

Appendix A: Notional HRI Interface Redesign

Objective: Complete a geographical survey of an ocean region		
Agent	Human	Robot
Description	Expert operator on nearby boat	Multi-robot system with anchors that manage localization and data relay and AUVs for data collection
Activities	Monitor state of incoming data to ensure sufficient coverage of target area Oversee robots; detect and respond to potential issues in operation	Conduct seismic imaging survey of ocean region
Actions	Analyze incoming scientific data Supervise state of AUVs to predict potential mission critical issues Take direct control of individual AUVs to avoid potential problems (e.g., missed regions, collisions) using waypoints and operational controls	Anchors: coordinate operator-AUV data relay AUVs: navigate between planned waypoints AUVs: collect seismic imaging data AUVs: respond to updated operator commands
Data Analysis Process	Knowledge	
	Data Tasks	
Autonomous Processes	Reasoning	See original paper for details
	Perception	See original paper for details

(a) Deconstructing the WiMUST Interface using the data-centric HRI framework

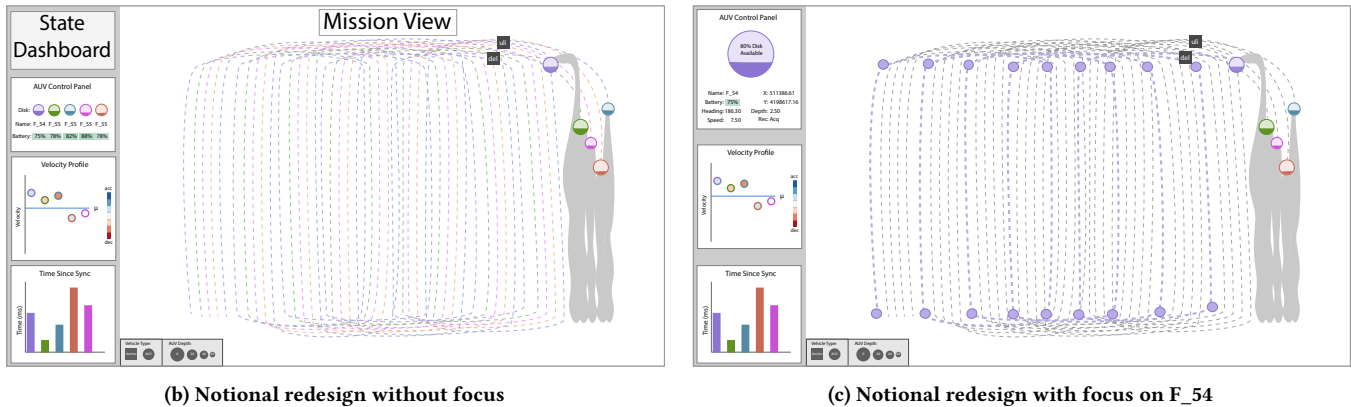


Figure 1: We used our framework to deconstruct the WiMUST interface design described in Simetti et al. [7]. We used our deconstruction to guide a notional redesign (Fig. 1f in the primary paper), described below.

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1 REDESIGN OVERVIEW

Our human-robot data flow framework allows interface designers to systematically deconstruct a given design scenario according

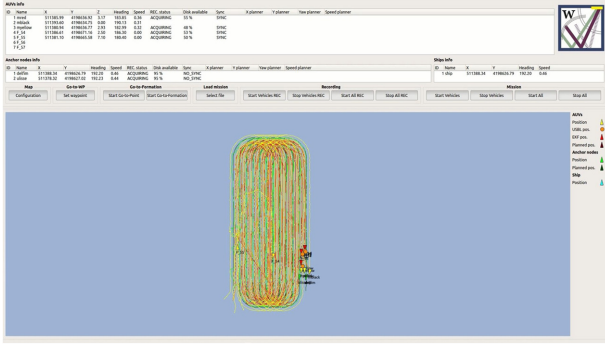


Figure 2: The original WiMUST interface from [7].

to the activities and needs of the human-robot team in working with the target data. This appendix provides a brief example regarding how one might apply the framework to design a prototype multirobot interface for scientific surveys based on the WiMUST interface in Simetti et al. [7] and using techniques and principles from data visualization. We note that this notional redesign is a preliminary, speculative exercise based on the system tasks and data inferred from Simetti et al. [7] and, as a result, may not precisely replicate the data and operational scenarios from the original system (a comprehensive redesign would require cohesive, iterative interaction among all stakeholders). We select this example as it offers a rich and complex set of visualization challenges in a data-centric application (surveying a region to collect scientific data). Figure 1a summarizes the framework deconstruction.

In the WiMUST interface, operators supervise teams of robots using tables to oversee robot state and a track-based interface to monitor robot operation. We focus our redesign on two primary **Human Activities**: monitoring the state of incoming data and overseeing robot operation. Our notional redesign emulates the target scenario by applying visualization principles to visually summarize robot state, direct attention to information, and focus detail on necessary information. Users can select individual robots in the team to reveal more precise information about the robot on-demand and issue commands to the system. The primary redesign consists of a robot state dashboard (left) and a mission overview (right).

2 MONITOR INCOMING DATA

Monitoring incoming data requires that operators *monitor data quality* in terms of coverage to assess completeness, *find relevant data* such as coverage gaps, and *make predictions* about the likelihood of mission completion. The original interface emphasizes precise details about the paths traversed by the AUV formation, focusing on distinguishing between the paths followed by individual robots. However, if the mission focuses on seismic imaging of the ocean floor, the visual clutter created by individual paths and lack of information about the aperture of the collected data based on ocean topography complicates assessing overall coverage. Our redesign instead provides a concise overview of coverage using a heatmap-style interface, where collected data is shown in grey. The space indicated by the heatmap corresponds to the likely image

coverage based on the depth of the ocean floor and AUV at time of collection (lower distances imply decreased image frustum width).

