Proactive Supervisory Decision Support from Trend-Based Monitoring of Autonomous and Automated Systems: A Tale of Two Domains

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Abstract. The digital technology revolution continues to roil work domains. An influx of automation and autonomous systems is transforming the role of humans from *operators* into *supervisors*. For some domains, such as **process control**, supervisory control is already the norm. For other domains, such as **military command and control,** the transformation to autonomous supervision is just beginning. In both domains, legacy operation-centric, real-time data displays and tools provide inadequate task support, leading to unproductive user work-arounds. They give rise to a *reactive* monitoring stance, and will not scale to meet the new, different task needs. We review advanced display design projects in each domain that, in contrast, provide *proactive* supervisory decision support. We identified key perceptual and cognitive challenges in supervision, and applied cognitive science concepts to the design of novel trend-based interfaces. We drew lessons from process control to combat the challenges likely to arise in military command and control.

Keywords: Visualization, automation, supervisory control, decision support, proactive monitoring, cognitive science, human factors, user-centered design.

1 Introduction

With *A tale of two cities*, his famous novel set during the French revolution [1], Charles Dickens created a story with a message. Dickens used the work to draw pointed lessons for his affluent readers in London of the perils of persistent social inequity and oppression that had recently led Paris to bloody insurrection. Those two cities, London and Paris, here, are metaphors for two work domains shaken by the modern digital technology revolution. Like Dickens's, our tale is cautionary. We draw lessons for a domain bracing for the influx of sophisticated automated and autonomous technologies - military command and control (C2) - from another domain that has experience weathering a similar influx of it, industrial process control.

The digital technology revolution in the latter half of the twentieth century created dramatic changes in the enablers of worker productivity [2]. Now, there are lofty ambitions for sophisticated new automation and autonomous systems to radically improve productivity and transform the roles of its human users. For example, in the

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military domain, it currently takes two or more humans to *operate* one unmanned aerial vehicle (UAV) performing one mission [3-4]. The future vision is for one human to *supervise* multiple autonomous systems performing multiple missions [5].

There are many questions about how to achieve this role shift. Here, we focus on how to support the information display requirements of the future multi-system, multi-mission supervisor. Will current, operation-centric display formats scale to meet the new task demands? Or is a fundamental shift to *supervisory decision support* tools and visualizations required? If so, what new display metaphors are needed and what science can be brought to bear to constrain their design?

To begin to answer these questions, we examine another domain for insights and lessons learned. Industrial process control and military C2 share a marked semblance. They are similar in overall task structure, organizational roles, and even control room layouts. In both domains, supervisors are faced with the task of monitoring unfolding situations and deciding whether, when, and how to intervene in processes or missions.

What *differs* across the two domains is the current state of automation adoption. Industrial processes have run on supervisory control [6] for decades. Process control experienced a revolution in the 1970s through the introduction of distributed control systems (DCS). DCS changed the nature of human work from active physical operation and control of elements across the plant, to passive configuration and oversight conducted from remote, central control centers via visual displays and automation [7].

We have taken advantage of the earlier adoption of automation in process control to apply lessons learned and to anticipate problems likely to arise as more automation is introduced into the military C2 domain. Additionally, we have capitalized on the similarities in task structure and shortfalls of current supervisory displays in both domains to develop solutions that apply *across* domains.

2 User Task Requirements: Proactive vs. Reactive Monitoring

To determine the information display requirements for supervisory control, we performed cognitive task analysis [8] in both application domains. This analysis also revealed the limitations and gaps in support for current practice. The task analysis was an integral part of our user-centered design (UCD) process. Our UCD approach stresses analysis of the cognitive and perceptual challenges of user task performance, and the application of relevant science to those challenges. The aim being to center tool design around users' work domain and task requirements, tailored to human cognitive and perceptual capabilities.

