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Human-System Interfaces for Highly Automated Plants: Project Profile

Greg A. Jamieson, Lars Hurlen, & Gyrd Skraaning jr

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Cognitive Engineering Laboratory, Department of Mechanical & Industrial Engineering, University of Toronto
5 King's College Road, Toronto, Ontario, Canada M5S 3G8
URL: www.mie.utoronto.ca/labs/cel/

Cognitive Engineering Laboratory

Directors: Kim J. Vicente, Ph.D., P. Eng.
Greg A. Jamieson, Ph D., P. Eng.

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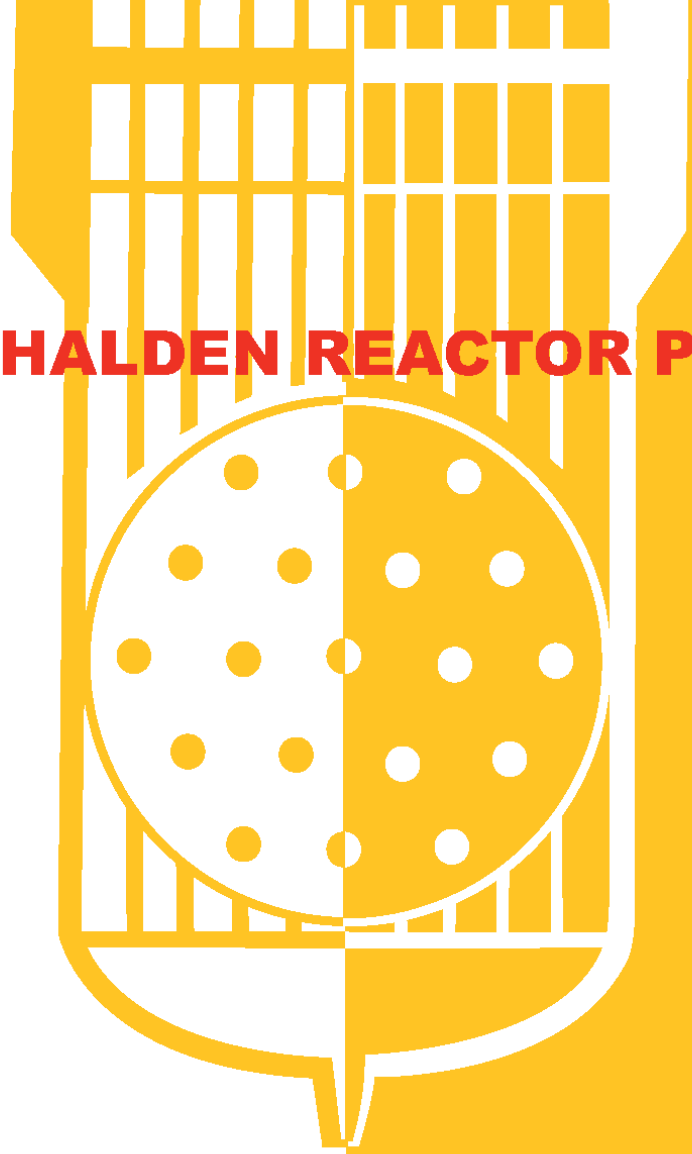

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INSTITUTT FOR ENERGITEKNIKK
OECD HALDEN REACTOR PROJECT
P.O. BOX 173, NO-1751 HALDEN, NORWAY

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OECD HALDEN REACTOR PROJECT

Human-System Interfaces for Highly Automated Plants: Project Profile

by

Greg A. Jamieson, University of Toronto; Lars Hurlen and Gyrd Skraaning Jr., OECD Halden Reactor Project

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OECD HALDEN REACTOR PROJECT

Title

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Author:

Greg A. Jamieson, University of Toronto; Lars Hurlen and Gyrd Skraaning Jr., OECD Halden Reactor Project

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Abstract:

We describe a new research and development program to anticipate design requirements, explore emerging human-system interaction technologies, and develop and evaluate design concepts for helping operators to cope with future NPP automation. This project profile details four key aspects of the program. First, it describes a grounded approach for predicting the future direction of automation technology and anticipating the challenges for operator interaction with that technology. Second, it introduces the iterative prototyping and evaluation process that we will follow and introduce a new lab facility that will support this way of working. Third, it provides an initial outline of the settings in which human operators and automated agents will interact – and the automation technologies that they might supervise and control. Fourth, it concludes with a sample of some of the key design decisions that will shape our vision of human-system interfaces for the highly automated plants of the future.

