellipse. This map is abstract, with a fixed scale (1:40) and no environment detail (Fig. 3). The map automatically rotates to match the main robot's look direction, to reduce the mental mapping. We place the map next to the video feed to avoid occlusions.

A. Teleoperation Adaption Challenges

Adapting these indicators to the teleoperation task is non-trivial; there are challenges and important differences that may hinder their performance.

All indicators assume that the screen represents a top-down view on an environment, as when using a map. This directly conflicts with the first-person perspective commonly used in teleoperation. Embedding these top-down indicators into first-person video feeds requires operators to mentally map between the two, which is not required in the original implementations: up for an indicator represents forward in the video feed, and down represents backwards (e.g., the green



A. Halo with illustration of calculation (participant only sees video feed)

B. Wedge with illustration of calculation (participant only sees video feed)

C. Arrow showing distance via size and direction from the center of the video feed to the object.

Fig. 2. The indicators used in our study. A and B show mock-ups of how Halo and Wedge work; only the viewport, with the indicators at the edges, are shown. C longer arrows are closer. In current setting, that the blue robot is to the right, and slightly in front of, the robot teleoperated by an operator.

wedge in Fig. 1 represents forward in the video feed). We note, however, that this is commonly used, for example, in car navigation and video games.

Further, the mobile mapping applications for which these indicators were designed and tested had static maps and points of interest. In contrast, robot teleoperation is dynamic, with both the main robot and team members constantly moving. Some of which may move at varying speeds. In particular, when the main robot turns, all indicators turn in the opposite direction to maintain relative angle, creating a great deal of visual noise. This results in constant indicator movement, possibly causing distraction and reducing legibility.

These issues motivate the need to explicitly test the techniques in teleoperation scenario, and not simply rely on previous results.

B. *Implementation*

We implemented our in-feed embedded indicators with graphic overlays on a video feed, programmed using Unity3D. To maximize indicator contrast given the changing and diverse nature of the video data, we used red, green, and blue, with white and black outlines.

One issue with implementation was that the scale of the indicators had to be changed in comparison with the original cases. The ratio between the viewport size and distance to robots was much larger in our case than in the mapping cases previously tested. In fact, it has been previously determined that Halo does scale well beyond 1.5 screen widths [25]. In our implementation, the large distances caused all but the closest robot circles to become very large, appearing straight. We scaled down the robot distances by 85%; thus, our Halo does not have absolute robot distance benefit.

With Wedge, the triangle bases were often larger than the viewport and thus not useful; we scaled Wedge's distances by 75% to fix this, similarly losing its absolute distance benefit.

IV. EVALUATION

We conducted a formal study to explore how the in-feed indicators perform compared against the standard mini-map (Fig. 3), in terms of providing coarse-grained peripheral awareness of robot group members' relative locations.

We conducted a within-participants study where participants completed a mock search and rescue task (the distractor), with their peripheral awareness of the other robots being regularly tested. The study included all three embedded indicators, and the mini-map. We also included a no-indicator case to examine if the inclusion of in-feed embedded indicators has an adverse impact on the primary task.

A. *Task*

Participants conducted a mock search and rescue task where they controlled one of four robots. Participants were informed that the videos were pre-recorded, but given that they had a task to complete we believe this did not hinder the results.

The task lasted for six minutes per condition, during which salient green lights appeared in the feed; these appeared on average every 30s, but were unpredictable. Participants were told that they had two tasks: to search for green lights, and to maintain awareness of where the other robots are.

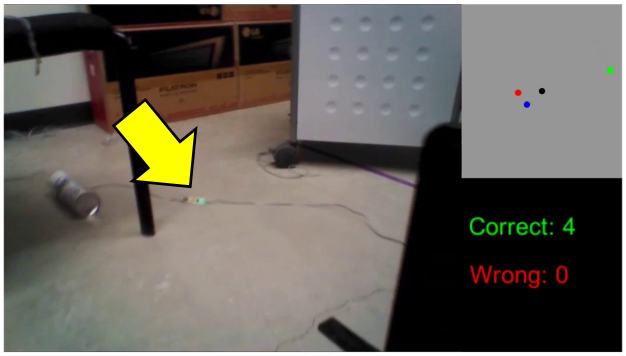


Fig. 3. Interface used by participants. Participants searched for green lights (one shown, indicated by a yellow arrow), while maintaining awareness of the other robots, and hit the spacebar when one was found (score shown). The mini-map was only shown in the mini-map case, with the region left black in the other cases.

