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AR Visualization for Coastal Water Navigation

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Abstract

When conducting Coastal Water Navigation, a ship's Navigating Officer (NavO) has multiple sources of data to consider. To obtain the information required to safely manoeuvre the ship, they make use of specialized equipment. The time spent interacting with the equipment is a risk, as it prevents them from visually monitoring the ever-changing maritime environment. Data visualization through Augmented Reality (AR) offers a way to obtain the information while maintaining a proper and effective lookout. Additionally, our research suggests that the information can be presented in new ways. We created a simulator that allows testing and evaluation of AR Navigation Aids (ARNAs). These visualizations were evaluated by subject matter experts through a user study. The user study suggests that ARNAs can improve maritime safety and assist in the conduct of navigation.

Introduction

The duties and responsibilities of professional marine navigators are outline in detail in the American Practical Navigator (Bowditch) [1]. These duties are onerous. They require that Navigating Officers (NavOs) spend years mastering an ability to maintain spatial awareness while conducting coastal water navigation (hereafter referred to as Pilotage). Pilotage is a form of marine navigation in which the NavO finds themselves near dangers while in high densities of vessel traffic. We use the word “dangers” to refer to potential hazards that may result in grounding of the vessel. This task requires managing multiple and variable inputs to prioritize actions.

To gather crucial information necessary for Pilotage, the NavO is forced at times to look away from the quickly changing dynamic environment to interact with equipment. For example, this may be the time spent interacting with an Electronic Chart Display and Information System (ECDIS) or a radar display. Although the information gained is vital to Pilotage, interacting with the equipment introduces necessary risk.

This research addresses this problem by using AR visualization to assist in the conduct of Pilotage. We suggest that the vital information required to conduct Pilotage could be displayed on the Optical See Through (OST) device without requiring the NavO to look away from the bridge windows. To examine this issue, we conducted a survey of many different fields of study and current research ventures.

Prior Work

We examined the evolution and current state of AR devices and their limitations. We look at the research related to designing AR visualizations, including using VR as a development platform. To determine the value of the created visualizations, we looked at some techniques to appraise and validate visualizations. This was followed by a more specific look at how current AR visualizations have been developed for Pilotage.

Current AR Device Limitations

The ability to augment the physical world with the digital world has widespread application. Use cases have been envisioned for many aspects of industry, from tourism and sightseeing to unmanned aerial flight systems. Increasing Central and Graphics Processing Units performance coupled with new innovations, such as the holographic processing unit of Microsoft’s HoloLens, mean these use cases can begin to be realized [2].

AR devices have improved significantly from the days of backpack computers and radio modems. Current trends indicate that untethered, standalone wearables are the future of AR. Better FOV arcs, more realistic rendering and better UX design may help to improve user engagement. As hardware becomes smaller, it is expected these devices will continue to become less cumbersome and lightweight. It may take many years before these devices become as lightweight and innocuous as reading glasses, but AR devices are currently finding a place in the market. Other implementations of AR, such as using smartphones, demonstrate the diversity of this technology.

Descriptors/Common Traits

By reviewing the different implementations of AR devices over time, we can see some trends that help to describe the state of AR devices. In this section, we propose descriptors that can be used to help describe the differences between AR device implementations, and which may allow us to estimate future implementations.

One such descriptor is weight. The trend here has been to move towards lighter weight devices. However, a common complaint with the HoloLens is that it is still too heavy, which becomes an issue when worn for prolonged periods of time.

Another descriptor is processing power, which has naturally increased with advancements in hardware over time. This has allowed the processing required to be done with smaller subcomponents. It has also allowed wearable devices to become untethered, such as with the HoloLens. When tethered, the components have also become smaller, as seen with the belt attachment of the Magic Leap.

Another way to compare AR devices is by the size of their field of view (FOV). A human’s FOV has approximately 210° horizontal arc and 150° vertical arc. The original HoloLens offers a much smaller field of view (35°) that can make the visualizations seem disconnected from the real environment. The HoloLens 2 increases this to 52°. The Meta 2 offers a much wider FOV of 90° but it requires the user to be tethered to a desktop computer.

Designing AR Visualizations

AR continues to become more prominent, and the visualizations used can take many forms. It is important to consider how these visualizations are designed to ensure user engagement is maximized. These visualizations can provide the end user with knowledge about his environment, but they should also avoid breaking the viewer’s immersion with the world around him [3]. Considering other avenues for visualizations, rather than just conveying pertinent information may be necessary.

Zollmann et al. tackled the problem of change blindness (a concept derived from psychology where a viewer fails to recognize changes in visual stimulus) when visualising time related data [4]. As an example, they applied AR visualizations of a building construction. They broke the visualization down into multiple layers of complexity, from overview to detail, in a blended view.

Chang et el. researched designing AR visualizations of a 3D crystal macromolecule. The modelling of the object was quite simply a combination of spheres (representing atoms) and pipes (representing the bonds between atoms) [5]. Chang et al. used ARToolKit to place the visualization in a position and orientation relative to placed cards. Through a process of computer vision, ARToolKit was able to calculate the placement of the models effectively and efficiently.

How each medium can exploit human perception and impact interactions with visualizations was studied in detail by Bach et al. [6]. They determined that no one medium is best overall for all tasks, each demonstrating that it could be better suited than the other's based on the task at hand. They also demonstrated that interacting with 3D models can help improve the user's perception of it. The way in which the model was interacted with also changed depending on the medium. They suggested many different combinations of mediums and interactions, swapping from one representation to the other, and combinations of real-world visualizations with augmented visualizations, is the future of this technology.

Methods of Appraising Visualizations

Visualizations provide a method for consumers of information to understand and interact with data. The quality of the graphical representation and the interaction are dependent upon the design and implementation of the visualization. Therefore, it is necessary to evaluate the efficiency and effectiveness of visualizations. How best to appraise visualizations is an area of active research interest.

Juarez, O. et al. considered appraisal methods that focus on the tasks being supported by the visualization [7]. They deemed it important to have evaluation methods that consider the time required to perform a task and the quality of the solution of the task. Unfortunately, they did not provide concrete ways of assessing the quality of the solution of the task outside of subjective evaluations. As such, they aim to provide a task taxonomy and "definition of quality solution for each type of task", developing models to analyse task performance, and consider other performance metrics such as data quality. That said, based on their subjective analysis, they formed a few conclusions: users did better when interacting with graphical visualizations and users were more interested in summaries of data than the details.

Larkin and Simon focus on what they called "external problem representations" [8]. They investigated methods of contrasting diagrammatic representations with sentential representations in information systems. Here, sentential representations form "a sequence corresponding, on a one-to-one basis, to sentences in a natural-language description of the problem." Diagrammatic representations provide the same one-to-one mapping but via components of a diagram. Unlike sentential representations, diagrammatic representations have the benefit of preserving spatial information.

Rhodes, P. et al. determined visualization quality to "mean those attributes that correlate with the ability of a visualization to convey a desired concept" [9]. They present a software package called VizEval that allowed them to design and evaluate visualizations, and experiment with the impacts of changing visualizations. They see the ultimate goal of a visualization as helping the user understand the intended message of the visualization, and as such looked at how visualizations impact user comprehension. They did experiments on how different visualization techniques impact a user's ability to notice change and to indicate where the change occurred (detection and localization).

Through experimentation, they found that changes in visualization techniques could help detection and hinder localization, and vice versa. This indicates that some visualization techniques may be better suited to some tasks than others.

