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AOA: Ambient Obstacle Avoidance Interface

Chua Wei Liang, Kenny [1], Matthew Johnson[2], Tom Eskridge[2], Brenan Keller[2]

***Abstract*— In this paper, we present a novel interface for teleoperating ground vehicles. Obstacle avoidance with ground vehicles demands a high level of operator attention, typically distracting from the primary mission. The Ambient Obstacle Avoidance (AOA) was designed to allow operators to effectively perform a primary task, such as search, while still effectively avoiding obstacles. The AOA wraps around a standard video interface and provides range information without requiring a separate screen. AOA combines and reduces different data streams into proportionately scaled symbology that directly shows important relationships between vehicle width, vehicle orientation and obstacles in the environment. The use of the AOA interface was tested in both simulation and on physical robots. Results from both tests show an improvement in obstacle avoidance during navigation with the AOA. In addition, results from the simulation test indicate that operators using AOA were able to leverage ambient vision such that the primary visual task was not impeded.**

I. INTRODUCTION

Most unmanned ground vehicles (UGVs) in use today are teleoperated and teleoperation remains an integral default mode [1] even in the few UGVs that claim to be semiautonomous. As an example, all of the 22 UGVs listed in the Unmanned Systems Roadmap [2] list teleoperation as a potential mode of operation and 17 of the 22 list teleoperation as the *only* mode of operation.

Teleoperation is a challenging endeavor for a variety of reasons, including limited field of view [3], viewing angle [4], degraded depth perception [5], difficulty maintaining situation awareness [1], and high workload. For teleoperation, the operator is burdened with the motor skill requirements for operating the vehicle, the need to establish and maintain situation awareness by building mental models of the remote environment, estimating distance, and detecting obstacles [6–8]. The task of navigating the vehicle imposes such a high workload that it often impedes the actual mission. The visual cues for a search or inspection task do not necessarily correspond to those of the navigation task and can therefore be overlooked if the operator is heavily burdened [1, 9].

To address the challenge of providing a better interface for remote operators, we present the Ambient Obstacle Avoidance (AOA) design concept. It is specifically designed to address the challenges of limited field of view, depth perception, difficulty maintaining situation awareness and high workload. The Ambient Obstacle Avoidance (AOA) interface advances UGV interfaces in two main ways. The first is by providing information lacking in many current interfaces. The second is by presenting the navigation data in a unique way that does not rely solely on focal vision, but can allow the operator to leverage ambient vision. This allows the operator to more effectively use their focal vision for the primary mission.

[1]DSO National Laboratories, Singapore (cweilian@dso.org.sg)
[2]Florida Institute of Human Machine Cognition (IHMC), Pensacola, Florida, USA (mjohnson, teskridge, bkeller)@ihmc.us

II. BACKGROUND AND RELATED WORK

Use of range data from sensors like laser or sonar range finders is a common technique employed to overcome the well-known limitations of video only teleoperation. The two main approaches to displaying range data are to provide a second window with an overhead map or to project data onto the video as can be seen adopted by many current robot user interfaces [10–14].

The overhead map (e.g. egocentric or exocentric map) technique provides spatial situation awareness with respect to obstacles in a 2D plane. This is the most common technique, as observed in the Robotics Rescue competition [15], as well as current operational control units. The video and map are typically displayed side-by-side in separate windows. These separate views lead to several problems. First, it requires operators to divide their attention between two displays. This can lead to missing important visual cues that may not appear in the overhead map, such as holes or other obstacles on the driving surface. It also means that the operator cannot as effectively perform a visually-based mission if their attention is frequently diverted to a non-camera based view. Lastly, separate displays increases the required screen real estate which results in a smaller video image. This may reduce an operator's ability to discern visual cues in the video.

Another less common approach to displaying range data is to overlay information on the video. There have been a few interfaces that have demonstrated this, such as Nielsen's work [16], but none have been adopted by others or integrated into deployed system. Additionally, a potential drawback of this approach is that overlaying depth cues on the display clutter the screen and obstruct the operator's view of the video. This can prevent the operator from picking up important cues from the video image which, in turn, could affect the mission or navigation task. More importantly, overlaying the same information as an overhead map is only effective if that information is sufficient to begin with. We discuss why we feel this is not the case in the next section.