This distractor task, searching for lights, was used to raise participant cognitive load and divide their attention, to increase ecological validity. Participants were told to press the spacebar when they found a light in the scene, to increase the importance of the distractor task. If there indeed was a light and participants pressed the spacebar, a pleasant tone audio feedback played. If they missed a light or hit the spacebar when there was no light, an unpleasant tone was played. At all times, the score was kept on screen to encourage participants to appropriately focus on the light-searching task. The overall interface is shown in Fig. 3; note that the mini-map is only shown in the map case, and the region remains black in others.

At unpredictable times, the interface paused the experiment and blanked the screen, and assessed participant awareness of the other robots. We blanked the screen, instead of simply pausing, to ensure that we assess peripheral awareness from an indicator and not overall legibility when given extra time to read it. To minimize the transition time from the blank screen to the questionnaire, the assessment was done on screen. This happened three times per task.

B. *Measures*

Our primary measure was participant awareness of the robot team members' relative locations. Given our task and interest in peripheral awareness, we are primarily interested in relative, coarse-grained awareness (which robot is closest, which robot is in front) and not necessarily high accuracy information. This measurement was accomplished with an on-screen interactive questionnaire, which asked participants to place the red, green, and blue robots at appropriate locations on a grid (for direction information), and then asked them to assess which robot was the closest and which was the furthest. In addition, we assessed participant confidence in their answers.

The direction was considered correct if it was reasonably close (within PI/16 radians). This thresholding was a more appropriate measure of our interest in coarse-grained awareness, and removes the unnecessary noise of absolute measurement (e.g., 90 or 180 degrees off should be considered equally as wrong). A participant could achieve from 0 (all three robots incorrect) to 3 (all three correct). The distance ordering question was coded from 0 to 2 (0=all incorrect, 1=one correct, 2=all correct); note that two were answers for the closest and the farthest.

Pre-test, we administered a demographics questionnaire. Post condition, we administered the NASA TLX to measure work load and asked participants to report their level of nausea, sense of response speed for finding the lights, and how much they felt the interface demanded their attention, was distracting, and helped them to maintain awareness. We asked participants to report pros and cons of the interface.

Post-test (after all conditions) we asked participants to rank the indicators in order of their preference, and to provide any comments they may have related to the indicators.

C. Instruments

Participants used a PC with a 22-inch monitor, keyboard and mouse. The chair, monitor, and keyboard locations were initially fixed although participants were free to adjust them.

The videos were methodologically created and fully prerecorded in a mock search and rescue environment. We ensured that only one light was on the screen at any given time.

To increase ecological validity, the videos were created by piloting an Aldebaran NAO H25 through the space using a WiFi connection, and recording the teleoperation video. Five such videos (with different environment configurations and light patterns) were recorded, with care to make them highly comparable, to enable five conditions in our within-participants study. Each video was exactly six minutes.

The three robots were entirely simulated (not told to participants), with the robot locations input into our indicators for visualization. The main robot's movements were mapped and input into the simulation for movement and rotation reproduction. Unique simulation datasets were created per video.

D. Procedure

Participants completed an informed consent form and were given honorariums at the beginning the study. The researcher briefed the participant on the study, and administered a simplified version of the Ishihara color perception test to exclude color blindness as a confound. After the pre-test questionnaire, the main study started.

Participants completed the task with each of three indicators, the mini-map, and no indicator. While the order of the video and simulations was fixed, the indicator orders were counterbalanced using an incomplete Latin Square. Before each task, they were trained on the indicator using visuals.

The entire study took approximately one hour and a half and was approved by our university's research ethics board.

V. RESULTS

We recruited 21 people (6 female) from our general university population (mean age 26), who received \$20 CAD for their time.

We found no effect of having indicators (vs. no indicator) on the search task performance (light-finding accuracy, One-Way ANOVA with planned contrast, $F = 2.1, p > .05$). The no-indicator case was excluded from all other statistical tests.

We use non-parametric statistics (Friedman's Test) on our ordinal awareness data. We found an effect of indicator type on awareness of relative robot distances ($\chi^2(3) = 11.2, p < .05$). The mean ranks were (lower scores are lower performance): Map=2.83, Halo=1.81, Wedge=2.93, Arrow=2.43. Planned contrasts were conducted against the map base case: people recalled the relative robot distances more accurately with Map than Halo ($Z = -2.1, p < .05$). Post-hoc tests (Wilcoxon Ranks Test with Bonferroni correction) found that people reported distances more accurately with Wedge than Halo ($Z = -2.7, p < .05$). All other comparisons were not significant. Fig. 4.A shows the within-participant performance of each indicator.

We found a trend for indicator to impact participant awareness of robot direction ($\chi^2(3) = 6.4, p < .10$). The mean ranks were (lower scores are lower performance): Map=1.95, Halo=2.69, Wedge=2.74, Arrow=2.62. Planned comparisons were conducted against the map base case, showing that participants recalled direction more accurately with Halo ($Z = -2.5, p < .05$) and Wedge ($Z = -1.9, p = .05$) than the map. Fig. 4.B shows the within-participant performance.