Fittkau et al. suggest that empirical methods, such as controlled experiments, are required to assess the efficiency and effectiveness of visualizations [10]. After they conducted an experiment to assess the difference between two different visualizations, they conducted a second experiment to validate their results. By successfully arriving at the same outcome again using a different group of participants, they were able to increase confidence in their results.

Yet another set of criteria is established by He et al. [11]. They suggest that visualizations, which are normally either three dimensional or two dimensional should "exactly and effectively reflect the information from the higher dimensional space." This may be problematic as visualizations may summarize data in a way that is more easily digestible to the user which would allow them to gain insights into the data without containing all information. They show that just as visualizations can be quite different, the methods in which they are compared can also take many different forms.

There is no single standardized way to evaluate a visualization as being superior to another. Many researchers apply different techniques to appraising the efficiency and effectiveness of visualizations. Likely, a combination of qualitative and quantitative data collection is necessary when attempting to compare different representations of data.

Visualizations for Coastal Water Navigation

In this section, we survey the current research into visualization of Pilotage data. We conduct a review of the domain issues identified by the current research.

Xueling Wu et al. examined organizing and describing geospatial data through the lens of cognitive psychology [12]. They examined the process of making mental transformations between the real-world view and the geographic representations. They determined that these mental transformations directly impacted decision making ability.

Morgére et al. indicated that the matching of items on a nautical chart to the real environment is error prone and has a large time cost [13]. They determine that this issue is made more challenging in cases of restricted visibility, at night and in bad weather, with operator stress being the greatest contributor to error. They identify that the unstable nature of a ship compounds this issue. Morgére et al. determine that displaying all available information at once would overload the user, and there needs to be a determination of what information is best to display.

Supporting these findings, Jaeyong et al. indicate that one of the main issues with current navigation equipment is the excessive amount of information [14]. This is compounded by large amounts of unnecessary information which they determined interfere with safe navigation.

Another factor affecting Pilotage is the current way in which the information is visualized. Current visualizations require the navigator look down and away from the bridge windows. Vlaming et al. indicated that when the officer is looking at instrument panels and charts, their attention is turned away from the view outside the bridge [15]. They refer to this as head-down time, the length of which has a direct impact on maritime safety and the officer's situational awareness.

From experimenting with their system, Jaeyong et al. found that the overlay of ship information was more effective than existing navigation systems [14]. However, sometimes the overlay interfered with recognition. In addition, they used the same size symbols for point features. This caused an issue with not being able to accurately judge distance. In addition, there were issues with the traffic information being impossible to distinguish as multiple ships along the same bearing had their information blended. Additionally, the GPS had location errors that caused registration errors. Also, there was a harder time distinguishing data due to excessive amounts of information on the horizon.

Xueling Wu et al. establish that registration is one of the key issues [12]. They conducted research in camera-based approaches, making a series of matrix transformations from real world coordinates systems to virtual coordinates systems and finally to screen coordinates as an attempt to solve the problem. They tackled the issue of registration by positioning the camera in virtual space based on latitude and longitude information from GPS and attitude (pitch and roll) information from an Attitude/Heading Reference System (AHRS) sensor.

Existing Navigation Aids and Tools

To establish domain knowledge and to determine the types of visualizations which would be beneficial in improving navigation, we briefly examine existing tools and aids to navigation developed for this purpose. We consider how real-world objects are visualized on paper and electronic displays in the form of chart symbols.

A nautical chart is a crucial element of navigation. It is used in the planning and execution of navigation passages. In the planning stage, it allows the NavO to identify courses and planned course alterations. These courses are plotted with consideration of hazards to navigation, ship's turning characteristics, depths of water in relation to the ship's draught and safety margins, and navigation aids. In the execution phase, the chart is used to fix the position of the ship in relation to the plan track and determine appropriate courses to steer to regain the planned track. In fixing and plotting the ship's position, the NavO can obtain the impact of ocean current and wind. The course through the water is a combination of ship's heading, speed rung on and environmental factors. This course is known as the Course Made Good (CMG). Once the NavO is able to determine the CMG, by correcting for this impact, the NavO is able to determine the Course To Steer (CTS) to maintain the desired course.

Although paper charts are still in use, they are primarily kept only as a backup in case of equipment failure. They need to be manually updated, and plotting position is much more time consuming than using a system that can interact with Electronic Nautical Charts (ENCs). ENCs allow interaction with sensors, such as the Global Positioning System (GPS) during Pilotage, to constantly update the location of the ship on the chart. These charts must conform to international standards to be deemed safe for navigation and to be used within Electronic Chart Display and Information Systems (ECDIS). Charts can be encoded in different ways, such as the S-57 Vector format used by Canadian Hydrographic Service CHS [16]. These layers can be decoded and analyzed using the Geospatial Data Abstraction Library (GDAL) [17].

ECDIS provides nautical chart data in an interactive way. One version, known as the SHip's INtegrated Navigation and Display System (SHINNADS) is used by the RCN. This system allows the NavO to augment the current nautical chart in many ways. These chart augmentations, such as Limiting Danger Lines (LDLs) and Clearing Bearings are carryovers from paper chart navigation. These augmentations will be considered when determining and designing ARNAs.

There are also various types of aids to navigation. Floating aids such as buoys convey meaning to the NavO through a combination of distinguishing features. In addition to determining the identity of a buoy by verifying its position with a navigation chart, there are visual cues that can help determine the buoy's identity.

Like floating aids, fixed aids use a combination of colour and shapes to help in their identification. Unlike floating aids, fixed aids can take advantage of their known position. Although floating aids are fixed to the ocean floor, ocean currents and sea swell can affect their exact location by several metres. In contrast, as fixed aid locations are known, they can be used in ways that are not feasible for floating aids. For example, ranges can help the observer know how they are in relation to the planned navigation track.

Radio Aids can be attached to fixed and floating aids. These emitters provide a signal that can be interpreted by a radar display and drawn when the ship is at a specified range from the beacon. The line originates from the estimated position of the beacon and is drawn in a line towards the ship. The line can take a pattern of short and longer lines, like the dots and dashes of Morse code, or it can be a solid line [18].

Radar is an essential tool in the conduct of navigation and collision avoidance. Even without electronic navigation charts and GPS, it is possible to conduct safe navigation in restricted visibility with the use of radar.

Upon examination of existing navigation aids and tools, we note that colour is an important component in determining the meaning behind navigation aids. We also observe that NavOs have experience with a standardized set of symbols representing objects of interest. These symbols are consistent across paper and digital mediums. As such, when designing ARNAs that represent these items it may help recognition if these symbols are incorporated.

IMO e-Navigation Strategy (IMO 2008)

In designing our AR navigation system, we adopt the International Maritime Organization (IMO) e-Navigation strategy [19]. IMO is working to produce guidelines and standards on how e-Navigation devices should be developed to ensure a harmonization of marine navigation systems. Although this strategy is still in draft form, the use of AR devices at sea for marine navigation will need to conform to the IMO e-navigation device guidelines once developed.

The IMO e-Navigation strategy analysis on the need for electronic aids to navigation are in line with the motivations of this work. The strategy's suggested solution to reduce this risk involves secondary review of decision-making processes and improved on-board systems. Although the approach taken by IMO to provide the secondary review is to send that review to a shore facility, improving onboard navigation decision making systems is one of the main motivators of this research.

