# Increasing the Transparency of Unmanned Systems: Applications of Ecological Interface Design

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**Abstract.** This paper describes ongoing efforts to address the challenges of supervising teams of heterogeneous unmanned vehicles through the use of demonstrated Ecological Interface Design (EID) principles. We first review the EID framework and discuss how we have applied it to the unmanned systems domain. Then, drawing from specific interface examples, we present several generalizable design strategies for improved supervisory control displays. We discuss how ecological display techniques can be used to increase the transparency and observability of highly automated unmanned systems by enabling operators to efficiently perceive and reason about automated support outcomes and purposefully direct system behavior.

**Keywords:** Ecological Interface Design (EID), automation transparency, unmanned systems, supervisory control, displays.

## 1 Introduction

Unmanned systems play a critical and growing role in the maritime domain, with coordinated air and water vehicle teams supporting an increasing range of complex operations, ranging from military missions to disaster response and recovery. Traditionally, unmanned vehicle operators have served as teleoperators, monitoring video or other sensor feeds and controlling vehicle behaviors through continuous "stick-and-rudder"-type piloting commands. However, significant advances in platform and sensor automation (e.g., flight control systems; onboard navigation; hazard detection; wayfinding capabilities) have increasingly offloaded these lower-level control tasks. This has allowed operators to instead focus on higher-order supervisory control activities, paving the way for a single operator or small team of operators to simultaneously manage multiple vehicles.

Despite advances in autonomy, unmanned system operators are still faced with significant challenges. As in other domains where operators supervise highly complex and automated systems (e.g., nuclear power, air traffic control), the introduction of support automation does not allow operators to simply shed control tasks and their associated workload. Rather, this automation shifts the emphasis of operator tasks from continuous display tracking and physical control inputs to activities that focus on system monitoring and understanding, coordination, and troubleshooting. In the

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case of managing autonomous vehicle teams, this supervisory role involves high cognitive workload, both in monitoring system performance and in supporting frequent re-planning and re-tasking in response to evolving mission needs and changes to the operational environment. These activities place significant demands on operators' taxed attentional resources and require operators to maintain detailed situation awareness to successfully detect and appropriately respond to changing conditions. Workload and potential for error is further increased when "strong and silent" automation support is not designed from inception to be observable by human users, making it difficult for operators to understand, predict, or control automated system behavior [1]. This typically results in users turning off or disregarding automated support tools or, paradoxically, completely trusting and over-relying upon automation even when it is insufficient [2].

The inherent challenges of supervisory control are further exacerbated by the growing size and heterogeneity of the unmanned vehicle teams themselves [3,4]. While automation provides significant support, operators of mixed-vehicle teams must still carefully consider and reason about the consequences of individual vehicle capabilities and performance parameters (e.g., platform speed, agility, fuel consumption and range; available onboard sensor and automation systems), as well as safety-critical differences (e.g., a specific vehicle's need to maintain a larger separation from other traffic due to its lack of onboard sense-and-avoid autonomy; the expected communication intermittencies and latencies for a long-duration underwater vehicle). Currently, much of these between-vehicle differences, and their associated mission impacts, are masked by opaque automation systems. This limits operators' ability to reason about platform differences and predict how these will uniquely affect mission performance. When such information is made available through operator interfaces, it is typically buried within individual vehicle specifications, accessible only through serial, "drill-down" exploration methods. More critically, this vehicle-specific information is rarely related to higher-order mission goals, nor is it presented in way that enables operators to anticipate or understand the behaviors of lower-level system automation. In this paper, we describe ongoing efforts to address these challenges by applying demonstrated principles of Ecological Interface Design [5,6].

## 2 Background

The effective supervision of complex and highly automated sociotechnical systems—of which unmanned vehicle teams are but one timely example—presents unique challenges to human operators. In light of this, highly specialized interfaces are required that enable operators to both: (1) readily perceive and reason about the critical functional connections across myriad system components; and then (2) expertly identify and execute strategies purposefully driving system behaviors. These interfaces must serve, in effect, to increase the transparency of otherwise opaque system automation and processes, providing operators with intuitive mechanisms for high-level understanding of, and interaction with, complex systems. Ecological Interface Design (EID) represents a promising and powerful approach to develop such interfaces.