The goal of supervisory control is to stay abreast of processes and situations and intervene to keep things on track. We focused on monitoring, as it is the most time-consuming and challenging aspect of supervisory control [6]. We created descriptive task flows of current monitoring practice and prescriptive flows of ideal practice. The descriptive flows were created from site visits and interviews with subject matter experts (SMEs) from process control and military C2 domains. The process control SMEs were interviewed in site visits to a large oil refinery and a chemical processing facility in Texas in 2011. 27 military unmanned system SMEs were interviewed in 4 site visits conducted across the US in 2012; detailed results reported separately [4].

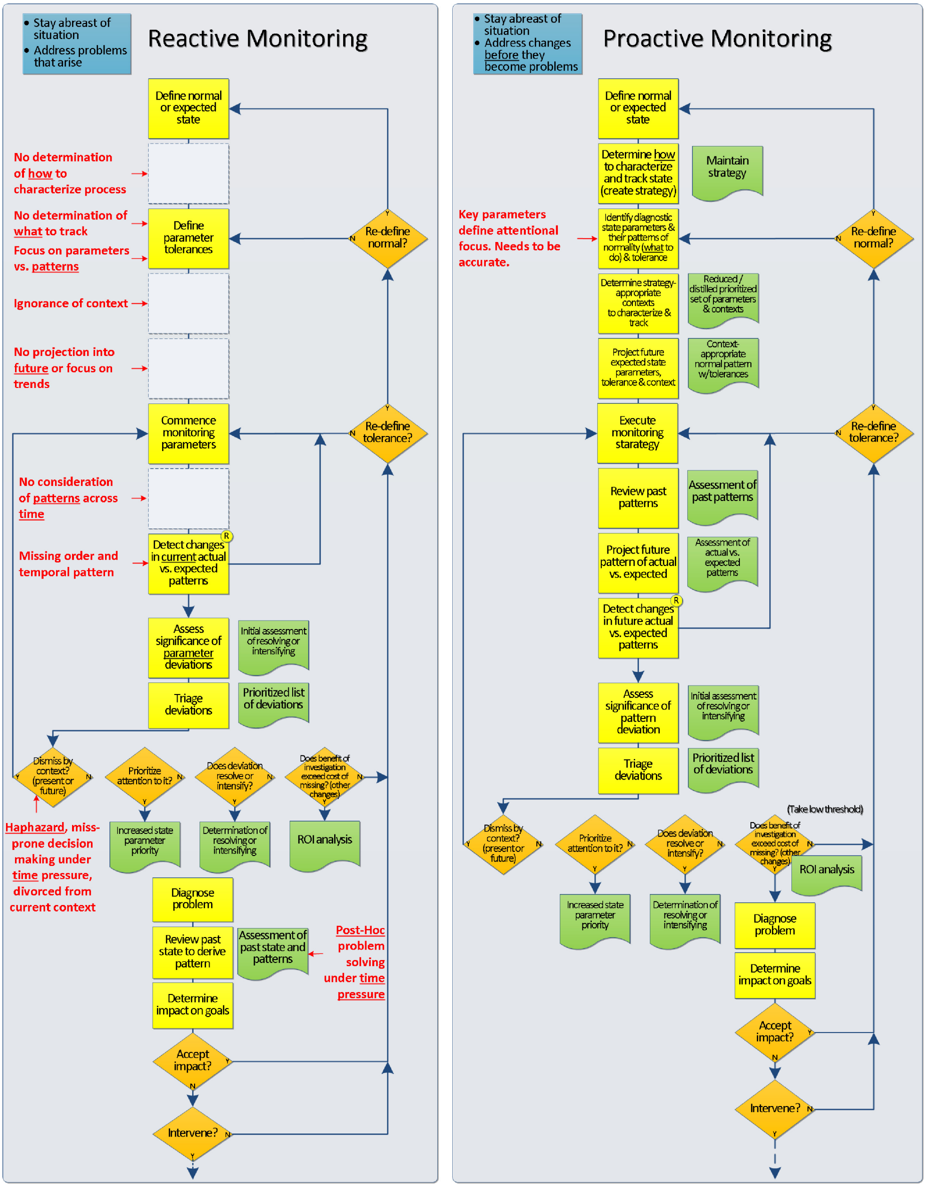

Fig. 1. Task flows for reactive (descriptive, left) and proactive (prescriptive, right) supervisory monitoring. Goals (blue), tasks (yellow), products (green), decisions (orange), and cons (red).