The strategy outlines the following vision: navigation systems that benefit from the integration of own ship sensors, supporting information, a standard user interface, and a comprehensive system for managing guard zones and alerts. Core elements of such a system will include, actively engaging the mariner in the process of navigation to carry out his/her duties in a more efficient manner, while preventing distraction and overburdening.

The IMO e-Navigation strategy outlines a series of basic requirements for the implementation and operation of e-Navigation.

These requirements are outlined here along with a summary of how the development of the ARNA system can fulfil the requirement

Requirement: User Needs

The strategy states that the "implementation of e-Navigation should be based on user needs not technology-driven and over-reliance should not be placed on technology to avoid". In the table below, we consider how the development of ARNAs relates to these considerations.

How ARNAs can mitigate impacts of technology

Impacts	ARNA Mitigation
Failures because ship is now deemed unseaworthy	ARNA augments decision making. Failure of system will not result in the ship being deemed unseaworthy, as current practice and navigation systems are still in use.
Loss of basic good seamanship by crews	ARNAs are in accordance with best practice for navigation. Rather than replacing current methods, ARNAs will visualize the method. This ensures navigator continues to implement these practices.
Inappropriate substitution of the human element by technology	The ARNA system is focused on providing visualization to assist the human decision-making process and does not aim to replace the navigator.
Degradation of bridge resource management & best practices by the crew	ARNA is aimed to facilitate bridge resource management by allowing the NavO to spend less time extracting information from data. By presenting information in a heads-up display, the NavO will be better able to make decisions and focus attention on managing the bridge and the team.

Requirement: Operating Procedures

The IMO e-Navigation strategy presents the following requirement: "operating procedures should be put in place and kept under review, most notably in relation to the human/machine interface, the training and development of mariners and the roles, responsibilities and accountabilities of ship and shore-based users". The development of an ARNA system will have training impacts. In initial cadre training, the NavO will require training with and without the ARNA system.

Requirement: Mariner continues to play core role

The IMO e-Navigation strategy presents the following requirement: "the mariner should continue to play the core role in decision making even as the supporting role of the shore-based users increases." The ARNA system is solely focused on providing an onboard system. Even if shore-based information is provided to the ARNA system the data would be presented to the user to assist in their decision-making process.

Requirement: Human Factors and Ergonomics

The IMO e-Navigation strategy presents the following requirement: "human factors and ergonomics should be core to the system design to ensure optimum integration including the Human Machine Interface (HMI), presentation and scope of information avoiding overload, assurance of integrity and adequate training".

Our research considers how best to visualize information and present it to the operator in a way to ensure an optimum HMI and information presentation. The purpose of ARNA is to reduce operator overload. As such, verification of this requirement is assessed via user study and results analysis.

Requirement: Adequate Resources

The IMO e-Navigation strategy presents the following requirement: "adequate resources should be made available and assured both for e-navigation itself and the necessary enablers such as training and radio-spectrum".

The number of resources should be determined through a risk analysis conducted for each end user. That said, a few basic assumptions can be made to provide resource recommendations. For every ship, there should be a minimum of 1 x headsets available for each operator. Discussion with end users in the development of the CONOP will indicate the number of end users.

Training facilities would require devices for the training of ship's officers for each of the center's Navigations and Bridge Simulator (NABS). For training facilities, every bridge simulator should have multiple headsets for use by students as well as instructors. As such, there may be 4 headsets in use at a time per bridge.

Requirement: Measured Implementation

The IMO e-Navigation strategy presents the following requirement: "implementation should be measured and not over-hasty".

An introduction of a system like the ARNA system proposed here will need to be phased in over many years. It is expected that it would be like the approach taken by the Navy to integrate the ECPINs system. The phased systematic role out will require individual training, team training, harbor and sea trials, and safety and security analysis. Additionally, each ship's crew would need to be periodically evaluated for competency using the system via the Navy's Sea Training work up schedule.

Requirement: Costs

The IMO e-Navigation strategy presents the following requirement: "costs should not be excessive". Considering that the MicroSoft HoloLens is available at approximately $3500 per headset, it is estimated that the manufacturing of the headset would not exceed $5000 [20]. Each computer system would require appropriate graphics cards and memory like an AR/VR enabled gaming computer. It is expected that this could be produced at no more than $10,000 for a commercial grade computing system.

The systems will need to be mounted inside cabinets that meet defence specifications. This could make use of pre-existing cabinets. The cable connections would need to make use of MIL-SPEC connectors to each rack's I/O panel. The costs of these cables would need to be considered when factoring in production costs. Moreover, the time spent by engineers to update shipboard drawings, develop engineering change guidance packages, and to create cable run sheets and pinouts would need to be factored into installation contracts

Systems and Hardware engineering design costs is highly variable and negotiable, but it is expected the work could be completed in approx. 1000 hours. Therefore, assuming an hourly rate of $150 per hour, then this could be achieved for approx. $150,000. Software development of the system would constitute the bulk of the effort required. It is expected that the software development would be more than 10,000 hours and would cost approximately one to two million. Additionally, testing of the safety critical system would require extensive effort that is likely to match the software level of effort.

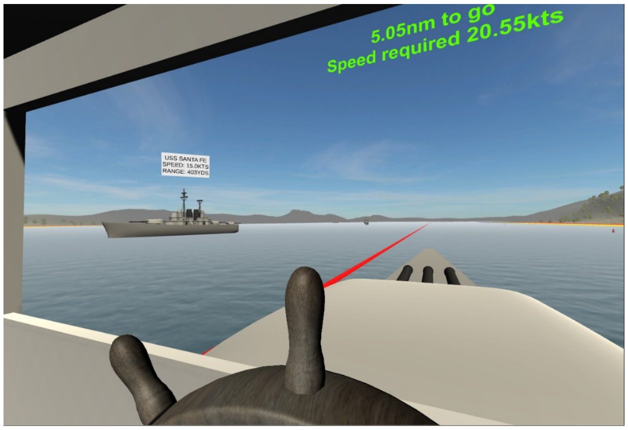

Figure 1: Screenshot from VR application. A few ARNAs are visible including (1) a Contact information panel, shown as a white background with black text above a ship (left), (2) a red line representing a navigation passage track that the user is currently starboard of (middle), and (3) a heads-up display (top) showing the distance to go and speed required.

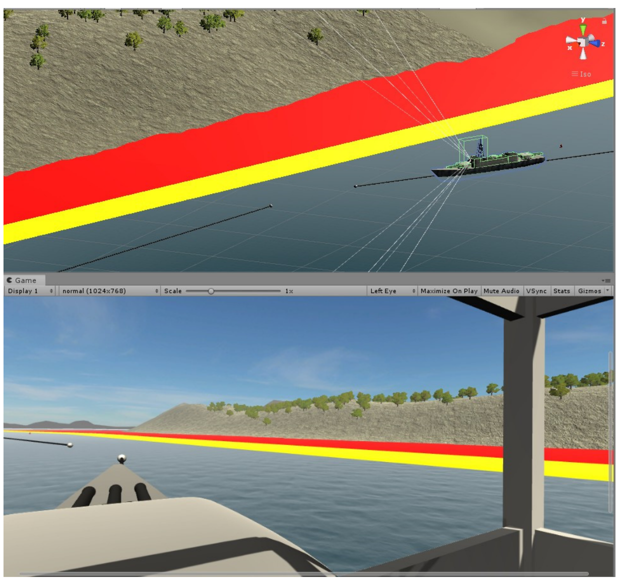

Figure 2: Screenshot showing Unity Application. We see the Unity Scene (top) and the user's view (bottom). LDL, Clearing Depth, and Track ARNAs are shown.