III. AOA INTERFACE DESIGN

AOA was designed by following a Coactive Design [17] approach and by going back to "first principles" of vision science [18], cognition and Human-Centered Computing [19].

Coactive Design [17] is a new approach to address the increasingly sophisticated roles that people and robots play as the use of robots expands into new, complex domains. It also provides an excellent guide to interface design, even when the roles are very basic, such as those of teleoperation. There are five main questions that capture the knowledge necessary to safely navigate:

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1) *Where are the openings (navigable areas)?*
2) *Can I fit through them?*
3) *Am I currently oriented in a way that allows me to fit through?*
4) *Have I past the obstacles?*
5) *How fast should I turn?*

Video alone only answers the first question. An overhead map or overlays address questions 1, 4 and 5. However, questions 2 and 3 are not adequately addressed by any current interface. Knowing whether or not the robot will fit through and opening based on its current orientation is a key navigation question that typically involves estimation by the operator. This is true of both the traditional overhead map systems as well as the overlay systems. The AOA interface aims to aid an operator to answer *all* of these questions better, which we will describe in detail in the following sections, and does so in a way that does not demand focal vision.

Our visual field can be divided into 3 main channels. Focal vision, which is closely related to central or foveal vision, is required for fine detail and pattern recognition. Visual search, object recognition and tasks that require high visual acuity (including reading text) are some of the primary functions of the focal visual system [20–22]. Peripheral vision involves detection of motion and contrast, and is primarily useful for attention getting. In contrast, ambient vision lies between focal and peripheral vision, and is used in spatial orientation and postural control that can be accomplished without conscious effort or awareness [22–24]. When a person is driving a car, all three of these channels are simultaneously active, as when a driver reads a road sign (focal), while steering a car through a turn in the center of the lane (ambient), and noticing another car pulling out into the street (peripheral). Reliance on the focal resources is prevalent in many current conventional robot interface designs, including the overhead map approach.

In order to leverage both the focal and ambient channels, the AOA design concept is constructed using visual perceptual primitives which are organized into a functionally relevant symbology using well-known principles from visual perception. This symbology uses dots, lines, and changes in color and motion to allow the visual system to extract information at the earliest stages of perceptual processing. Lines and dots, for example, are a notation that is easy to read, because the visual cortex of the brain contains mechanisms specifically designed to seek out continuous contours [25, 26]. The addition of color, scaling, and motion were used to cause the primitives to achieve a "pop out" effect. A target can be easily detected if it differs from its surroundings by orientation, direction of motion, or color. All of these differences trigger a greater neural response in the primary visual cortex [27, 28]. These "pop outs" serve as preattentive cues and allow operator to detect changes and quickly make the necessary adjustments.

To reduce the cognitive workload of instrument scanning, AOA uses an egocentric frame of reference that complements the video feed to provide a single unified display that can be clearly and quickly understood. Egocentric maps or rotating maps are better for navigation of the robots as it avoids the cost of mental rotation due to its robot centric reference [5, 29]. In addition, AOA combines and reduces different data streams into a proportionately scaled symbology that directly shows important relationships between vehicle width, vehicle orientation and obstacles in the environment. This enables the operator to easily understand the available options and react to them quickly. The next section elaborates on use of the AOA interface.

IV. Using the AOA Interface

The AOA uses range data, but unlike other approaches it does not add additional views or windows. It is incorporated into an existing camera view by wrapping around a standard video interface. The AOA interface is composed of two primary visual cues: a range ring and a vehicle width indicator (Figure 1). The range ring displays information about the range and bearing of obstacles. Darker shading of the ring indicates closer obstacles and lighter shading indicates obstacles that are further away. We also used a non-linear grey scale which provides better "pop out" of corners. The vehicle width indicators are composed of two red dots and one green dot. The green dot corresponds to the centerline of the vehicle while the two outer red dots correspond to the left and right edges of the vehicle, respectively. The red dots scale appropriately with the distance to the nearest object and provide obstacle clearance information. The width indicator provides a dynamic vehicle width indication that accounts for actual vehicle width current obstacles. It uses a separate calculation for the right and left markers.