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MAIL	TELEPHONE	TELEFAX		TELEFAX	
P.O. BOX 173	+47 69 21 22 00	Administration	+ 47 69 21 22 01	IND/OC div.	+ 47 69 21 24 90
NO-1751 HALDEN		Nuclear Safety	+ 47 69 21 22 01	VISIT/RID/COSS div.	+ 47 69 21 24 60
Norway		Purchasing Office	+ 47 69 21 24 40	Reactor Plant	+ 47 69 21 24 70

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1. INTRODUCTION

Future NPP operators will probably share plant control with powerful automated agents. Designing the interaction will be difficult, and there are safety consequences for failing to meet the challenge. Therefore, we undertake a research and development program to anticipate new design requirements, explore emerging human-system interaction (HSI) technologies, and evaluate concepts for helping operators to cope with automation in future NPP control environments.

This document speaks to the initial stage of the project: anticipating future design requirements. It has several objectives:

1. Describe an approach to finding, developing and evaluating HSI design concepts for future automated plants.
2. Define a fertile design space for future HSIs for NPP operation.
3. Explain the premises, assumptions and decisions that shape the design space.

The document has several intended audiences:

- Halden Project Members, who will judge the merit of the project,
- Process experts, scientists, and HSI designers who may contribute to the project, and
- NPP operations experts who may participate in an iterative development process.

2. GENERAL APPROACH

Human factors practitioners have identified a host of problems that arise from poor human-automation interaction (see Lee, 2006 for a summary). These include:

- Out-of-the-loop unfamiliarity: Operators tend to be poor at detecting and mitigating automation failures;
- Clumsy automation: Automation reduces demands on operators during low workload periods, increases demand during high workload periods, and fosters abrupt transitions between these extremes;
- Automation-induced error: Automation exacerbates operator errors and creates new opportunities for mode and configuration errors;
- De-skilling: Manual skills degrade during automation-enabled periods of dis-use; and
- Inappropriate trust and reliance: operators place too much or too little trust in automation, and over-use or under-use automation.

Researchers have traced many of these problems to a lack of feedback from automation about its goals and activities. Operators rely on such feedback to anticipate the behaviour of automated agents.

Human factors practitioners have a tradition of employing a reactive-mitigation approach to design. They work to identify and characterize interaction problems, and then suggest design techniques to solve them. Much of the human-automation interaction literature conforms to this tradition. One pitfall to designing reactively is the possibility of incorrect or over-generalized problem identifications. For example, Sarter and Woods (1995) described the mode awareness problem that plagues pilots using flight management systems. Subsequent treatments have elevated this observation to a general symptom of poor human-automation interaction. Yet Jamieson and Guerlain (2000) failed to observe mode awareness problems amongst process operators using advanced control and optimization automation. Designers should be careful in assuming that human-automation interaction problems observed in one domain will obtain in another. Rather, it is important to be aware of the recurring problems and observe which persist in the domain of interest; in this case NPP automation.

In contrast to the reactive-mitigation approach, here we seek to take a *progressive-generation* approach to the design problem. We will explore new approaches to joint human-machine control of nuclear power plants with the goal of discovering interaction schemes that circumvent the familiar problems and create new techniques for multi-agent control.

Although we seek to develop an alternative vision for human-automation interaction, our knowledge of the potential problems serves to bound our design scope. We must seek a vision of human-automation interaction that guards against casting humans as passive monitors, deskilled agents, or poorly calibrated trustors. Rather, as we discuss in detail below, we envision human operators as active participants in control and as powerful problem solving agents. We intend to design interaction schemes that nurture these attributes and avoid the familiar problems.