The practice of EID stems from decades of applied research focused on understanding how expert knowledge workers monitor, identify problems, and select and execute response strategies in complex systems. While early applications typically focused on physical process systems, such as nuclear power generation and petrochemical refinement [9,10], the EID approach has been extended to settings as diverse as anesthesiology [11], military command and control [12], and the supervisory control of unmanned vehicles and robot teams [13,14]. The EID approach derives its name and underlying philosophy from theories of ecological visual perception [15], which propose that organisms in the natural world are able to directly perceive opportunities for action afforded by elements of their surrounding environment ("affordances") without the need for higher-order cognitive processing. Unlike cognitive, inferential activities—which are slow and error-prone—control actions or responses based on direct visual perception are effortless and can be performed rapidly without significant cognitive overhead.

EID techniques strive to capture similar intuitive affordances for control actions within highly automated and display-mediated systems, whose inner workings are otherwise fully removed and hidden from the operator. Within such complex technological systems, decision-critical attributes of the operational domain are typically described by abstract properties, such as procedural doctrine, physical laws, mathematical state equations, or meta-information attributes (e.g., uncertainty, pedigree, recency of available information), in addition to traditional data resources. In contrast to natural ecologies, these critical properties cannot be directly perceived and acted upon by human operators. For this reason, EID attempts to increase system transparency and observability to "make visible the invisible" [5], using graphical figures to explicitly map such abstract properties—and their tightly coupled relationships across system components, processes, and operational goals—to readily perceived visual characteristics of interface display elements (e.g., the thickness, angular orientation, or color of a line; the size or transparency of an icon).

Various tools and methodologies have been proposed to generate such visual mappings from underlying analyses of the cognitive work domain [6,16,17] and interface designers may also able to incorporate or otherwise adapt a wide variety of demonstrated, reusable ecological interface display components [6]. Purposefully designed arrangements of these simple display elements can facilitate direct perception of system state and support the rapid invocation of operator's highly automatic, skill- and rule-based control responses during normal operations. Also, because these graphics provide veridical, visual models of system dynamics across multiple levels of abstraction, they provide a useful scaffold for supporting deep, knowledge-based reasoning over system behavior during novel situations or fault response [8,18].

Our own work builds upon and extends previous applications of EID to the unmanned systems domain, focusing specifically on the challenges of enabling operators to supervise teams of heterogeneous unmanned vehicles. In these situations, differences in the operating characteristics of individual vehicles (e.g., platform capabilities and handling, available sensor systems, extent of onboard autonomy) can have a profound impact on how the operator must interpret system information and interact with individual team components. In the remainder of this paper, we describe our ongoing applications of the EID approach to the unmanned systems domain and discuss several exemplar design outcomes from this process.

## 3 Approach

The development of EID displays begins with a structured analysis of the work domain the interfaces are intended to support. Although specific approaches differ across the practitioner community, these underlying work domain analyses typically involve the development of an abstraction hierarchy model (AH) [18], often as part of a broader Cognitive Work Analysis (CWA) effort [5]. The AH structure provides a scaffold for representing the physical and intentional constraints that define what work can be accomplished within a technical system. An AH model describes these constraints across multiple levels of aggregation (e.g., system, subsystem, component) and functional abstraction. Connections between elements and across levels of abstraction in the model represent "means/ends" relationships, describing how individual, low-level system components relate to complex physical processes and the achievement of higher-order system goals. These maps closely correspond to the problem-solving strategies of system experts [18] and they are used to directly inform the underlying informational content and organizing structure of EID displays [6].