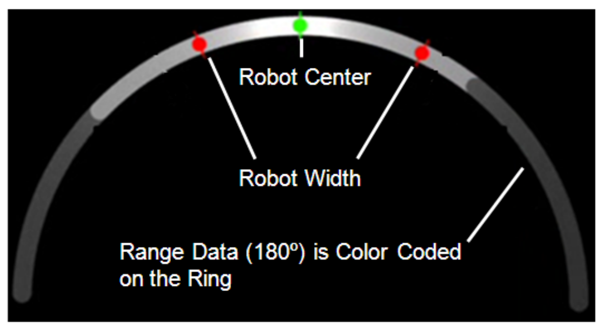

Figure 1. Various components of the AOA design

Since the nearest obstacles can be closer on one side than the other, the width indicator can be asymmetric, meaning the left red dot may not be the same distance from the green center dot as the right red dot. From Fig. 2, we can see that the red dots form an asymmetric width due to the left object (barrel) being closer to the vehicle as compared to the right object (distant wall).


Figure 2. Illustration of asymmetry in the vehicle width indicator due to the left object (barrel) being closer to the vehicle as compared to the right object (distant wall).

The lighter zones of the range ring answer the question about where the openings are. Range sensors typically have a much wider range then a video image and leveraging range information in the interface can reduce the need to pan the camera or maneuver the vehicle in order to know where to navigate. Overhead maps do provide this information, but require shifting focus to a separate display.

The relationship between the red width indicators and the darker zones of the range ring provide the answer to the second question about whether or not the vehicle will fit through an opening. As an example, Fig. 3 shows the red width markers are in the grey zone, which means the vehicle cannot fit between the barrels in the camera image. Neither cameras nor range data alone can provide this directly. For example, overhead maps and even the overlay techniques require the operator to mentally project their vehicle width to the opening and estimate if there is sufficient room. This typically results in overly cautious driving. Not only can the AOA interface provide this information, but it can provide it from a distance, up to the full range of the sensor.

Figure 3. AOA answering: Can I fit?

It is also important to know if the vehicle's current orientation allows it to fit. Fig. 4 shows a very wide opening to the right of a wall that the vehicle can easily fit through. It is unclear from the camera image if the vehicle is aligned to fit through the opening. This form of representation clearly allows the operator to interpret the vehicle width with respect to the obstacles directly while reducing the need to constantly switch, remembering and estimating information obtained from overhead maps and range data overlays. The AOA interface clearly indicates that the vehicle will clip the wall on the left side. This is indicated by the left red width marker overlapping the gray zone on the range ring. Not only does the AOA interface indicate the pending collision, but it specifies how much change needs to happen to remedy the situation. Simply turn until the red width marker is in the lighter zone. Again, neither cameras nor overhead maps provide this information.

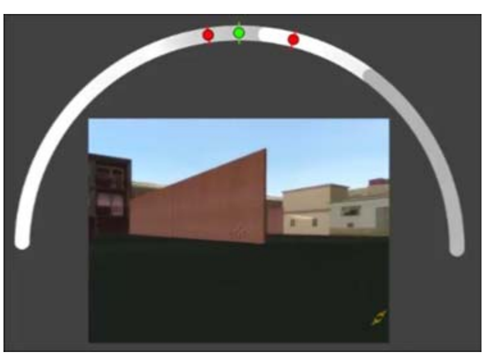

Figure 4. AOA answering: Am I currently oriented in a way that allows me to fit through?

The fourth question is about whether the vehicle is past an obstacle or not. This is not available to video-only interfaces, but is readily available with overhead map interfaces. Fig. 5 shows a vehicle approaching a right hand turn (right side) and the AOA interface view from onboard the vehicle (left side). With video-only, the operator usually has to constantly check by turning or panning in order to be aware of the edge/corner due to the limited field of view. This constant checking can slow down the vehicle transit. From the range ring, the dark/light boundary indicates the corner, as it approaches the right edge of the range ring it indicates it safe to turn. This is available on overhead maps, but requires focal vision. The AOA interface allows the operator to sense the corner with the ambient channel. You can try this by staring at the center of the video image on the left side of Fig. 5 and noticing that you can still sense the corner.

Figure 5. AOA interface: When and how fast should I turn?

Similarly, the fifth question about rate of turn is typically not available in video only interfaces, but is easily accessible in interfaces that leverage range data. Typical overhead map-style interfaces use the relative motion of a vehicle icon to range measurements, though the vehicle icon may not accurately represent the vehicles dimensions. The AOA interface uses the relative motion of the red width indicators to the darker regions and is accurately scaled to the vehicle dimensions. Additionally, it can leverage the ambient visual channel.