Similarly, our iterative evaluation will seek to determine whether operators using novel interaction schemes experience out-of-the-loop unfamiliarity, encounter workload imbalances, commit mode and configuration errors, suffer de-skilling, trust in and rely on automation inappropriately. We must ask whether the familiar problems are systematic of human-automation interaction as opposed to specific to the interaction scheme. We must also bear in mind that new interaction schemes will likely spawn new classes of interaction problems.

2.1 Gathering Information and Finding Inspiration

We will seek to educate ourselves about forthcoming developments in plant technology, process information and automation systems. Not to become experts in these systems, but rather to anticipate human-automation interaction needs before they become apparent through unsafe, ineffective, or inefficient interactions. We can draw insight about such failed interactions from other industries, particularly civil aviation, that have experienced the serious consequences of these failures (e.g., Nelson et al., 1995). Similarly, we will search wide for inspiring interaction techniques. Not to become proponents of those techniques, but to anticipate which can foster rich interactions between future automation and the future NPP operator.

2.1.1 Research institute and industry organization publications

Process industry trade publications offer insight into the future of process automation. Many process industries are more aggressive in their technology adoptions than can be considered safe in the nuclear industry. Regardless, it is reasonable to expect that the automation technologies that appear in the next generation of NPPs will be those that succeed in other process industries (e.g., Leimbach, 2009). Similarly, nuclear industry associations and research institutes anticipate future challenges and set expectations for which technologies might be employed to address them (e.g., Dudenhoeffer et al, 2007; O'Hara et al., 2008). We will consult the future-oriented publications of these organizations and include their insights in our design efforts.

2.1.2 Human-Computer Interaction, visual design and new media literature

We anticipate that new media technologies and applications will spur many design ideas. We will consult the academic and trade literature in these areas for inventive ideas. More and more often this literature is accompanied by demonstration vehicles such as demonstration videos or other early prototypes. We already see a rich set of design interface concepts that may lend themselves to NPP control, including portables, large multi-touch surfaces and tangible interfaces (Ishii, 2008).

A key drawback of this line of design stimulation is that most of the concepts suffer from a lack of evaluation. Much of what is demonstrated and circulated will hold little promise even for its intended application. The project team must therefore anticipate which ideas might find fertile ground in the NPP domain, without the benefit of knowing whether any satisfy even basic usability criteria. We have to expect and risk failure in the search for capable design concepts for the operation of future NPPs.

2.1.3 Encounters with industry

Interactions with industry will inform the design process in two ways. First, we will seek to identify *control challenges* related to the operation of future automated plants by exchanging ideas with a variety of existing and developmental process facilities – and in a variety of control settings within those facilities. Second, we will seek to identify *control solutions* related to the operation of future automated plants. These may include a) solutions in place at existing process facilities that can be adopted in or adapted for use in the NPP setting, or b) solutions advanced by innovators who seek to push developmental technologies toward industry.

The advantages of the industry path to deeper understanding and insight are twofold. First, the challenge and solution cases will be concrete. They will provide a probable anticipation of future industrial control room applications. And they will suggest plausible test scenarios for subsequent design evaluations. Second, we may be able to gain access to operators who have encountered control challenges and solutions in their work. Acquiring feedback from such operators could accelerate adaptation of solutions for the nuclear industry.

A disadvantage of the industry path is the difficulty of not accepting existing solutions too readily. In our effort to escape the grasp of the present set of design solutions, we must take care not to allow ourselves to be primed by the current notion of what process operators do, and of the tools with which they do it.

2.1.4 Developments in Other Domains

Finally, we will examine selected developments in human-automation interaction in other domains. These will include commercial aviation and military command and control. We emphasize these domains because they reflect the origins of human-automation interaction study (commercial aviation) and the current focal point for research and development (military command and control). As well, the characteristics of both domains match those of process control in important ways. Commercial aviation, for example, is a safety-critical domain where, under normal operating conditions, the functions of the aircraft can be fully automated. Command and control presents the challenges of coordinating multiple independent agents, be they governed by human or machine intelligence. Take, for example, the research on delegation policies and interfaces for control of multiple heterogeneous autonomous vehicles (e.g., Miller, 2007). Effective HSI solutions to this problem may yield substantial insight into the problem of operator control of multiple agents in an NPP setting.