To ground our own design efforts, we have developed multiple models across the naval unmanned systems domain, including abstraction hierarchies that focus on teams of heterogeneous vehicles operating collaboratively within a single mission context. These models have explored a number of operational scenarios built upon emerging concepts of operations for collaborative vehicle teaming. As such, they feature a number of elements relevant to challenging supervisory control, including large numbers of mixed military and civilian vehicle types in a constrained physical space, manned/unmanned traffic mixing, and communication intermittency. In developing our domain models, we have collaborated extensively with subject matter experts, building upon an extensive foundation of prior knowledge elicitation efforts, cognitive task analyses, and simulation-based modeling efforts that our team has conducted within the heterogeneous unmanned systems domain (see [3,4]). Throughout these efforts, we have considered how the constraints imposed by complex, dynamic operational environments affect the ability of a team of vehicles with varying capabilities to support mission goals. We have also explored operators' need to understand and purposefully direct automation, particularly when interacting with vehicle tasking and route planning tools in dynamic operating environments with significant and shifting operational hazards, including weather and traffic.

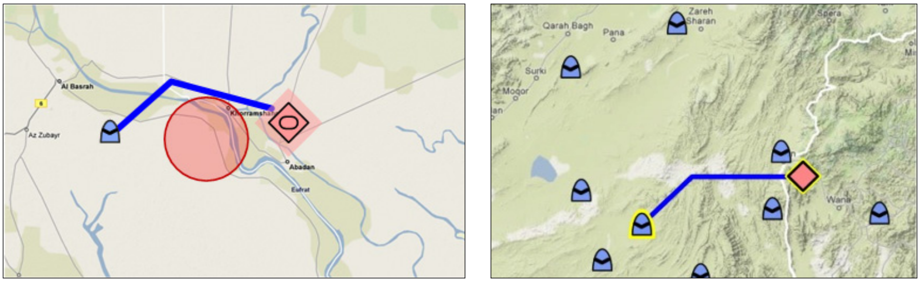
Building upon these AH models, we have applied EID techniques to identify and explore methods to integrate displays of relevant system information (e.g., airspace, bathymetry, and terrain maps; sensor data; vehicle health and status; weather reports; threat conditions; target locations), and automated planning products (e.g., vehicle routing and task assignments; alternative plan options; safety alerts) in ways that facilitate operators' awareness and deep understanding of critical system interactions, as well as constraints and affordances for control. The outputs of these analytical efforts led to descriptions of key cognitive tasks and interaction requirements. These products drove multiple loops of design, prototyping, and evaluation activities, which allowed us to rapidly assess the technical risk and feasibility of emerging design concepts, while simultaneously gaining feedback from domain experts and potential users. Key findings from these design efforts are described below.

## 4 Ecological Design Strategies for Automation Transparency

Based on the modeling activities described above, we designed and prototyped a series of ecological mission display concepts for supervising heterogeneous unmanned vehicle teams in a variety of operational contexts. These concepts ranged from individual, task-specific display forms (e.g., a widget optimized for managing available fuel considerations when addressing pop-up tasking; a multi-vehicle mission timeline) to full workspaces that incorporate and coordinate such display components within navigable views that can be tailored to address specific mission configurations and operator roles. Across these efforts, we have applied general EID design heuristics (see [6] for a comprehensive primer) to address the specific operator support needs, information requirements, and underlying functional structures gleaned from our domain analyses. The resultant interface solutions have been tailored to particular missions, vehicle configurations, and operator tasks. However, they also highlight a number of generalizable design strategies for increasing the transparency of unmanned systems, much as prior EID literature has provided similar exemplars for the process control and medical domains [6]. A subset of these applied EID strategies is discussed here.