To explore the performance potential of the AOA interface, we conducted two experiments, one a simulation experiment and the other a physical robot pilot study.

V. Simulation Experiment Method

The primary focus of the experiment was to evaluate the effectiveness of this interface in the teleoperation of a UGV through space without colliding with hazards. A secondary focus will be to evaluate the performance of using this interface with an addition of a secondary focal task. This secondary task will engage the focal vision and help evaluate the operator's ability to use the ambient channel for navigation.

A. Experimental Design

The overall design of the study was a one-factor, within subject design. The three within study variables in this study were video only (V), video and AOA (VA), video and AOA with a secondary task (VAT).) The participants took on a role of an operator teleoperating a robot through a one-way course. The primary task for the participant was to finish the course as fast as possible without colliding with any obstacles. In the VAT condition, there was an additional secondary task where the participants were required to constantly read out a number (1 number/second) that was displayed in the middle of the video feed. In this study, time to complete course, number of collisions, NASA workload score [30] and feedback were the performance measures collected.

B. Experiment Setup
This experiment was conducted on a simulator using the Virtual Battlespace 2 (Bohemia Interactive) simulation environment. Test participants were taken through programmable scenarios in the simulated world. The simulator included test scenarios for training which were different from the scenarios used for the actual experiment (Fig. 6). Careful considerations were made to ensure that the scenarios were of similar difficulties. Each scenario contained four tight right and left turns, two narrow alley ways, one slanted alley way and two rooms for open search. The sequence was counterbalanced across participants to reduce the effects of learning.

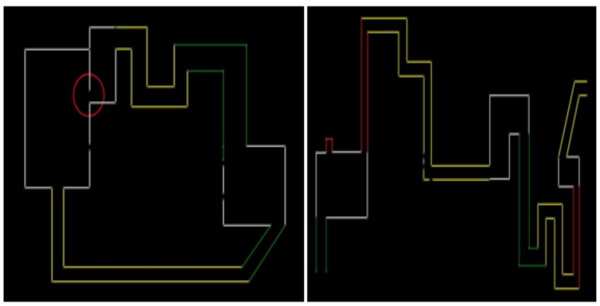

Figure 6. A training scenario and one of the actual scenarios

C. Participants
A total of 15 participants took part in this study in Singapore. The group of participants came from either the user community or from the project management team. Training was carried out before the experiment to ensure that the participants understood their roles and were familiar with the controls.

VI. Simulation Experiment Results and Discussion

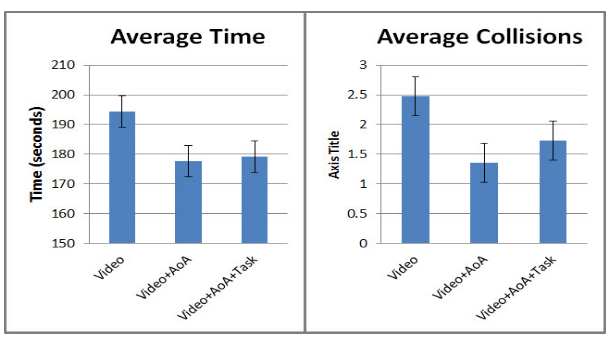

Figure 7. Results for time to complete and number of collisions.

The results from the simulation experiment are summarized in Fig. 7. As we predicted, the AOA interface showed significant reduction in collisions over video alone. It also showed a significant improvement in time to complete the course. (177.6s and 1.36 collisions) against V (194.33s and 2.47 collisions) (Fig.7). Based on observations, participants using the video mode only tended to be more cautious and took wider turns when approaching corners. This behavior could be an explanation for the longer time needed to complete the course. In addition, AOA presented the environment and location of obstacles in a way which could possibly improve the situation awareness of the operator leading to better navigation performance as compared to the video only mode. Comments from participants supported this view as most participants commented that the addition of AOA allowed them to sense the environment and location of obstacles better.