2.2 Rapid Prototyping and Testing

We intend to use the "design thinking" approach to learn about well-functioning human-automation teams in future plants. This new paradigm is both grounded in empirical research on designer behaviour, as well as in a closer examination of the premises for design in real-world problems. Real-world design problems typically involve several dimensions of complexity: technical complexity, social complexity and problem "wickedness" (Veland, 2010). Any successful joint team structure must work across all these dimensions at once, and this method seeks to tackle the challenge holistically rather than by isolating and studying parts.

Central to design thinking is the prototype-evaluation cycle where rough models are refined and detailed in an iterative way as insights are gained throughout the project. We thus intend to produce prototypes as our central tool for expressing ideas, discussing performance shaping factors and gathering feedback. These prototypes may be simple or advanced, and may take different forms. We do not see them as goals in themselves, but as the products of being immersed in an active, flexible, reflective exploration of the problem/solution-space. The prototypes are expected to mature through the project, without becoming fixed to specific automation technologies.

This means that concepts emerging from this project will not necessarily be evaluated through controlled experiments. Broadly speaking, we expect that the evaluations might have to sacrifice external validity in terms of participants and tasks in favour of retaining ecological validity. That is, the evaluation efforts will prioritize the realism and credibility of the design prototypes and de-emphasize representative sampling of users and test scenarios. This is dictated by the futuristic nature of the research, where task characteristics and operator competencies/roles will remain ill-defined throughout the concept development phase.

In part, the intended evaluation approach runs counter to some contemporary HCI research, where the design (and subsequently the evaluation) problem is conceived such that the solution is inherently appealing. For example, media manipulation is the task foil for a majority of multi-touch surface development and research described in the HCI literature. Users are portrayed gathering, cropping, re-sizing and sharing personal images and movies. Although these uses of multi-touch interaction are compelling for social communication applications, it is difficult to imagine how the interaction scheme would be useful in a control room (or almost any other work) setting. The result might be described as a set of “nice ideas with no place to go” – a trap that we hope to avoid.

We will create opportunities to put operations specialists in touch with design concepts early and often in the development process. This will result in several departures from HRP design projects with a short-term objective. First, we intentionally refer to “users” as opposed to “operators.” Although we will seek to involve NPP operators in the project, we will also seek out other “operator-like” users to react to our design concepts. These could include operators from non-nuclear, or even non-process industries; pre-operator trainees; as well as experts on use such as, HF specialists, engineers, HSI designers, industrial psychologists etc. Second, among our prototyping tools we may employ non-simulator (e.g., Wizard-of-Oz) and scaled world settings to put users in touch with design ideas early. Finally, we plan to conduct workshop sessions that are non-evaluative of user performance. These workshops will place participants in the roles of critic, co-designer, and even prognosticator as they help us to filter out ideas worthy of further development.

2.3 Design and Testing Facilities

The design and evaluation approaches described above cannot be carried out in a single setting. We will therefore rely on a combination of current and future MTO lab facilities to evaluate new design concepts.

2.3.1 HAMMLAB

The Halden Man-Machine Laboratory (HAMMLAB) is a test and research environment for experimental simulator studies in nuclear process control, and was established by the Halden project in 1983. A major purpose of the laboratory is to develop improved control room solutions that produce safe human performance. Design prototypes are evaluated through convincing and lifelike simulations without sacrificing experimental control. HAMMLAB has two advanced nuclear simulators, the HAMBO simulator (BWR, simulates the Forsmark-3 plant in Sweden), and the RIPS simulator (PWR, simulates the Ringhals-3 plant in Sweden). The plant models run on a software integration platform in the HAMMLAB Experimental Control Room. Separate computerized human-machine interfaces, representing the process graphically, are developed for each plant model. In the HAMMLAB Experimenters Gallery, researchers monitor and manipulate the simulators during experiments with licensed NPP operators.