### 4.1 Increasing the Perceptual Availability of Task-Critical Information

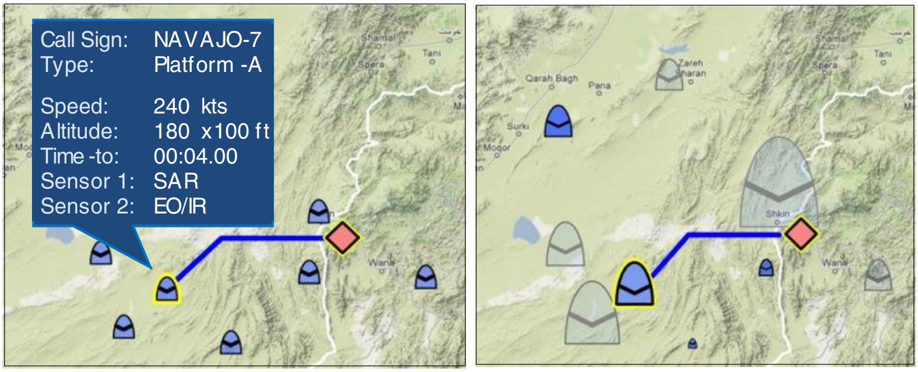
One of the key challenges facing supervisory controllers is that of understanding and confirming (or recognizing the need to intervene and adapt) automated decision outcomes, such as vehicle tasking or path planning. To do this effectively—and avoid automation evaluation errors that can lead to surprise or disuse [7]—operators must recognize and efficiently access the key system variables that affect automated outcomes. Unfortunately, geospatial (map) displays, which are the dominant frame of reference for most supervisory control interfaces, do not comprehensively support this need. Geospatial displays excel at conveying spatial constraints, as seen in Figure 1(a), where an automated path plan (blue line) can be intuitively perceived as avoiding a navigational threat (red circle) on its way to a target. However, when automation outcomes are driven by constraints that are not directly spatial in nature (such as the time it would take for a vehicle to reach a location, or the ability of a vehicle's onboard hardware to support a specific sensing task), typical geospatial display approaches are insufficient to support operator understanding. As seen in Figure 1(b), it may not be readily apparent why an automated planner has chosen to route a particular vehicle to a target when other vehicles are physically much closer.



(a) (b)

**Fig. 1.** (a) When key planning constraints are spatial in nature, automated planner outputs may be intuitively presented in a map display; (b) However, when key constraints are not directly spatial (e.g., the travelling speed of a vehicle; the efficacy of onboard sensor payloads), map-based displays of automated outcomes are much less intuitive

In geospatial displays that use standard military symbology (MIL-STD-2525C; [19]) vehicle icons typically encode only spatial locations and gross platform differences (e.g., whether a vehicle is friendly or foe, ground or air-based, fixed-wing or rotary). In this case, to understand how individual vehicle differences have affected an automated tasking response, the operator must perform multiple drill-down searches through vehicle details, for example clicking on individual vehicles to identify their sensor payloads and travel speeds, as in Figure 2(a). With this approach, the operator must mentally consider and compare other vehicles to the one selected by the automation, using a serial exploration process that is time consuming and places a significant load on working memory.


Call Sign: NAVAJO-7
Type: Platform -A

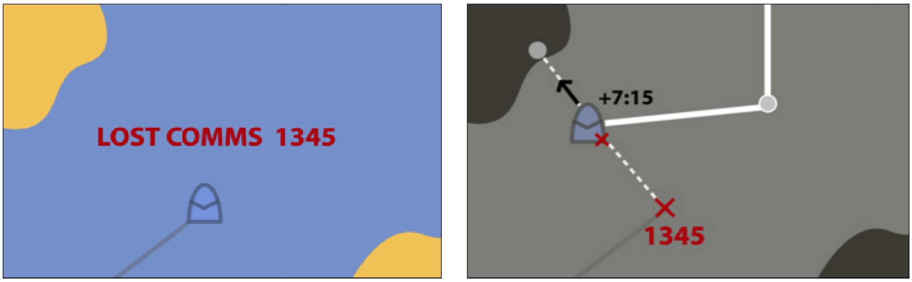
Speed: 240 kts
Altitude: 180 x100 ft
Time-to: 00:04.00
Sensor 1: SAR
Sensor 2: EO/IR

(a) (b)

**Fig. 2.** (a) Traditional drill-down display, with hidden data accessed serially through pop-up windows; (b) An example of an ecological display alternative, with data provided in parallel through explicit visual cues—in this case *time-to-location* coded as icon size, and *sensor efficacy* coded as icon opacity

In contrast, ecological display approaches, such as Figure 2(b), can support operators' direct perception of the non-spatial considerations that led to an automated planner's decision—in this case, by visually mapping calculations of sensor/target pairing efficacy (icon opacity) and time-to-target estimates based on platform speed and distance (icon size). This mapping "makes visible the invisible," while also increasing the perceptual salience of the most promising vehicle options (i.e., those that can get to the target both quickly *and* with ideal equipment). Combined, this enables the operator to rapidly consider alternative choices across the vehicle set in parallel, and intuitively interpret automated planning outcomes. While this example focuses on geospatial displays, we have similarly applied a range of chained visual transformations (including manipulations of hue, saturation, blur, and animation effects; see [20]) across mission timelines, asset/task link diagrams, and health and status views.