Reading numbers aloud while driving is a demanding task due to the overloading of the focal channel which is usually used for hazard detection and identification. The number was presented in the middle of the video (1 number/second) and required the participants to constantly focus at the center of the video in order to read the number. If AOA supported this auxiliary focal task, it would indicate reliance on the ambient channel and that the AOA symbology permits parallel comprehension of information. Results from this study indicated no significant difference in performance for VA (177.6s and 1.36 collisions) in comparison to VAT (179.14s and 1.73 collisions). This result suggests that with the introduction of AOA, the auxiliary focal task did not impact the navigation performance. Based on the workload scores compiled, the introduction of the secondary task did caused a significant increase in perceived workload ($p=0.001$) especially in mental workload but that did not significantly affect the navigation performance. Thus, AOA supported an operationally relevant focal task, reading, without significantly impeding navigation performance.

VII. Physical Robot Pilot Study Method

We conducted a pilot study using physical robots. We did not employ the secondary task for the physical robot experiment and focused solely on the primary task of teleoperation of a UGV through space without colliding with hazards.

A. Experimental Design
The overall design of the study was a one-factor, within subject design. The within study variables in this study were video only (V) and video and AOA (VA). The participants took on a role of an operator teleoperating a robot through a course. The primary task for the participant was to finish the course as fast as possible without colliding with any obstacles. In this study, time to complete course and number of collisions and feedback were the performance measures collected.

B. Experiment Setup
This experiment was conducted on a Pioneer 3AT robot (19" wide) using three different obstacle course environments. The operators were situated remotely and were given a training period before 5 tests were conducted, alternating the interface from video only (V) to video and AOA (VA), for a total of 10 runs per participant for the experiment. The runs included 4 runs on a wide maze (~55" wide), 2 runs through an open room with obstacles, and 4 more runs through a narrow maze (~33" wide). The course layouts are shown in Fig 8. Due to our limited number of participants, we did not counterbalance for this study, but this would be useful for future work.

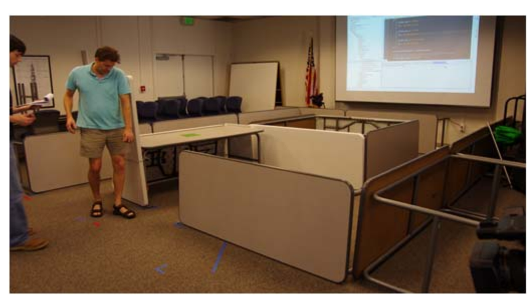

Figure 8. Test environments for physical robot experiments. A) A wide maze B) an open room with obstacles C) A narrow maze

C. Participants

A total of 5 participants took part in this study in Florida. This group of participants were co-workers in our organization, though none worked on this project. Training was carried out before the pilot study to ensure that the participants understood their roles and were familiar with the controls.

VIII. Pilot Study Results and Discussion

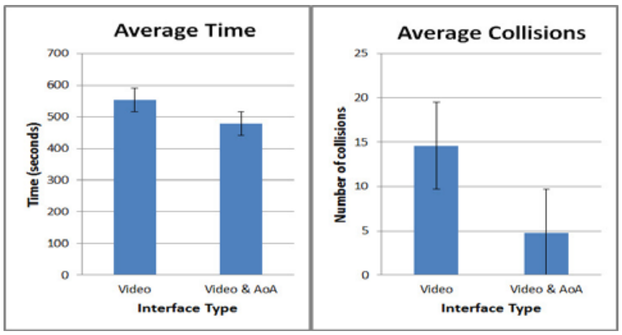

Figure 9. Results of pilot study for time to complete and number of collisions across all runs

The results are summarized in Figure. 9. As we predicted, the AOA interface showed a significant reduction in collisions (p=0.003) over video alone. Interestingly, it also showed a significant improvement in time to complete the courses (p=0.01). This is consistent with our simulation results. Additionally, the improvements are consistent across all challenge types, as shown in Fig. 10. It should be noted that the more difficult challenge, the narrow maze, shows the greatest improvement.

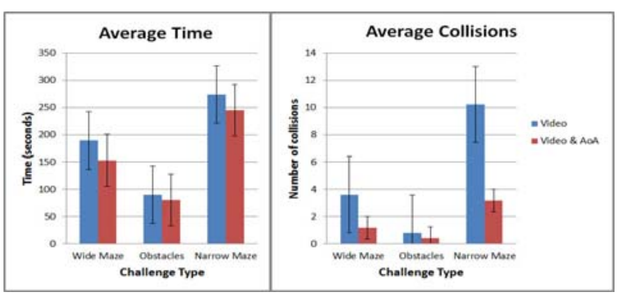

Figure 10. Results of pilot study for time to complete and number of collisions across by challenge type.