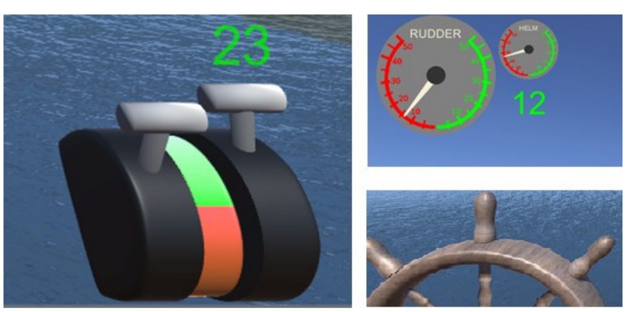

Figure 3: Port and starboard throttles (left), Rudder/Helm indicators (top-right), helm (bottom-right).

VR Implementation

A VR application was developed for Oculus Rift in Unity3D that allowed for the development, visualization, and testing of ARNAs. The application simulated being on the bridge of a frigate transiting a navigation passage. The ship follows a planned series of tracks in close vicinity to underwater hazards, buoys, and other shipping. As seen in Figure 1, the user is able to look around the environment in 3D wearing the headset as the ship travelled the navigation passage free of user input.

Implementation Details

The application was written in C#, Python and Bash, and it was developed in Unity3D [22], as shown in figure 2. Standard Assets provided by Unity3D were used to for terrain generation and water simulation. 3D models, such as those visualizing ship controls and point features (buoys and lights, etc.) were created using Blender [23]. Textures for the 3D models and 2D UI elements were created using Inkscape [24] and GIMP [25]. The VR headset was the Oculus Rift Development Kit 2. This headset provides 960x1080 resolution per eye via a low-persistence OLED display [26].

Feature Extraction

S57 is a publication by the International Hydrographic Organization (IHO) that standardizes the storing of chart data into a multi-layer data structure. Using GDAL, information about individual layers of instances of this data structure can be extracted. For example, lateral buoys are navigation aids defined by the International Association of Lighthouse Authorities (IALA) that help to define safe water and navigable channels [75]. Within the S57 data structure, there exists a feature layer called BOYLAT that contains data related to lateral buoys within the extents of the ENC. Each of these feature layers contains structured data with specific details such as location, colour, and name.

Ship Simulator

Figure 3 highlights some visualizations of ship controls and indicators in more detail. The user interacts with these ship controls via mouse or a laptop's trackpad.

The port and starboard throttles can be manipulated independently, thus allowing control of each engine (the prototyped ship assumes a ship with two propellers). When adjusting the controls, the speed that is being set appears above the throttle being manipulated. Once set, the assigned speed fades to no longer clutter the display. In the screen shot in figure 2, we see the speed already beginning to fade for the starboard throttle, and the port throttle speed is not visible. The throttles can be set forward or in reverse. The differences between the two are visualized using green and red colours on the throttle base. The speed values that are displayed are colour coded accordingly.

Rudder and Helm indicators are provided. The rudder indicator shows the current rudder angle while the helm indicator shows the ordered rudder angle. The rudder adjusts its angle to be closer to the ordered rudder angle. Both angles are important in controlling the ship, however the rudder angle is the most important as it what directly impacts the ship's movement in the simulator. As such, its importance is emphasized by size.

The helm is a textured 3D model. It rotates left and right when clicked and dragged by the user. The angle that the helm can be turned is clamped to 60 degrees starboard and port off centre angle. This angle is converted to a maximum 30 degrees of rudder angle. The difference in the two allows greater fidelity of movement when manipulating the helm and more accurately simulates physical controls.

Layers of ENCs can be extracted and processed using methods outlined above. Each layer presents an opportunity for visualizing the structured data in 3D space. For this prototype, lateral buoys, point lights, and depth sounding layers were used as inputs for visualizations.

Ship's Movements

Ownship and other ship models were moved through the environment by providing an individual ship's speed and a series of waypoints. This allowed ownship and other ship's to proceed along pre-planed routes. When moving ownship towards the next waypoint, the height position of the next waypoint was set manually. This allowed for simulation of ocean movement and helped to avoid the ship model from moving outside realistic vertical positions in the water.

The orientation of the ship would rotate towards the next waypoint and move towards it at the indicated speed. The rotation speed was a function of the ship's speed and angle of rotation. This mimicked turning the ship more sharply at higher speeds.

ARNAs

This section describes the proposed ARNAs and how each can be generated in real time using common navigation sensors and a priori data. By creating an ARNA prototype and then viewing it through the Oculus Rift in the VR application described above, we could develop and modified the proposed ARNA until it was deemed ready for evaluation by subject matter experts.

Track ARNA

The Track ARNA helps to visualize the ship's location in relation to a planned navigation passage, as shown in Figure 4. A navigation passage is a series of disjointed tracks. Each track consists of two waypoints and a leg. The two waypoints are the starting waypoint (latitude and longitude) and the ending waypoint. The leg of the track is the line that connects the two waypoints. Tracks are disjointed in that they do not connect directly to other tracks, i.e.. the ending waypoint of a track is not equal to the next track's starting waypoint. Instead, the ending waypoint can be considered the "wheel-over" position of the ship, which is the geographical position when the ship plans to begin turning to the next track. The starting waypoint of the next track is the location expect upon completing the turn and steadying the ship on the next track. To determine the waypoint position, the NavO uses the ship's turning characteristics and planned rudder angle.

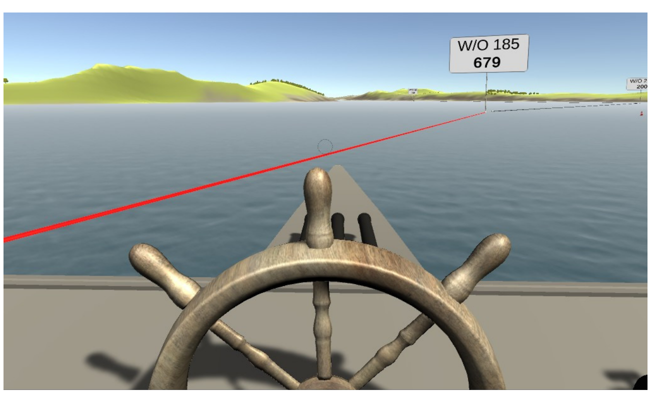

Figure 4: The Track ARNA allows the NavO to visualize the ship's location in relation to the planned navigation passage.

User Interaction - Track ARNA

The Track ARNA uses colour to inform the user of location relative to the planned track. When on track, it is coloured black. Black was chosen as it is the colour used for tracks on the ship's ECPINS as well as the colour of tracks drawn on paper navigation charts in pencil. When starboard of track, the track is coloured red.

Red was chosen because it is the colour associated with port in the Navy, and reflects the track is to port, and making the colour reflective of the helm ordered to return to track. With ships with a rudder, the order would be "Port" + the number of degrees of rudder angle (such as "Port 15"). When port of track, the track is coloured green. Likewise, green was chosen because it is associated with starboard in the Navy. By choosing the colour associated with the direction of turning and thus the helm order required, it is expected that this would decrease the delay in reaction time caused by the Stroop effect and minimize the occurrence of incorrect helm orders [27].