We found an effect of indicator type on how much it demanded participant attention ($F_{3,60} = 2.7, p < .05$, Fig. 5.A), with planned contrasts against the map base case showing that map (Mean=8.2) demanded more attention than arrow (Mean=4.9). Other contrasts are not significant.

We found an effect for participant confidence in their distance reports ($F_{3,60} = 4.8, p < .05$, Fig. 5.B), with planned contrasts against the map base case showing that participants were more confident with the map (Mean=22.8) than with Halo (Mean =15.5). No other effects were found.

No effects were found on confidence in direction, cognitive load scores, nausea, sense of speed, or how much participants felt an interface helped them maintain awareness.

A. Participant Feedback Analysis

We analyzed participant written responses, from the post-task and post-study questionnaires, to gain insight into some of the factors impacting indicator performance.

1) Readability

Many participants (15/21 people) explicitly mentioned how easy or difficult it was to extract information from an indicator. Nine found that Map was easy to understand for both the direction and distance, e.g., *"the scheme was easy to understand" – P4.*

In contrast, embedded indicators received fewer positive responses. Six people praised Halo for reading direction, e.g., *"easy to find the direction of other robots" – P20*, six praised Wedge, e.g., *"direction was easy to determine" – P14*, and eight praised Arrow, e.g., *"very easy to tell what direction the other robots are away from you" – P9*. Halo did not receive any praise for reading distance, whereas eight praised Wedge, e.g., *"easily able to tell which robot is the closest to my position" – P10*, and five praised Arrow, e.g., *"easier to tell the distance" – P8.*

Ten people said Halo was difficult to understand, e.g., *"not much cue for distance and specific direction" – P15*, four said Wedge, e.g., *"hard to tell the distance" – P7*, and four said Arrow, e.g., *"the size is difficult to see" – P14.*

2) In-feed Integration vs. Separation

Four people commented on the benefits of the integration of the embedded cues, e.g., *"the cue [Wedge] is part of the screen so you see them simultaneously with the green light" – P17.* Inversely, eight people commented on the problems of

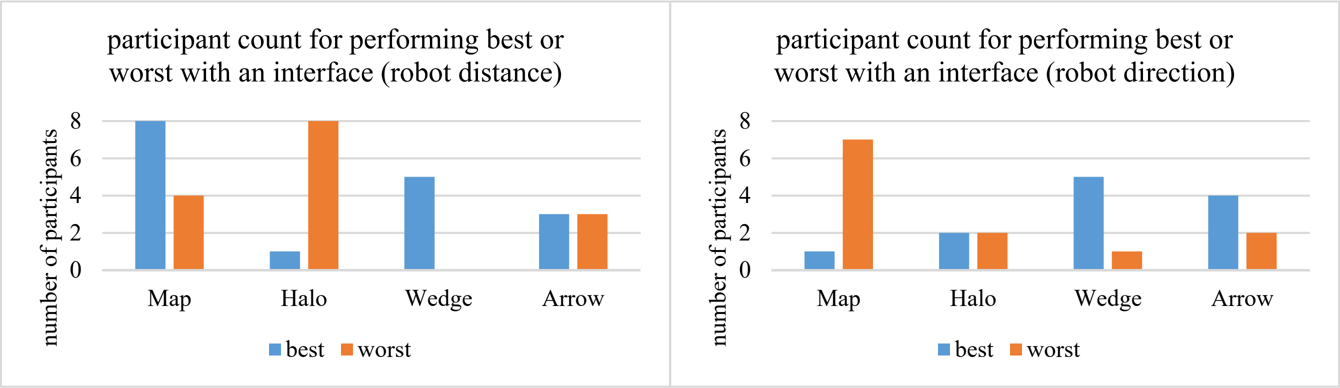


Fig. 4.A

Fig. 4.B

Fig. 4. Charts represent relative performance showing how many participants performed, best or worst, with a specific interface.

the separation with the map, e.g., *"in a way it [Map] was like a rear view mirror in a car … it was so detached that it felt like I had to take my eyes off the road to make a note …" – P13*.

3) *Difficulty and Confusion*

Ten participants noted difficulty distinguishing distances with Halo, e.g., *"very difficult to tell the direction because it is hard to distinguish curvature quickly" – P14*.

Further, two mentioned difficulties with cues, e.g., *"the wedges can overlap each other so it's harder to distinguish" – P3*, and one noted confusion with the length, i.e., *"I intuitively thought longer arrows would mean further away" – P3*.