Essentially the same main supervisory monitoring control loop was found across domains, so only one is reported. The descriptive task flow is shown on Fig 1, left. It is centered on responding to system alarms and alerts. It is labeled 'reactive monitoring' because controllers diagnose and act on problems only after they've manifested.

The prescriptive flow of ideal monitoring practice reflects input from the SMEs [4], previous task analyses [9], literature [10] and doctrine [5]. It is labeled '*proactive monitoring*' in Fig 1, right, after terminology in widespread usage [9-11]. Burns [10] previously listed three phases of proactive monitoring as (1) deviation detection, (2) problem prediction, and (3) compensatory action. We expanded these phases into a detailed task and decision flow. The flow is *proactive* in stressing recognizing deviations from normality before they become critical problems, to give time for appropriate diagnosis. Further, proactive monitoring is characterized by defining a monitoring strategy before engaging in monitoring. This strategy is geared around hypothesis testing (e.g., "the process is stable"). Proactive monitoring has also been referred to as "cognitive," or "knowledge-driven" monitoring, to reflect its top-down nature [9].

The juxtaposition of the task flows in Fig 1 reveals their relative strengths and weaknesses (shown in red text). Reactive monitoring has many disadvantages [9-10, 12-13]. The absence of an explicit monitoring strategy can result in delayed or missed detection of deviations. Because diagnosis tasks are only performed after problems manifest, they must be performed under time pressure, often accompanied by a further stream of distracting and uninformative alarms. In addition, a reactive posture can result in an overall sub-optimal system operation, in continual alarm state, instead of in more optimal state conditions [12].

The only downside of proactive monitoring listed in Fig 1 is its reliance on an accurate definition of diagnostic, key performance indicators to track. The restricted attentional set, when accurate, streamlines proactive monitoring, but when inaccurate, may inadvertently delay problem detection.

SMEs from both domains are aware of the overall advantages of proactive monitoring [9]. To the extent they are able to be proactive, though, it is despite their displays and tools, not because of them. We turn to this issue next.

3 Legacy Display Metaphors: Naïve Realism and Reactivity

In a long-running research project, we studied the basis of military situation display design [14-19]. The project was motivated by a U.S. Navy interest in moving from conventional top-down geospatial displays to *spatially realistic* three-dimensional (3D) perspective view displays. In a series of studies, we found a consistent preferences and positive intuitions for spatially realistic displays that performed poorly. For example, both naïve and expert participants expressed a preference for realistic 3D icons (Fig 3, left). However, in controlled testing, participants identified track attributes more slowly and less accurately with the 3D icons than with less realistic symbols [14].

Conventional situation displays are also *temporally realistic* - they show the current state of the situation. In controlled studies, we revealed the parallel limits of temporal realism. Real-time situation displays performed poorly for monitoring for tactically-relevant changes in naval airspace and reporting those changes after an interruption [15]. Further, a temporally realistic instant replay tool actually degraded performance for these tasks below baseline [16]. Alternative, less realistic approaches that presented automation-extracted changes were shown to be far superior, though their utility was underestimated by participants [15].

We developed a theory called *Naïve Realism* to explain the paradoxical desire for spatially and temporally realistic information display, theorizing that it was based in folk fallacies about the workings and output of perception [17-18]. Naïve Realism has led to display metaphors that unhelpfully mimic spatio-temporal aspects of physical task domains that then predispose their users to monitor reactively.