In addition, the NavO is provided with a range to the track (both port and starboard) as text on a white panel. This is only displayed when the ship is more than 50 yards from the track. The text positions are positioned at the intersection of the track with a line directly abeam of the ship.

Real World Source of Information - Track ARNA

A NavO plans a navigation passage using an ECPINS laptop. The passage information is saved to file. Part of this information is the track data, including the expected wheel over positions. Multiple options exist to have the data imported into the ARNA system such as:

1. OSI Maritime Systems could be used to establish an ARNA-ECPINS interface design document to communicate the data between the two systems [34];
2. OSI Maritime Systems could be used to establish an export option to disk of the track data in an agreed upon format;
3. If not proprietary, the exported format used for the navigation radar could be examined & parsed for the ARNA system;

Without an automated function, the NavO could read the information from the track created in the ECPINS and enter it manually into the ARNA system.

Danger Area

When creating a navigation passage, the NavO establishes a Limiting Danger Line (LDL), as shown in figure 5. That is, a series of connected points that follow a pre-calculated depth of water. Crossing the LDL and entering the area between the LDL and the land could result in grounding of the ship. Calculation of the LDL uses the following information:

1. The draught of the ship;
2. Safety Margin - an additional safety margin is often 2m, but can be increased or reduced based on approval by the Commanding Officer;
3. The squat calculation of the ship - "the squat effect is the hydrodynamic phenomenon by which a vessel moving quickly through shallow water creates an area of lowered pressure that causes the ship to be closer to the seabed than would otherwise be expected" [28]. The squat calculation uses the ship's hull characteristics, expected depth of water, and expected speed of the ship. As the expected speed of the ship varies throughout the navigation passage, this squat value can be different throughout the passage; and
4. The height of tide - the expected height of tide is impacted by the location and the expected time of day the NavO will be conducted the passage.

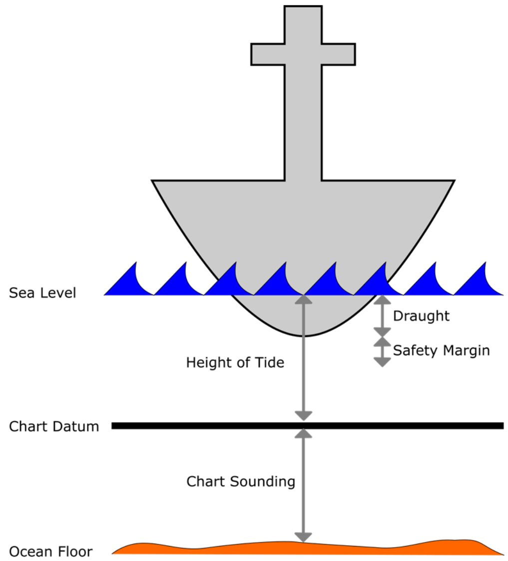

Figure 5: Limiting Danger Line (LDL) is calculated by adding the ship's draught and a safety margin (normally 2 metres) and then subtracting for the height of tide. LDL = Draught + Safety - Height of Tide. The safety margin can also consider the impacts of squat.

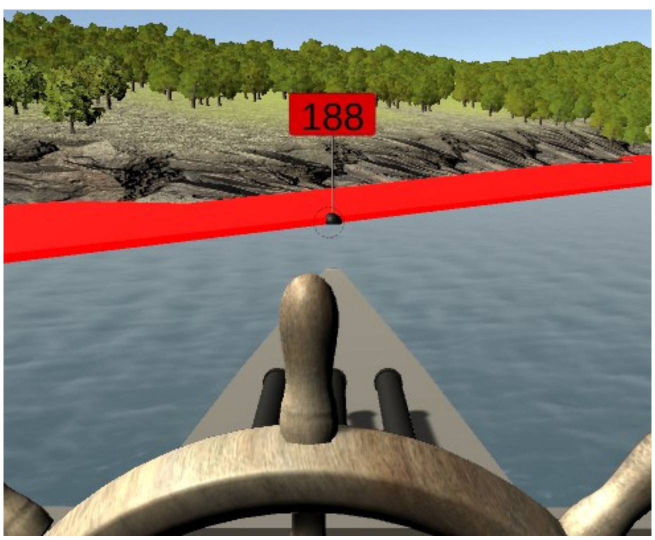

Figure 6: The Danger Area ARNA represents the area where the ship is in danger of running aground and should be avoided.

User Interaction - Danger Area

When planning a navigation passage, the NavO measures the distance to the LDL from visually recognizable navigational marks along the planned track and records this information in a notebook. This allows the NavO to know how far the dangers extend from a point of land. In addition, the NavO must measure the corresponding planned CPA to those danger if on track. For example, they might record the dangers extending from a prominent point of land or those marked by a navigation mark like a lateral buoy and then calculate how much safe water they will have when abeam of those points. When conducting the navigation passage, the NavO conducts a track assessment to see how far off course they are and then correlates the information in the notebook to determine the new amount of safe water remaining.

The Danger Area ARNA can reduce the cognitive load of the NavO by making that assessment. Or, at the very least, it can confirm the assessment made by the NavO. The area between the LDL and the coastline is the Danger Area. The Danger Area ARNA displays that area as a red plane which follows the contour of the land and the planned LDL. An assumption is made that a red area in proximity to land would be associated with danger (especially contrasted to the yellow clearing area described later) instead of port. This would be similar to other ship's systems such as the ECPINS and the GPS, which shows alerts and dangers in red and warnings in yellow.

As seen in Figure 6, the visual overlay of the danger area allows the NavO to easily see where the dangers are located. In addition, the NavO is provided with a range to the dangers ahead, astern, and abeam (both port and starboard) as text. The text positions are positioned at the intersection of the LDL with the lines directly ahead, astern, port and starboard of the ship.

When conducting Pilotage, a NavO is always concerned about the availability of safe water. As a result of the Danger Area ARNA, the NavO can instantly know the amount of safe water available along with visually seeing the proximity to dangers.

User Interaction - Danger Area

To create the Danger Area ARNA, the LDL and the contour of land is required. Similar to the Track ARNA described previously, the LDL can be obtained via an export from the ECPINS system or through a direct interface. In this case, it would be a path of connected geographic positions. This would ensure that the information contained within the ECPINS system and the NavO's navigation notebook is consistent. To form the area, the LDL path can be combined with the path of the contour of the land. This contour can be obtained from the S57 chart loaded into the ARNA system by extracting the LNDRGN layer or the LNDARE layer [29]. In a similar fashion, the land contour information is extracted from the chart by the ECPINS system already and could be made part of the ECPINS export or via a developed ARNA-ECPINS interface.

Clearing Area

The Clearing Area ARNA is similar to the Danger Area ARNA in that it marks an area of interest to the NavO. The Clearing Area is the area between the danger area and the point at which the ship can still turn 180 degrees away from the danger. That is, if outside of the clearing area, the NavO is assured that he can direct the ship to be turned as much as possible without concern that the stern of the ship will run aground.

Clearing Area

A NavO calculates clearing bearings, which are predetermined magnetic bearing lines from prominent points of land and navigation marks to indicate the extent of the clearing area. A track of a navigation passage can have as little as one clearing line or many depending on several factors including:

1. the proximity to dangers;
2. the availability of navigational marks ahead of the ship;
3. contour of the dangers in relation to the planned track; and
4. the length of the track, where a short track has fewer clearing lines.