Beyond visually encoding the key system and environmental attributes that drive automation outcomes, we have also explored methods to visually represent automated behaviors themselves, and particularly the ways in which these may differ across heterogeneous vehicle teams. For example, differences in platform type and onboard sensing and processing capabilities may have profound impact on how different vehicles within a team may respond to abnormal events, such as a lost communications link. While better-equipped vehicles may be able to continue autonomously for some time on a pre-filed course in the absence of communications, it is also typical for many vehicles to continue at their current heading and altitude indefinitely, or to abandon an established flight plan after only a short period time and proceed directly to a pre-configured emergency landing location.



(a) (b)

**Fig. 3.** (a) A typical display, communicating only the location (and time) of a critical event (e.g., lost communications), and forcing the operator to reason about future vehicle behavior; (b) Example of an ecological display alternative, using explicit visual cues to inform and augment the operator's mental modeling of vehicle state

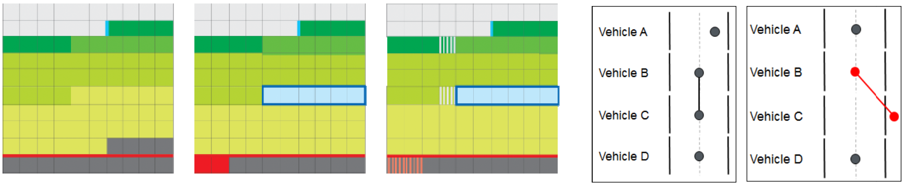
Unfortunately, if they show anything at all, supervisory control displays often simply reflect the location, and possibly time, of a system state change (e.g., a comms link switching from "active" to "lost"), and not the *impact* of this event, as in Figure 3(a). This forces the operator to anticipate how the particular vehicle will respond to this new situation and invites significant opportunity for operator surprise in the event of an incorrect or misapplied mental model [1]. In contrast, an ecological approach such as that shown in Figure 3(b) increases system transparency by explicitly representing the processes governing system behavior. In this particular example, the display not only indicates the lost communications event time and location, but also explicitly represents anticipated behavior based on the vehicle's loaded operating protocol (proceeding directly to a an emergency landing site), the estimated progress against that plan in the time since the event, *and* the expected behavior should communications be regained (an immediate redirection to the next waypoint).

## 4.2 Presenting Information in Context

Beyond simply increasing the perceptual availability of task-critical information, ecological design techniques emphasize situating this information in context. As with more traditional process control systems [9,10], unmanned system displays benefit when health-and-status and automated planning outcomes (e.g., available pounds of fuel; engine speed; altitude; time-on-station) are provided against the framing of expected values, nominal minimum/maximum ranges, and critical limits (e.g., total fuel capacity and minimum-remaining fuel requirements; normal and red-line RPM levels; aircraft flight performance envelopes). Additionally, useful temporal context can be provided by showing changes in data values over time (e.g., a trailing graph of engine pressure) or calculating and then graphically representing instantaneous rates of change ("engine temperature is 280 degrees, but RISING RAPIDLY") Such visual depictions of range and temporal context aid the operator in interpreting how current system operations compare to expected behaviors and critical safety boundaries, and support timely perception of when such boundaries may be breached.

Supervisory control displays can also be improved by presenting information attributes not only within the context of their own expected limits, but also within the context of other information that pertains to related system functions (with the structure of these relationships identified through the previously described AH modeling process [5,6]). Unfortunately, many supervisory control displays artificially disperse related system information over discrete, stovepiped views (e.g., maps, timelines, health-and-status dashboards), both as a matter of convention and convenience. This approach inadvertently serves to mask critical relationships that occur across view boundaries—for example, relationships such as those between engine RPM, altitude, wind speed, and the aeronautical distance of a mission leg, all of which directly impact fuel consumption and, with it, available time on station.