To help with assessing the future state of the data collection activities, we encode the current position, available disk space, and planned trajectory of each robot. Each robot is represented as a circular glyph with its path shown as a trajectory line with reduced opacity to manage clutter and a dotted line to indicate incompleteness [1]. We additionally encode anchors using shape to indicate a different category of device. We redundantly code anchors using color, as in the original design, but opt to use a neutral grey to help manage clutter and focus attention on the AUVs used in data collection.

Depth and disk availability (originally in the table view) provide additional cues as to the robot’s location and likelihood of mission completion. Depth is encoded as mark size, where marks become smaller as the depth increases. The vertical “fill” of each circular glyph encodes disk availability, allowing users to assess the available disk in the context of the current state of data coverage to better predict whether the robots have sufficient resources to complete the mission. We choose to use the vertically filled glyphs as they offer comparable accuracy to a traditional pie chart, but are more robust for small and large amounts of fill [2, 8], which are critical for making decisions near the end of the mission. Showing depth and disk in the context of the mission visualization allows analysts to have access to key aspects of mission state in context, allowing for more holistic assessment and prediction.

3 SUPERVISE ROBOT OPERATION

Supervising robot operation requires careful attention to the motion profiles of the target formation. Specific **Data Tasks** include *identifying anomalies* in each AUV’s motion profile, *assessing risks* of collision or *predicting* deviations from the planned path to adjust the path accordingly, *finding information* about disk availability and battery, and *monitoring data quality* by supervising how frequently each AUV syncs. While the original interface uses text labels to distinguish robots precisely, we opt to use distinct colors optimizing nameability and aesthetic preference generated using Colorgical [3]. Optimizing for nameability helps enhance the user’s ability to distinguish between different robots while aesthetic functions help manage clutter and visual dissonance. This color scheme allows us to intuitively align robots across the two visualizations and to better distinguish the predicted paths for each robot, indicated using the trajectory-based representation in the original design.

We use the same color mapping in the state dashboard (left). The dashboard pulls state information from the table to highlight two key sets of relationships for monitoring operation: motion profiles and data “freshness.” The original scenario notes that the motion profile can help indicate challenges in maintaining the AUV formation, specifically noting acceleration and velocity. In an ideal configuration, all AUVs are moving at a consistent velocity with little acceleration. We present the velocity for each robot as a dot plot (middle), with the mean velocity indicated using a blue line. Plotting acceleration against velocity would likely result in high levels of *overdraw*, where points occlude one another [5]. While techniques like splatterplots [5] can manage overdraw in systems with larger numbers of points like swarms, we instead opt to encode

acceleration using a diverging color scale from ColorBrewer [4], with blue indicating acceleration, red deceleration, and white no change in speed. Users can, at a glance, determine whether robots are moving towards a constant mean speed or if there are robots accelerating away from the mean velocity of the system.

We additionally use a bar chart of time since last synchronization to help people understand how “fresh” the represented data is in order to reason about any uncertainty introduced by stale data. We use a bar chart as it allows people to readily assess the mean while also rapidly detecting outliers [9].

To support operators in detecting and responding to potential failures with individual robots, such as full disk, low battery, potential collisions, or missed regions, we allow operators to access details about individual AUVs on demand in the control panel (upper left). Clicking on a robot in any of the windows will bring it into focus, populating this window, highlighting the path in the mission view, and revealing waypoints for direct control (e.g., F_54, purple, is selected in Figure 1c). From this interface, operators can inspect specific aspects of operation and use *direct manipulation* [6] to click and drag waypoints to adjust the planned paths.

REFERENCES

- [1] Nadia Boukhelifa, Anastasia Bezerianos, Tobias Isenberg, and Jean-Daniel Fekete. 2012. Evaluating sketchiness as a visual variable for the depiction of qualitative uncertainty. *IEEE Transactions on Visualization and Computer Graphics* 18, 12 (2012), 2769–2778.
- [2] William S Cleveland and Robert McGill. 1984. Graphical perception: Theory, experimentation, and application to the development of graphical methods. *Journal of the American statistical association* 79, 387 (1984), 531–554.
- [3] Connor C Gramazio, David H Laidlaw, and Karen B Schloss. 2016. Colorgorical: Creating discriminable and preferable color palettes for information visualization. *IEEE Transactions on Visualization and Computer Graphics* 23, 1 (2016), 521–530.
- [4] Mark Harrower and Cynthia A Brewer. 2003. ColorBrewer. org: an online tool for selecting colour schemes for maps. *The Cartographic Journal* 40, 1 (2003), 27–37.
- [5] Adrian Mayorga and Michael Gleicher. 2013. Splatterplots: Overcoming overdraw in scatter plots. *IEEE Transactions on Visualization and Computer Graphics* 19, 9 (2013), 1526–1538.
- [6] Ben Shneiderman. 1997. Direct manipulation for comprehensible, predictable and controllable user interfaces. In *Proceedings of the 2nd international conference on Intelligent User Interfaces*. 33–39.
- [7] Enrico Simetti, Giovanni Indiveri, and António M Pascoal. 2020. WiMUST: A cooperative marine robotic system for autonomous geotechnical surveys. *Journal of Field Robotics* (2020).
- [8] Drew Skau and Robert Kosara. 2016. Arcs, angles, or areas: Individual data encodings in pie and donut charts. In *Computer Graphics Forum*, Vol. 35. Wiley Online Library, 121–130.
- [9] Lei Yuan, Steve Haroz, and Steven Franconeri. 2019. Perceptual proxies for extracting averages in data visualizations. *Psychonomic bulletin & review* 26, 2 (2019), 669–676.