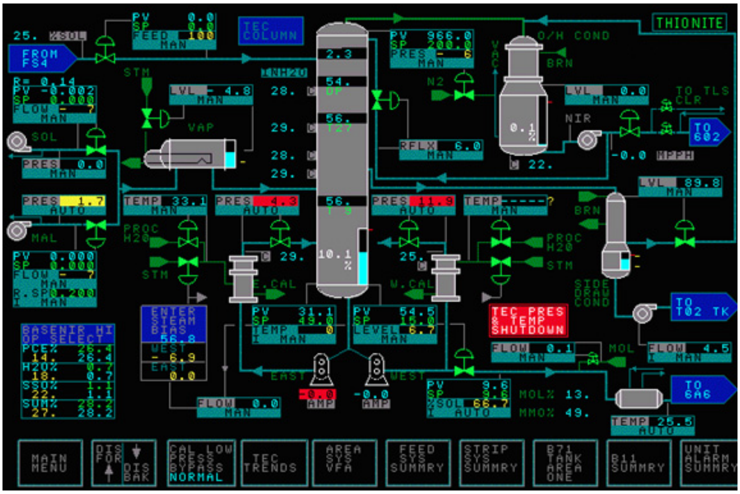

Fig. 2. Example of the traditional piping & instrumentation diagram (P&ID) mimic display format of process control (Source: [20] *InTech* magazine, Nov/Dec 2012. © 2012 ISA. Reprinted by permission. All rights reserved).

In process control, for example, the predominant display metaphor is the piping and instrumentation diagram, or "P&ID," which is a mimic of the plant engineering diagram. The P&ID is often densely superimposed with real-time process parameters (see Fig 2 for an example). Like our experiment participants who struggled to detect changes in real-time Navy situation displays [15], users of P&IDs must extract temporal context and trends from real-time data with their eyes, and stitch it together over time in memory to infer potential deviations. Process control experts may engage in workarounds to combat this difficulty. For example, in the nuclear industry, operators have been observed to print out copies of control screens and subsequently write down observed values to externally reconstruct temporal context missing from their displays [9]. Expert users may also overlay miniature trend graphs next to process elements on P&IDs, or create separate custom displays of arrays of trend graphs [11]. Unfortunately, these work-arounds are of limited utility as they lead to more cluttered and inconsistent P&IDs to monitor, and more displays to track and mentally relate.

Naively realistic users pack P&IDs with too many undiagnostic parameters partly because they overestimate their ability to extract information from cluttered displays and underestimate the effect of that clutter on their search performance [19]. This clutter makes scanning for deviations a slow and error-prone process [20]. This exacerbates the reactivity problem, putting operators in the mode of playing constant catch-up when monitoring, and hindering their ability to get ahead of problems.

Finally, the alerting schemes for P&IDs invariably use data-level, context-insensitive thresholding, issuing alerts simply when a parameter exceeds some threshold value. During crisis episodes, this can result in unhelpful "alarm flooding" with little or no context available to help triage and rationalize alerts and resolve problems [12-13].

4 Trend-Based Monitoring for Process Control

In a UCD project conducted for a large process control manufacturer, we addressed the limits of the legacy P&ID format, applying lessons from the Naïve Realism research to the design of display concepts for proactive, trend-based monitoring. In the military domain, we had previously combatted the shortfalls of spatially realistic 3D icons through the design of novel hybrid symbol-icons (***Symbicons***) that graphically encapsulate, caricature and emphasize key task-relevant attributes of military tracks [14], see Fig 3. Instead of the complex and indiscriminable 3D shaded icon, the Symbicon simply, quickly, and unambiguously conveys a friendly fighter aircraft and its heading. Symbicon advantages were confirmed by significantly faster and more accurate identification performance in controlled studies [14]. In the process control domain project, we combatted temporal realism in an analogous way by designing and prototyping ***Trendicons*** (patent pending) to graphically encapsulate, caricature, and emphasize key task-relevant attributes of parameter trends. The Trendicon in Fig 3 simply and quickly conveys a process parameter that is above normal (black bar thermometer), trending upward (triangle) and getting worse (bold outline) but not yet reached alarm state (grey fill color, instead of yellow or red).