The NavO must negotiate the complexity of having too many clearing lines against needlessly limiting navigable water. That is, too many lines are of no value because the NavO could never reasonable be assured he was using the right bearing.

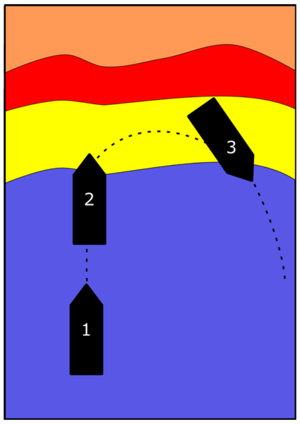

Figure 7: The Clearing Line Area (depicted in yellow) marks an area where the ship can still turn 180 degrees away from the danger area (shown in red). The diagram shows the ship (depicted in black) making a turn in positions marked as 1, 2, and 3. The Clearing Line Area is measured from the ship's Polaris to the stern of the ship, such that upon completion of the turn the ship's stern remains outside of the danger area.

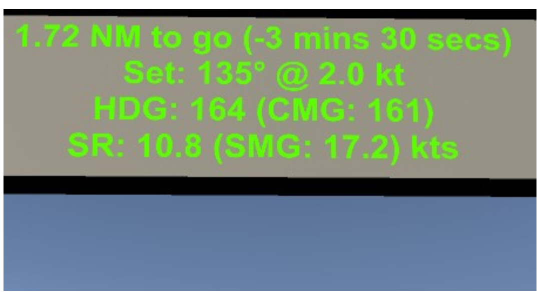

Figure 8: The Passage Manager provides the NavO with information on the distance to go to the end of the navigation passage, the current tidal set, the current speed made good and the speed required in order to arrive on time.

The Clearing Area ARNA is not impeded by the same restrictions imposed upon clearing lines. For example, proximity to danger, availability of navigation marks and length of track have no impact. Rather, the area is depicted as a yellow area lying on the water line adjacent to the red Danger Area ARNA. The size and shape of the area can be calculated irrespective of planned clearing lines and thus provide a more accurate representation of when the ship can safely turn. In addition, this area can be made dynamic by considering the turn radius and speed of the ship to indicate when the ship is running into danger.

Real World Source of Information - Clearing Area

To calculate the clearing area, the ARNA system requires:

1. the Danger Area ARNA, with requirements indicated previously;
2. the Ship's turning characteristics, which is part of the ship's navigation data sheet and can be loaded in as a priori information; and
3. NMEA data (for dynamically updating the danger area).

As shown in Figure 7, the clearing line marks the point at which the ship can still commence a 180 turn and still clear the dangers. As a ship's turning diameter is influenced by the speed of the ship, the size and shape of the Clearing Area could be recalculated. The data for this calculation can be obtained using the ship's navigation data from its MK 49 ring-laser gyro navigator (RLGN) INS and Navigation Data Distribution System (NavDDS) [30]. That is to say, the ship's ability to clear the dangers is influenced by the speed of the ship and the angle at which the ship is proceeding in relation to the danger.

Passage Manager

When conducting a navigation passage, the NavO regularly must recalculate the speed required and estimated time of arrival (ETA). This is normally done once per track. This is required to ensure that the ship arrives at the end of the navigation passage on time. The speed required can be influenced by several factors, including the SMG and the CMG of the ship. For example, if the ship is consistently maneuvering to regain track, then the overall distance travelled would be greater than anticipated. If the ship is steaming into a tidal stream, then the ship would have to increase speed to compensate.

User Interaction - Passage Manager

Without the Passage Manager ARNA, the process for calculating engine speed orders is done using multiple steps. These steps serve to determine the distance remaining in the navigation passage and what speed to order to maintain the speed plan. The speed plan is the planned speed made good throughout various stages of the passage. This is not normally the same speed throughout due to requirements to reduce speeds when appropriate such as for harbour regulations, wake restrictions and confined waters.

The SMG through the water is affected by the tidal set. Knowing the tidal set and the speed required, the NavO can make appropriate recommendations of what speed to order to maintain the required speed plan. The speed ordered is known as the "Speed Rung On" (SRO).

The first step to calculate the SRO is to accurately determine the ship's current position. This is normally done by plotting a fix of the ship's position, which is triangulating the ship's position using some combination of bearing lines, radar ranges, and possibly depth soundings. This is known as fixing the ship's position. GPS fixes can also be used but are not normally used in Pilotage waters due to the frequent errors introduced by fouled GPS signals. As such, the location of the ARNA placement should make use of the ship's NavDDS which makes use of various sources to determine the ship's position more accurately.

Secondly, the NavO needs to determine the distance to go to the end of the navigation passage. To aid in this, in the planning stage, the NavO calculates the distance to go to the end of the passage at various points along the route. They then plot these distances as "Distance-to-go bubbles" on the chart and in the Navigation notebook. Knowing the current position and reviewing the recorded data in their notebook, the NavO can approximate the current distance to go and determine what the speed required is.

Thirdly, the NavO must calculate the current tidal set. This is done using a series of fixes. After the second fix, the NavO or designated Fixing Officer (FixO) can determine the tidal set by measuring the difference between the dead-reckoned position and the plotted position.

The Passage Manager ARNA alleviates the NavO and the FixO of needing to calculate this information. It provides real time information including the distance to go (DTG), ETA, tidal set, SMG and speed required information. As per Figure 8, this information is provided as a heads-up-display (HUD). Given this information, the NavO or OOW can easily determine the appropriate SRO and to manage the speed plan, and CMG to maintain track.

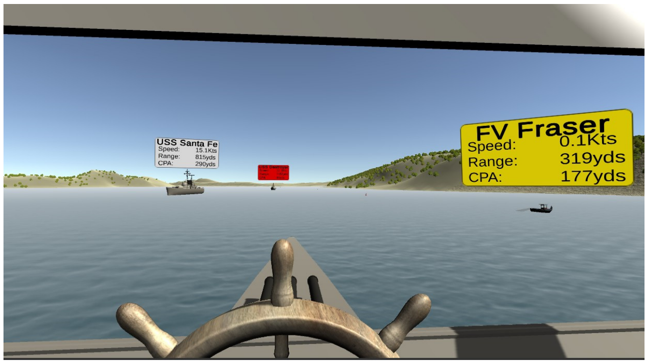

Figure 9: The Ship Avoidance ARNA provides a textual overlay in position with other vessels. The text is displayed upon a panel that remains oriented towards the observer. The text informs the NavO of the name of the vessel, current range, and CPA.

Real World Source of Information - Passage Manager

The Passage Manager system requires the following:

1. the planned tracks - the sources for this information were described previously when discussing the Track ARNA;
2. the ETA - this information needs to be configurable and the ARNA system should allow the user to input this value; and
3. NMEA information from the ship's NavDDS.

Using the planned tracks, the ARNA system can calculate the total distance to go. This is done by adding the distance to the next waypoint to the remaining distance from that waypoint, along the route, to the destination. In addition to providing the current position of the ship, the ship's NMEA information also provides an accurate time signal. After which, the speed required is simply a function of the distance and time remaining.

Ship Avoidance

Shipping avoidance, including the arrangement of safe passage, is an essential component of Pilotage and is one of the major sources of operator overload. One crucial aspect of shipping avoidance is accurately identifying other vessels. This helps to correlate the visual picture with other contact avoidance systems such as automatic identification system (AIS) [31], navigation RADAR, and Marine Communications and Traffic Services (MCTS).