In contrast, EID methods purposefully seek to integrate these diverse representation modalities within coordinated display perspectives that explicitly reflect these complex relationships. Figure 4(b) shows how such an approach could support common fuel or power management tasks (which are often performed in-the-head during re-plan, relying on heuristics and estimations that are subject to calculation error). The left-most image depicts estimated fuel to be consumed by each leg of the mission flight (green shaded segments) against the context of overall fuel capacity (full set of squares), the amount of fuel that is currently available (sum of all shaded squares), anticipated fuel reserves (dark grey), and the minimum amount remaining reserve fuel that is required by mission safety doctrine (red line). If this particular vehicle is allocated to a pop-up task (center image), the fuel cost of this activity is added to the display (indicated by light blue squares) and the total fuel consumption is visibly pushed beyond the minimum safe reserve amount required (indicated by red squares). As the operator directly manipulates elements of a coordinated mission plan display (not shown here, but see Figure 6 for an example)—perhaps by increasing the altitude of the first mission leg and reducing the travel speed of the third—the efficiency gains anticipated by these changes are represented directly within the context of the fuel display. The coordinated behaviors enable the operator to intuitively sense of the maximum gains to be had in manipulating attributes of a particular mission leg, as well as when the combined impact of some set of changes is sufficient to overcome the negative impact of the pop-up task on the fuel safety margin.



(a) (b)

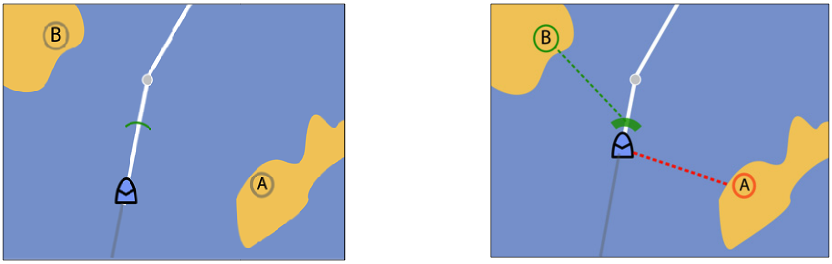
**Fig. 4.** (a) Example of an ecological fuel management display (left), showing the relative impact of a pop-up tasks on available fuel reserves (center), as well as efficiency gains as altitude and time-on-station variables are manipulated in a coordinated flight plan display (not pictured); (b) Example of an ecological mission coordination display, showing the relative impact of two different vehicle retasking options on overall team and mission efficacy as these plan alternatives are selected on a map (not pictured)

In a similar example of context, Figure 4(b) shows a mission coordination display that presents the relative timing vehicle activities with respect to established goals and windows of opportunity. Continuing the example of the pop-up task, automated recommendations for vehicle-retasking strategies (and their resultant path plan modifications) may be depicted in a map view (not shown here). As the operator explores alternative retasking plans by selecting them in the map view, this coordinated display provides a depiction of the relative impact on current vehicle tasking, against the temporal context of acceptable servicing windows (e.g., the time during which the current tasks must be completed for the mission to be of value). In this example, assigning Vehicle A to the new pop-up (left) results in a delay to the primary mission, but one that is within acceptable bound. In contrast, assigning vehicle C not only pushes that vehicle's primary task out of the acceptable window, it *also* negatively impacts vehicle B, which must perform a coordinated task within a similar period of time). Such explicit context enables the operator to readily assess automated behaviors.

## 4.3 Managing Operator Attention

One of the central design strategies of EID is to create display figures whose emergent visual behaviors—driven by mapping graphical sub-elements of the figures to specific low-level attributes of the dynamic work-domain—reflect higher-order system properties [5,6]. When designed well, these mappings (which can be as simple as the scale and opacity icon transformation strategies shown in Figure 2b) modulate the perceptual salience of elements across the display, automatically directing the operator's attention towards critical system process information and causing less critical information to recede into the background.