Trendicons transform monitoring. Instead of monitoring real-time values, or even *trends* of those values [11, 21], users monitor the *task-relevant aspects* of trends that the Trendicons emphasize. Instead of extracting features like actual vs. target value and rate of change (Fig 3, right) themselves, this burdensome work is offloaded to the display, freeing users to devote their efforts to what is most critical: monitoring proactively. Unlike real-time parameters, trends buried in cluttered P&IDs, and banks of trend graphs, the visual format of Trendicons is tailored to human attention and perceptual capabilities. Users can quickly and accurately identify, compare, and prioritize key attributes across several parameters. Further, Trendicons provide a natural task entry point for navigating to more detailed parameter information, through a semantic zoom into underlying trends. This approach allows users to naturally progress into deeper levels of detail when needed, building context useful for diagnosis, *before* problems manifest in alarms and alerts. Other approaches, have targeted the shortfalls of P&IDs through solutions grounded in sophisticated work domain analysis [e.g., 22] but less focused on design solutions matched to users' perceptual and cognitive limitations and their flawed metacognition.

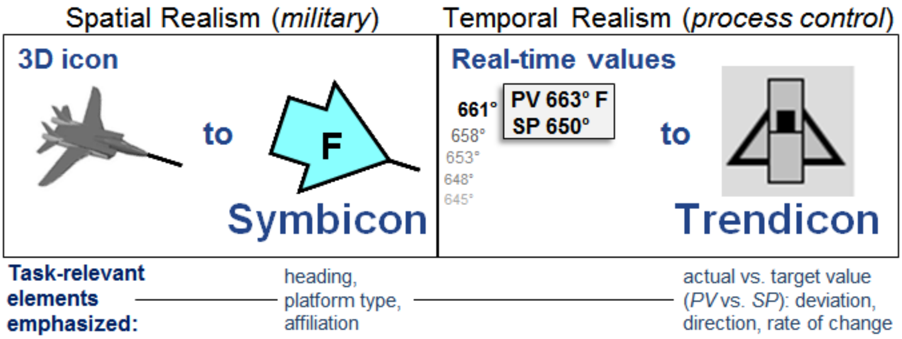

Fig. 3. Combatting Naïve Realism in the military (left, ***Symbicons*** [14]) and process control domains (right, ***Trendicons***, patent pending)

5 Proactive Decision Support for Autonomous Military C2

We are currently folding the lessons learned from process control into advanced concept development for proactive supervision in military C2. Many of the issues and problems are similar across domains. As in process control, today's military unmanned vehicle control displays are characterized by dense, real-time depiction of vehicle and sensor parameters. As in process control, alarms and alerts are generally uninformative, simplistic data-level thresholds not prioritized or aligned to task, and lacking the context necessary to process them effectively. As in process control, SMEs report engaging in work-arounds to facilitate monitoring UAV status from dense displays of real-time vehicle parameters [4]. In interviews, military SMEs reported circling key parameters on their screens to help guide attention, and annotating starting values as references for comparison against current values. The common theme is that legacy, operation-centric display metaphors are not providing good task support. Instead, users are burdened to develop, train, and implement work-arounds external to the systems that should be *intrinsically* supporting their task needs. With the conservatism of large military system development, absent clear guidance and demonstration of these issues, these metaphors are likely to persist.

Motivated by the failures of the current displays and tools, we scoped a UCD effort to define new display metaphors to support the desired shift to multi-system, multi-mission supervision. As in the process control work, the effort was centered around the requirements of the proactive monitoring task flow of Fig 1. However, unlike the process control work that supported *current* activities, the military UCD work defined a *future* vision of how to support multi-system, multi-mission supervision.

For adaption to the future military autonomous C2 domain, our display concepts for current process control were tailored and evolved in several key ways. The future timeline and different scope of the military domain application enabled us to invoke several additional capabilities. These included (1) supervision of multiple instead of single processes and missions, (2) monitoring performance indicators instead of individual operating parameters, (3) parameterizing and integrating context into trended indicators vs. context not parameterized and not integrated, and (4) automated projection of future state vs. no projection automation.

The scope and span of supervisory oversight determines what type of indicators to show. For example, for today's process control, we focused on proactive monitoring of process *parameters*. For today's military C2, we will separately apply these concepts to help unmanned vehicle operators proactively monitor vehicle and sensor performance indicators. However, for future military C2, the focus is on proactive monitoring of multiple missions. This entails aggregating vehicle and sensor indicators to mission level *performance indicators* so that supervisors can better answer questions such as "how are my missions doing? are they meeting their objectives?"