Extensive amounts of data are collected and analysed in these studies, such as simulator logs, audio-video recordings, operator and expert performance ratings etc.

The simulators in HAMMLAB represent present systems, and would have to be enhanced (e.g., by adding advanced automation) or used strategically (e.g., by emphasizing passive processes) to serve our purposes. Alternatively, we may expand the simulator park by introducing future-oriented process systems. The computerized control room would also have to be upgraded with new technologies that represent future systems. The advantage of performing evaluation studies in HAMMLAB is the spacious control room facility with rigid data collection equipment and a separate observation gallery.

2.3.2 MTO FutureLab

A new MTO FutureLab facility is under development to support concept development, prototyping and evaluation (see Figure 1). FutureLab will support exploration of HSI concepts earlier in the development stage. Technology resources include:

- a workstation desk with a flexible set of ceiling mounted high-resolution projectors
- "ultra short throw" (i.e., close-range) projectors and a wall-mounted touch sensor to create a "touch wall", and
- a multi-touch table and wall-mounted display.

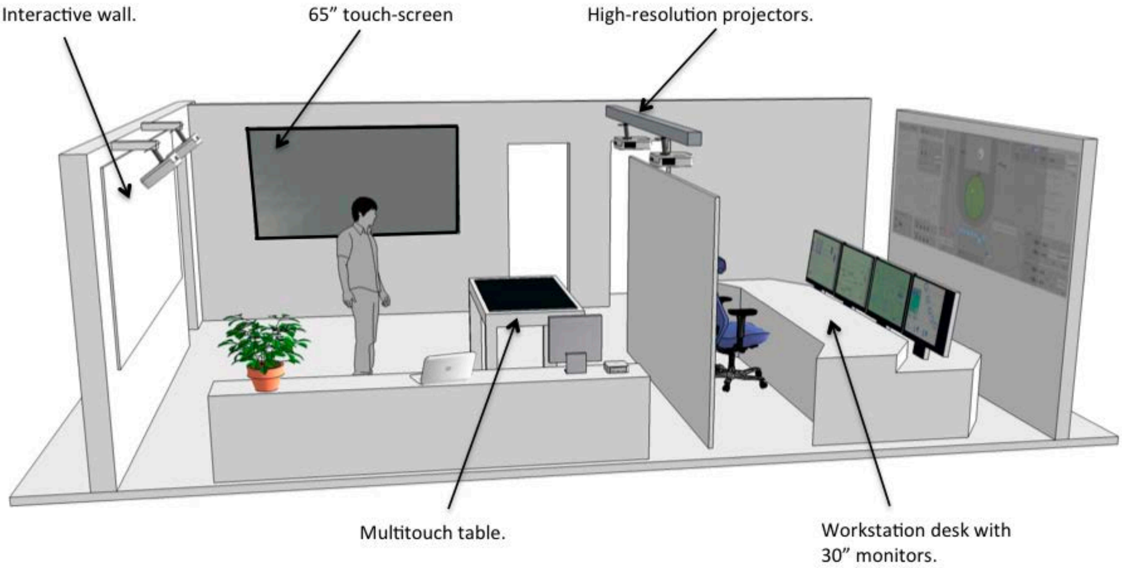

Figure 1: The MTO FutureLab and the adjacent Integration Lab

FutureLab will be separated from the existing Integration Lab by a removable barrier. The Integration Lab includes an operator workstation and multiple projectors enabling a high-resolution large-screen display. The combined FutureLab and Integration Lab environments will allow for flexible configuration of interface elements and quick deployment of simple prototypes. The combined space will support interactive workshops to express, demonstrate and discuss innovative solutions.

2.3.3 Choosing a Design Setting

We will choose to build and evaluate prototypes in FutureLab or HAMMLAB based on the characteristics of the design idea and the evaluation objective.

FutureLab will better suit design ideas that:

- will benefit from development in a rapid prototyping environment,

- are more prone to failure,
- lend themselves to usability testing,
- require rapid development or adaptation of measurement tools, and
- can be evaluated in a non-simulator or low-fidelity simulator environment.