As seen in Figure 9, a Ship Avoidance ARNA was developed to provide the NavO with real-time shipping information. This information assists in identifying the vessel and determining if risk of collision exists.

User Interaction - Ship Avoidance

Without the use of the Ship Avoidance ARNA, the Navigator makes use of multiple techniques to identify other vessels:

1. Using a Vessel Traffic Service (VTS): stationed on the bridge are naval communicators [32];
2. Using AIS: the NavO may look at an AIS graphical plot, such as on the ECPINS system, and see icons of other ships;
3. Using navigation RADAR: the NavO would make plots on the navigation RADAR and allow the ARPA system to provide information on movements of other ships;
4. Using the Operation's Room: the Operation's Room will have personnel manning radars and using cameras to help identify vessels;
5. Using Lookouts: the bridge will have multiple personnel acting as lookouts; and
6. Visually: The NavO will look out the windows, take visual bearings and use binoculars.

This information will come in at different times through a series of formal block reports that will require context switching and concentration by the NavO. The NavO must anticipate how the current navigation plan will be impacted and make prudent decisions to either change course and/or speed in a manner adhering to the International Regulations for Preventing Collisions at Sea (COLREGS) and available safe water.

With the Ship Avoidance ARNA, the NavO will be able to look at the contacts around him and immediately be able to correlate vessel identity via a textual overlay. As the information is received from other systems and through block reports, the NavO can confirm what is reported with what is seen to build confidence in the track picture.

In addition to identifying the other ships, the NavO must also appropriately avoid collision. Without the Ship Avoidance ARNA, the NavO relies upon multiple inputs for collision avoidance, including:

1. visual bearings of the ship are the primary method in determining if risk of collision exists;
2. RADAR ARPA, which will provide a course, speed and CPA for the other vessel; and
3. Marine VHF radio [33] - the NavO can broadcast on appropriate VHF channels to contact the other ship and make passaging arrangements.

With the Ship Avoidance ARNA, the CPA is provided to the NavO via the textual overlay. It is expected that the NavO will continue to verify the visual bearing as required by the COLREGS.

Real World Source of Information - Ship Avoidance

Much of the information required for the textual overlay can be created using AIS. As discussed previously, the ARNA system is expected to have an interface with the NavDDS system. As such, the NavDDS system can provided AIS track information. The textual overlay can then be positioned based on AIS track's reported position and masthead height. Alternatively, the ECPINS system has an AIS feed and could provide AIS track information via the ARNA-ECPINS interface.

The CPA can be obtained using different methods, including calculating it from NavDDS track information (including AIS and RADAR). This is a simple relative velocity problem that can be programmed into the ARNA system using linear algebra.

User Study

A user study was conducted over a period of three weeks. The user study demonstrated ARNAs to professional mariners and obtained written and oral feedback. Eleven (n=11) participants participated in the study, with expertise including Bridge Watchkeepers, Fleet Navigating Officers, and Commanding Officers. Participants were mostly Officers of the Royal Canadian Navy (RCN), but participants also stemmed from the Royal Australian Navy (RAN) and private industry.

User Study Overview

This user study was conducted remotely to ensure participant safety during the COVID-19 pandemic. Subject Matter Experts (SMEs) were solicited through email and social media. SMEs were defined as professional mariners who had at least one year of experience navigating ships at sea and were familiar with the principles outlined in Bowditch. Those that responded indicating interest were provided with a consent form.

A Microsoft Teams meeting was scheduled with those participants who agreed to the consent form. Immediately prior to the scheduled meeting, the participants were provided with a link to download the desktop application, that was designed for the testing and evaluation of the proposed ARNAs.

The participants were requested to download the application to their computer and share their screen with the researcher while using it. The application displayed each visualization in series to the user. The participant was first provided with a description of the ARNA and instructions on its use in Pilotage. Then, the ARNA was demonstrated using a ship simulation. During the ship simulation, the participant could move the mouse around to view in first person the marine environment and ARNAs being demonstrated.

Finally, the desktop application gave control to the user to allow them to control the ship's movements using keyboard arrow keys. They were provided with directions to avoid collisions with other shipping vessels and to arrive at the destination on time. In particular, they were required to stay within 200 yards of the track, to remain outside of 100 yards from other ships, and to arrive at the destination within 30 seconds of the planned time. All participants were successful on their first try.

After the desktop application portion, the participants were provided with an online survey questionnaire to obtain feedback. A series of statements were provided about each visualization. Each participant indicated how much or how little they agree with the statement. For each visualization, the participant was provided with an opportunity to provide written feedback to the researchers. After completing these sections, the participant was provided an opportunity to provide written feedback on the use of ARNAs as whole. A summary of the results is provided in the sections that follow.

Track ARNA SME Feedback

The consensus was that the Track ARNA was effective in determining if the ship was port or starboard of track and how far off track the ship was, with 10 out of 11 participants from the user study agreeing. One user indicated that "the visual feedback was unobtrusive, obvious, and provided an immediate and easy-to-understand measure of location relative to track." Another user indicated that the ARNA is a "good tool to indicate where the ship is relative to its planned course." Additionally, the Track ARNA was said to do "its job very well" and to be "unobtrusive" and "obvious."

Additionally, there was agreement that the Track ARNA helped to determine when the ship would need to alter for the next track, with 10 agreeing (9 strongly agreeing and 1 somewhat agreeing, and 1 strongly disagreeing). The consensus was that the track ARNA was not confusing and would improve safety, with 10 out of 11 participants agreeing. It was the general consensus that the Track ARNA was not distracting and that the colour choices were helpful (with 7 strongly disagreeing with it being distracting, 3 somewhat disagreeing, and 1 neither agreeing nor disagreeing).

Oral feedback from the user study suggested that the display of the distance off track panel was the most important part of the Track ARNA. This was consistently met with approval and was noted by the participants, with 9 out of 11 participants making statements of approval of this feature about the Track ARNA. It was said that knowing how far off track with a glance would greatly assist the conduct of the navigation passage.

Passage Manager ARNA SME Feedback

The consensus from the user study was that the Passage Manager ARNA was effective in providing pertinent navigation information and was useful in the conduct of a navigation passage. All participants agreed that the Passage Manager ARNA was useful in the conduct of navigation, with 10 strongly agreeing and 1 somewhat agreeing. All participants strongly agreed that the Passage Manager ARNA was effective in providing the distance to go and speed made good. 9 strongly agreed that the Passage Manager ARNA was effective in providing the speed required, with the other 2 somewhat agreeing. 10 strongly agreed that it was effective in providing the estimated time of arrival, with the other 1 participant somewhat agreeing.

Additionally, it was suggested that the Passage Manager ARNA would "greatly assist with heads up navigation". Additionally, another user expressed approval of the Passage Manager ARNA by saying:

> This is vital information that every navigator is constantly checking. Having it to hand instantly while maintaining a heads-up perspective is invaluable and can only increase safety.

One participant said the Passage Manager ARNA was "an excellent and obvious tool to make passage navigation safer, especially in close waters." This feedback helps to support the assertion that ARNAs could improve maritime safer.