The current state of the prototype is an initial "*Contextualized Trend Board"* user interface concept, shown in Fig 4. The aim is to support proactive monitoring of multiple missions through an interface that summarizes trends in key status icon indicators, and that helps direct attention to those with the most pressing, developing issues.

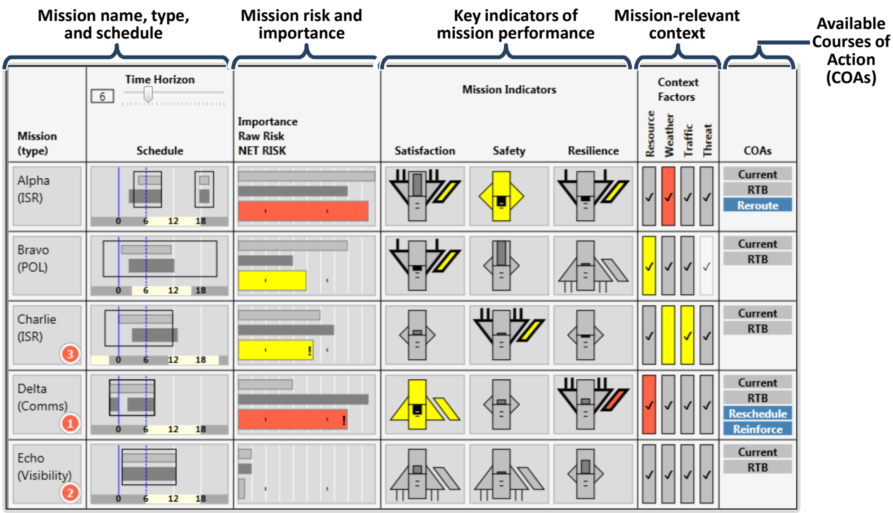

Fig. 4. Contextualized *Trend Board* concept prototype. A top-level overview in a hierarchy of displays for proactive monitoring of multi-mission autonomous military C2.

Triage and diagnosis tasks are supported by a key innovation of directly factoring context into the trended values. In the fourth row of Fig 4, the large red bar for mission risk directs a supervisor's attention to a potential problem in an ongoing communication mission. The resilience of the mission is degrading and projected to become critical, as indicated by the red flange to the right of the status icon. But rather than have no context to understand the reasons for this degradation, the interface shows that mission-relevant weather context is available, impactful, and factored into the indicators (penultimate column) providing the supervisor with an awareness that the resilience problem may well be weather-related, facilitating triage of the problem.

All elements of the proactive monitoring task flow have been woven together in the interface concept and are currently being refined in a rapid prototyping spiral with military SMEs. Fig 4 shows only the top overview layer of a more extensive tool and display set composed of progressive layers that will enable navigation into other layers for detailed diagnosis and intervention tasks related to each mission.

The majority of research and development efforts aimed at reversing the many-operators to single-vehicle ratio have been focused on the technology capabilities, which are necessary but not sufficient to achieve the vision. The future multi-vehicle, multi-mission supervisor will need displays and tools to oversee the autonomy and missions. The work shown here, though initial, provides new metaphors and concepts to define and guide development on a path to the vision.

6 Conclusions

We are entering the age of autonomy with high hopes for advanced technologies, on the one hand, yet only questionable legacy interfaces for them, on the other. These legacy displays often mimic superficial aspects of the work domain, either by showing information realistically in space or time, or through recapitulating paper artifacts from an operation-centric past. These displays provide inadequate support for current tasking, as evidenced by the poor performance they support in controlled testing and the similarity of workarounds they force users to engage in across application domains. Complicating matters, users may believe they are able to extract more information from these displays than they actually can. Legacy display metaphors do not provide a promising basis on which to build needed supervisory decision support for managing the influx of automation.

The autonomy revolution is nearly upon us. All is not bleak, but now is the time to clean house of outmoded display formats.

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