HAMMLAB will better suit design ideas that:

- can be most effectively developed as iterations on existing automation systems and interaction schemes,
- are expected to succeed locally, although opportunities for improvement might be identified,
- lend themselves to evaluation in the form of stringent and systematic experimental testing,
- can be evaluated using established tools for simulator experimentation, and
- require more rigorous validation.

Finally, we leave the door open for two additional design venues. First, it is possible that future simulators may enable implementation and testing of design concepts linked to alternative plant systems that cannot be effectively simulated in either HAMMLAB or FutureLab. Second, contact with industry may present unique opportunities to explore design concepts – more than likely for existing plant systems that are not easily incorporated into HAMMLAB or FutureLab.

2.4 Transferring Ideas

The project has no single intended technology application. Rather, the project seeks to deliver promising design concepts for future automated plants across a variety of applications and projects. In the near term, those concepts can be transferred to current and near-future HRP control room design projects. The aim is to seed those projects with pre-tested concepts and accelerate adoption of promising ideas. In this way, advances in human-automation interaction realized in this project will undergo parallel development in multiple settings, leading to a more critical understand of the benefits and drawbacks of the underlying concepts. Where warranted, focused implementation and systematic validation projects might be undertaken to establish the technical basis for the transfer of concepts to industry.

In the long term, the project seeks to discover new human-automation interaction challenges, operator needs, technology directions, and principles and knowledge for successful human-automation interaction. These could take the form of task allocations, team structures, interface design principles, training approaches, or even management policies. The most compelling of these ideas will feed into future HRP research projects.

3. A PROBLEM SPACE FOR FUTURE NPP AUTOMATION

Thus far we have explained how we will identify, develop, evaluate and transfer design ideas. In this section, we establish some constraints on future operators, control rooms and automation technologies that will bound our design exploration. Doing so involves predicting the future – an activity with many inherent risks.

We seek to mitigate those risks by avoiding two pitfalls. First, we will not attempt to paint a detailed picture of the future NPP control room. Second, we will not connect our vision to a specific point in the future. We can anticipate neither exactly what nor exactly when the future will hold. Rather, we seek to determine enough of the what and when to establish the contours of HSIs that enable safe and effective interactions with likely future automation technologies. We seek to anticipate the future of NPP supervisory control with sufficient clarity and at ample proximity to develop interaction schemes that can either *enable or alter* that future.

We say “enable or alter” to signal that the project can achieve two ends. First, a vision for future control room automation can make it possible to introduce new automation technology into a control room effectively. Second, that vision can influence the design of the automation technologies themselves, thereby altering the design of a future workplace. Both outcomes are to be considered valuable products.

A vision of future control room automation thus serves three purposes in the project. First, it provides an initial set of design requirements to help instigate the design thinking process described above. Second, those requirements constitute a (similarly rough) basis for early design evaluation and subsequent iteration. Third, it provides a basis for dialogue with stakeholders who may hold competing visions that could as easily motivate the design process.

3.1 Cast and Setting

Our vision of future NPP control begins with a description of the context of operator interaction. We describe the future operator, the future crew and the setting in which we anticipate they will work.

3.1.1 A Sketch of the Future NPP Operator

We expect that future operators will be comparable to today’s operators in terms of plant knowledge, skills, motivation and aptitude. However, they will likely have a greater degree of comfort with increasingly prevalent and powerful automated agents. We expect that greater comfort will manifest as a higher level of trust in automated systems and a greater willingness to rely on automated agents. However, we conjecture that future operators may also harbor unrealistic expectations of those agents. Their trust may not be well calibrated to automation capability and this may encourage inappropriate reliance.

In an effort to mitigate against the risks of inappropriate trust and reliance, operators will likely be trained to judge the capability of the automation and to throttle automation authority accordingly. Despite this new knowledge and skill, operators will not likely have command of the technical basis for those agents. This partial knowledge will invite scripted and heuristic interactions with the agents, creating new opportunities for error.

This sketch, although incomplete, provides insight into the characteristics of the cognitive activities that operators will undertake. Specifically, operator work will be better characterized through a problem-solving paradigm as opposed to information-processing paradigm. We therefore envision HSI technologies that support operators as (predictably fallible) problem solvers working in constantly changing task contexts (e.g., start-up, maintenance during operations, testing).