As no counterbalancing was done, one effect that could affect our results in this physical robot study was the learning effect. The results of the maze runs, where each participant did four runs alternating video only and video and AOA, are shown in Fig. 11 for each maze type. There seems to be some learning going on, particularly when you look at the average times which got better with each run. However, the average from run 2, the first video and AOA run, to run 3, the second video only, did not show much improvement. Additionally, collision results revealed a very different story. There was no discernible learning on the video only runs as they had very similar average number of collisions. The video and AOA runs showed improvement on the narrow maze, but the wide maze had so few errors that there seem to be no discernible learning. From these preliminary results, we would suggest that there is some learning with video only, but its effects are not significant. We hypothesis that the video only lacks integral information needed to answer the questions on the operator's mind, and thus many of the operator's decisions were guesses. In contrast, the video and AOA interface showed a great capacity for learning since it provides additional important information required by the operator. Both of these hypotheses still requires further investigation.

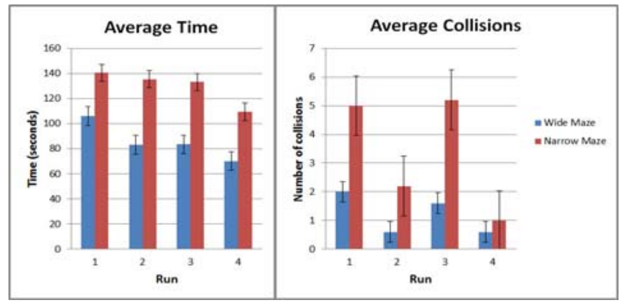

Figure 11. Results of pilot study for time to complete and number of collisions by run number for each maze type. Runs 1 and 3 are Video only and runs 2 and 4 are AOA.

There is another effect observed during UGV operation that is not easily captured in the data: the quality of driving. While we can only support the claim with our observations, there were notable driving differences with the two interfaces. The video and AOA interface had several quality improvements over the video only display. These differences included:

- Less "guessing" and more calculated measuring
- No stop-and-look maneuvers
- Smoother cornering
- Error correction
- Preemptive collision avoidance

An example of guessing was observed with the video only display as operators tried to enter the maze. It was common for the operator to make a single alignment far from the door and to go forward without any adjustment, in a sense "guessing" that they were aligned. This resulted in several collisions. With the video and AOA display, operators would make several small alignment maneuvers and then adjust as necessary as they got closer to the door.

The stop-and-look maneuver is where the operator would approach a corner, but could not tell if they were past it in order to turn. The typical video only behavior is to stop, turn the robot to look if the robot is past the corner, then turn back and go a little further and stop-and-look again until the corner is past. The video and AOA display eliminates this behavior entirely.

Video only turns tend to be square. The operator drives to the middle of the turn, then commences a ninety degree turn (after a series of stop-and-look maneuvers) and drives straight again. The video and AOA display encourages a smoother turn that begins at the corner and follows a rounded trajectory to the center of the next passageway.

There was very little correction to small errors with the video only interface. If the vehicle is not centered in the passageway, it will continue off-center. If it happens to be close to a wall, it will continue, seemingly oblivious to the nearness to a collision. With the video and AOA, operators are observed correcting these small deviations, indicating a greater awareness of the situation.

Operators are bound to make some errors during operation. One sign of a good interface is if it can give the operator feedback that indicates the error *prior* to a collision. The AOA interface does just that. A few collisions were avoided entirely by the operator with video and AOA stopping prior to impact. This preemptive collision avoidance never occurred with video only.

These observations indicate that the AOA interface promotes a better quality of driving which probably contributes to the collision reduction.

IX. CONCLUSION

Our initial experiments have shown that the Ambient Obstacle Avoidance (AOA) interface is an effective tool for assisting in the teleoperation of remote vehicles. Our initial results in both simulation and physical robots indicate that the interface does indeed leverage ambient vision to allow the operator to more effectively navigate while still being able to focus primarily on the mission. The AOA interface has potential beyond remote teleoperation as well. It could be useful in any domain with similar issues such as driving in reduced visibility or firefighters navigating a smoke filled building. More evaluation is needed, but the AOA interface has shown great potential.

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