4) *Attention Grabbing vs. Distracting*

Distraction was only mentioned by a few participants. One mentioned Halo was not distracting, e.g., *"not distracting when it comes to telling where the robot is from your position" – P10*, whereas another participant mentioned it is distracting, e.g., *"very distracting" – P20*. Similar words were mentioned for Wedge, e.g., *"less distracting than other cues" – P20*, with two people finding it, e.g., *"kind of distracting from the cue" – P9*.

Two participants reported that the map grabs too much attention e.g., *"not sure why but I find I was pretty absorbed into the cue [map indicator] that sometimes I missed the goal [light]" – P3*. This was not mentioned for other indicators.

VI. Discussion and Future Work

Overall, our results indicate that embedded, in-feed indicators serve as viable alternatives to mini-maps for helping a robot teleoperator maintain awareness of robot team members' locations. All three embedded indicators performed as well as or better than map for awareness of robot direction, and while the map appears to be the strongest performer for awareness of distance, Wedge and Arrow performed well in comparison to the map.

Among the embedded variants, there are signs that Wedge may be the best performer. The raw score data suggests that it may have performed better among all indicators, although further experimentation is required. Halo was generally a poor performer, as also commented on by participants, although it still performed better than map for direction awareness.

While overall there was no interface which outperformed the mini-map, both our quantitative results and participant feedback suggest that the map may demand more attention and require more operator monitoring than the other interfaces. In contrast, this was not clearly reflected in participant performance, and participants reported reasonably high confidence in their use of map. One possibility is that the difficulty of our primary task was not sufficiently high enough for this to impact the participant; this should be formally investigated.

The indicator is aligned in a way that the 3D world's surface direction information is placed in 2D in top-down (top as forward and down as backward). We believe that as many applications use this (e.g., navigation), people may be familiar with such translation. For future applications with 3D location information, we need to explore good perspective mapping of the embedded indicators to convey the information.

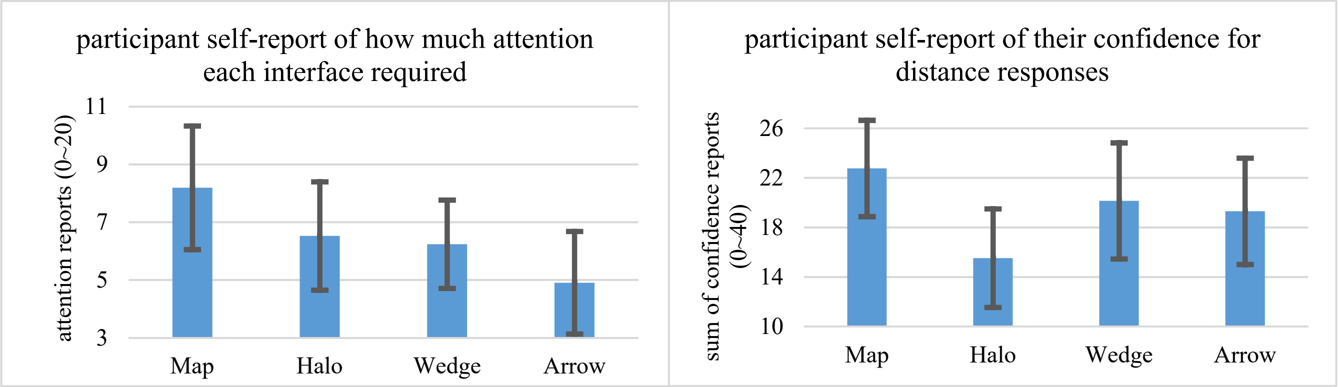


Fig. 5.A

Fig. 5.B

Fig. 5. All scales were 0~20, with higher scores indicating more attention demanded and higher confidence. Confidence was measured twice (once for closest, once for furthest, robot) and summed. Error bars indicate 95% confidence intervals.

This paper is a proof-of-concept step for using embedded indicators to support peripheral awareness of robot team members. Looking forward, we need to further investigate indicator design, looking for teleoperation specific improvements such as improved legibility in peripheral vision, while concentrating heavily on a target task. Further, we need to investigate how indicators can move beyond the top-down paradigm to fully utilize the 3D perspective, to further reduce mental mapping requirements.

In addition, we will survey existing techniques that scale up to many off-screen points (e.g., for swarms of robots), such as EdgeRadar [24].

VII. CONCLUSION

We demonstrated how in-feed embedded indicators of robotic team member locations can be applied when teleoperating a robot. Compared to a mini-map, which is an obvious solution for location information, they use less screen real estate, demand less attention, and require less mental mapping.

In addition, our results provide insight into some of the trade-offs between the in-feed embedded indicators, such as which are better for distance or direction information, or which demands more or less operator attention. This provides a roadmap for future work, continuing to improve location indicator design using peripherals.

Overall, our work contributes to the problem of teleoperation interface design, providing a way to support operators as they operate an increasing number of robots in various environment.

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