Collision Avoidance ARNA SME Feedback

The consensus from the user study was that the Collision Avoidance ARNA was effective in providing pertinent collision avoidance information and was useful in determining if a risk of collision existed. All participants strongly agreed that it was effective in providing the CPA of other ships and that the use of colours (white, yellow, and red) helped to prioritize which ships required monitoring. The Collision Avoidance ARNA was generally assessed as not being confusing and that it would improve safety, with 9 strongly disagreeing with the statement "The Collision Avoidance ARNA is confusing." The general consensus was that the Collision Avoidance ARNA would not distract the navigator in the conduct of the passage, with 7 strongly disagreeing with it being distracting, 2 somewhat disagreeing and 2 somewhat agreeing. It was indicated that the use of colours and the option to be able to fade out the display was highly effective.

It was also suggested that the Collision Avoidance ARNA would assist with heads up navigation, with one participant saying:

> Many navigators end up standing in front of the radar, staring down. This can negatively affect their perception of their surroundings. The Collision Avoidance ARNA removes this scenario and improves safety and allows the navigator to stay more alert and able to monitor several vessels at once.

Danger Area ARNA SME Feedback

The overwhelming consensus from the user study was that the Danger Area ARNA was very effective in providing the area marked by dangers, would improve safety, and was useful. All participants strongly agreed that the Danger Area ARNA would improve safety. There was unanimous consensus that displaying the range to the danger area was useful, in all directions. There was strong consensus that red was an effective colour choice for the Danger Area ARNA, with 10 strongly agreeing that red was an appropriate colour. That said, one participant expressed concern about the choice of also using red with the Track ARNA to indicate when starboard of track:

> As red is already used in the navigational track, I worry about the confusion between navigation and danger. Perhaps an orange for the danger area? Or no colours for the navigational track, but have the port or starboard side of the line turn to grey when off course?

There was less consensus on whether or not the Danger Area ARNA would distract the navigator, but results tended towards it not being distracting, with only one participant suggesting otherwise (7 strongly disagreed with it being distracting, 2 somewhat disagreeing, 1 neither agreeing nor disagreeing, and 1 somewhat agreeing). Some believed that blanking out the entire area would possibly impact visibility.

As such, future work could implement visualizing the Danger Area ARNA as a red dashed line to gather more user feedback on the preferences between the two. The ship simulation could be reused to obtain this feedback by adding additional shipping vessels operating inside the danger area.

Clearing Area ARNA SME Feedback

The consensus from the user study was that the Clearing Area ARNA was effective in providing the area marked by clearing bearings and/or clearing depths, would improve safety, and was useful. All participants strongly agreed that yellow was an appropriate colour for the Clearing Area ARNA. Likewise, all the participants agreed that the Clearing Area ARNA would improve safety, with 9 strongly agreeing and 2 somewhat agreeing. Also, all of participants agreed that the Clearing Area ARNA was effective in visualizing clearing bearings and/or clearing depths, with 10 strongly agreeing and 1 somewhat agreeing. When asked if the Clearing Area ARNA was effective in alerting the navigator to monitor the proximity of the ship's stern to dangers when altering course, all participants agreed (10 strongly agreed and 1 somewhat agreed). Also, all the participants disagreed with the clearing area ARNA being confusing, with 8 strongly disagreeing and 3 somewhat disagreeing.

Limitations

The conduct of this research user study has limitations that impact the conclusions that can be made. Some of the limitations involve ecological validity, the potential of confirmation bias, and a lack of a comparative condition.

Regarding ecological validity, the ideal presentation of the ARNAs in the desktop simulation is significantly removed from the quality of visualizations capable of being displayed using current AR technology. For example, the desktop simulation displayed the visualizations with complete FOV. The impacts of a limited FOV should be evaluated and considered in future work. Additionally, the desktop simulation did not address impacts on light intensity. This would have impacts on depth perception and occlusion, as well as impacting the usefulness of ARNAs for night-time scenarios. A way ecological validity issues were addressed was by creating ARNAs such that aspects could be viewed even with a limited FOV. For example, the Passage Manager ARNA and the distance panels in the Track, Danger Area, and Clearing Area ARNAs could be viewed in their entirety even with a limited FOV. Visualizations that would be most impacted would be the Clearing Area and Danger Area planes, as they span a large area.

Another limitation is the impacts of confirmation bias. As the researcher was familiar with the conduct of navigation and designed the ARNAs to meet the expected need, there is likely a tendency to seek out support of the assumptions made. For example, when making subjective observations about where the participant was directing their attention, it is possible the researcher focused on those moments where the attention was directed towards ARNAs. One way this was countered was by using video and audio recordings of the user study. This allowed for verification and confirmation of noted observations.

Another limitation of the user study was the lack of a control condition or comparative condition. As the desktop simulation evaluated the participant conducting a navigation passage, it would be useful to see how well the participant could conduct the passage void of any ARNA. This would not have been possible without traditional navigation aids, such as ECPINS, RADAR, lookouts, a ship's Polaris, and access to navigation charts. As this was not feasible within the confines of the desktop simulation, no baseline was established. One avenue to address this would be to collaborate with an entity that has a bridge simulator for navigator training. This would require integration of the ARNAs into the existing visuals of the bridge simulator. This would allow comparison of ARNAs to traditional navigation methods.

Conclusions

In this work we looked at how AR can be used to assist Pilotage and improve maritime safety. It was determined that despite the current AR device limitations, AR visualizations can still be created and pre-validated using other mechanisms such as VR and desktop simulations. We leveraged existing work in the field, current navigation aids and tools, and the IMO e-Navigation Strategy to form the basis of our approach.

We examined the sources of information readily available on a ship to ensure that the visualizations being proposed were feasible. Additionally, in the creation of a ship simulation, we showed how existing data could also be used to generate realistic VR environments more readily. This was shown to have benefits in creating a navigation passage planning tool, where the NavO could simulate driving their planned navigation passage before entering the area.

Finally, we conducted a user study where we presented our proposed ARNAs to subject matter experts for feedback. The user study confirmed the hypothesis that ARNAs would assist in the conduct of Pilotage and would improve maritime safety. As such, it is suggested that ARNAs would be an excellent complement to e-Navigation systems. Additionally, based on user feedback and the ability to visualize real world locations in situ, it is also suggested that this technology could be useful to assist in training of Navigators and to assist in visualizing and planning navigation passages.

Future Work

One avenue for future work is to create alternate implementations of the ARNAs based on feedback and then conduct another user study. Examples of alternate implementations include having opacity control of the Danger Area and Clearing Area ARNAs. That user study would present both options in sequence and ask the users to rate and compare the variants. Also, if the COVID-19 pandemic continues to ease, it may be possible to conduct a user study using VR systems as originally planned.

Another avenue for future work would be to explore porting the ship simulator and VR terrain generation into a navigation passage planning tool. Such a tool is envisioned to allow a NavO to import updated S-57 navigation charts, a database of terrain data, and the Navigator's planned passage from an ECPINS. The NavO could then use a desktop simulation or VR headset to conduct the Navigation passage with various scenarios (fog, rain, heavy shipping, strong tidal set, etc.). It is expected that this tool would allow for better preparation and improve maritime safety. It is also envisioned that video files from the simulation could be exported and selectively used in Navigation Briefs to the bridge team.

Another potential use case for this technology is in Navigator training. As proposed by users, the ARNAs were an effective tool in visualizing concepts of navigation. It was suggested that this would allow Navigator trainees to better understand the concepts being taught.

The ARNAs fuse multiple sources of data together in ways that can be beneficial to navigation through mediums other than AR. Future user studies or prototypes could look at the benefits of the ARNAs in other mediums, such as displaying on fixed screens mounted on the bridge, on handheld devices/screens or on laptops. Such implementations should be evaluated via a user study.

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