An example of this salience mapping approach can be seen in Figure 5 (a), where a vehicle is traveling out of the range of its primary emergency landing site, at which point the operator must confirm a secondary site. When this transition point is far in the future, the boundary is flagged as a simple stroke across the planned path. As the vehicle approaches this point, however, the stroke gradually grows in size and salience, and additional cues (all of which would otherwise clutter up the display) are incrementally added to increase the salience of the pending alert, clarify the specific nature of the alert type, and recommend a secondary sight for selection, as in Figure 5(b).



(a) (b)

**Fig. 5.** Example of an ecological display using variable perceptual salience cues to direct operator attention while managing clutter; (a) a simple marker (green arc) flags an upcoming event boundary; (b) as the vehicle approaches the marker (both in space, and in time) the cue becomes more salient and additional information regarding the anticipated automation behavior is provided—in this case signaling that the aircraft is about to head out of range of the primary emergency landing location and the operator must confirm a secondary location

Unfortunately, it is impractical to support all management of operator attention through emergent display features—both because display designs would quickly become overwhelmingly complex, and because not all requirements for directing operator attention can be known *a priori*. Through our interactions with operators—both during our analyses of the work domain and in our subsequent walkthroughs of our design prototypes—we learned that it is often the relative amount of time until key events (e.g., "check the available fuel and confirm the emergency landing site location *when we are five minutes outside of the search area*") that is more critical to cueing and directing operator attention than absolute timing (e.g., "check the fuel *at 1345*"), particularly when the future time in question is not easily calculated from available display information. This is particularly true in directing operators' prospective memory, or the memory to recall and perform a task in the future. Unfortunately, supervisory control displays rarely capture and manage such relative times explicitly. Instead, they must be calculated and then later recalled by the operator, often via physical reminders, such as Post-it Notes. In addition to being error prone under high-workload settings, these methods are divorced from the actual supervisory control information system and thus become inaccurate (or irrelevant) when changes occur to vehicle plans or in the environment (e.g., an unanticipated headwind aloft adds 30 minutes of travel time to the search area).

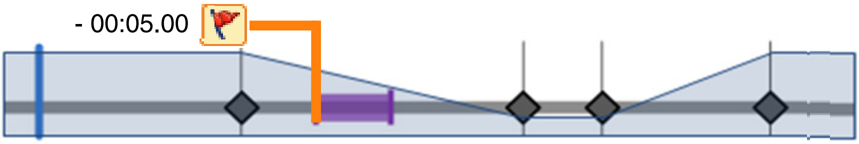


**Fig. 6.** Example of a prospective memory aid in the context of a mission timeline/altitude display; the operator has chosen to pin a notification not to a specific mission time, but rather a relative one—in this case the traversal of a marked airspace (purple shading)

To address this need, we have designed a number of light-weight interaction methods that enable operators to readily establish and manipulate such relative-time reminders within the display itself. For example, as shown in Figure 6, the operator can select an element within a timeline display—such as a waypoint, or a marked airspace that is being traversed—and with a single click, pin a notification to the start of that event, regardless of the absolute mission time at which it occurs. Similarly, the operator can leave reminders by interacting with route plans, waypoints, or other objects across the display (e.g., selecting a distance or time range from a location pin on a map), aiding their future recall to perform critical control tasks.

## 5 Conclusions

This paper has presented the results of several recent and ongoing efforts to improve the transparency of unmanned system automation through the design of ecological supervisory control displays. Although this work has focused on supporting specific missions, vehicle teams, and operator tasks within the maritime domain, we believe that many of the display concepts described may be generally applied to the design of supervisory control tools for heterogeneous unmanned systems. As such, we hope these concepts provide useful resources for other developers of unmanned systems. We are currently undertaking an effort to further refine these and other related design concepts, as well as to formally evaluate their utility in enabling operators to more efficiently and effectively supervise heterogeneous teams of unmanned vehicles. Based on the outcomes of these evaluations, we hope to leverage our efforts to guide capabilities requirements and design guidelines for new and emerging unmanned vehicle control systems, such as the Navy's Common Control Station.

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