3.1.2 The Future NPP Crew

We subscribe to the notion of a multi-person crew in future NPP control settings. In other production- and safety-critical domains (e.g., aviation and defence), increased use of automation has allowed for reduced crew sizes. Although this trend will factor in to our design concepts, it is noteworthy that smaller teams (as opposed to single operators) dominate in these other domains. Effective teams remain highly conducive to safe operations.

Human interaction with automation in collaborative settings requires greater coordination between human and machine agents. Moreover, in some operational concepts, remote team members may provide support for the smaller teams working closer to process. Thus, supporting distributed problem solving may emerge as a key design challenge.

3.1.3 The Future NPP Control Setting

We will consider any new operational concept for future plants that includes direct control over nuclear processes – so long as that control is characterized by heavy operator interaction with active and intelligent automation systems. This scope includes:

- multi-unit and remote reactor operation,
- distributed teamwork and virtual teams,
- strategic decision making in transient and accident situations,
- field operator support and coordination rooms
- "SWAT team" control centres (elite tactical units that respond to plant upsets),
- plant and operations expert centres (to be consulted by plants), or
- any simple or complex combination of the above.

In short, we may consider any safe and rational way of organizing the process control work arising from any highly automated future operational concept. It is not necessary that we ascertain the viability of any of these concepts. Rather, the intent is to expose ourselves to many operational contexts that might bring design inspiration.

In practical terms, simulating many of these environments would be difficult in the design settings described above. We can extend our capabilities by accessing the advanced video conferencing resources in the IO-lab, or the Halden VR Centre. As well, combinations of these labs may provide suitable settings for simulation. Regardless, the order in which we explore different settings may be constrained by the availability of appropriate settings. However, we will endeavor to create appropriate settings to explore new operational concepts whenever we see promising directions for new ways of interacting with automated agents.

3.2 The Automation

We continue our description of the anticipated characteristics of the future NPP control setting by introducing some key characteristics of the automation and automated agents that may populate it. The discussion revolves around two inter-related questions: "How much automation?" and "What sort of automation?" will operators contend with in future plants.

3.2.1 Extent of Automation

What would it mean for an NPP to be "fully automated"? The question is clearly related to the notion of Level of Automation first advanced by Sheridan and Verplank (1978). However, that taxonomy describes a trade-off between human and computer authority for task execution. At the lower extreme, the human operator performs the whole task up to the point of turning on the machine to carry out an action. Whereas the upper extreme states that, "The computer does the entire task autonomously." The Sheridan and Verplank taxonomy casts the human vs. automation decision as a zero sum game.

What if advances in technology enables new aspects of the task that were not previously possible? That is, if technology evolves such that, rather than merely assisting the human in doing current tasks, automation enables a new aspect of the task. If those new task aspects are automated, is that task said to be more highly automated that the one that came before it?

These are not merely esoteric questions. Modern automation systems regularly perform tasks on processes that humans have never performed and cannot perform without the computer. For example, human operators cannot solve quadratic optimization functions in real time, yet this is now a normal function of widely-used model-based predictive controllers. Thus, the notion of a "fully automated" function evolves with technological progress. How can we bound the future of NPP automation when the potential scope of the automated task increases constantly?

For the purposes of this project we adopt a series of assumptions about the extent of automation technology in future NPP control rooms. They are grounded in observation about the historical progress of automation.

- Future NPP automation will assume all functions currently allocated to it in modern control rooms (e.g., safety systems). That is, there will be no reversal of automation progress.
- Technology developers will attempt to automate any function currently allocated to human operators.
- New functions in NPP designs will be conceived and implemented as automated functions.
- Automated agents will eventually manage all ‘programmable’ events (i.e., any within-design basis scenarios, normal or non-normal).

3.2.2 Role of Humans in the Control of Automation

An alternative to the above approach is to anticipate the human operator’s role in a highly automated plant. Once again, we base our expectations on observations of historical progress of automation (e.g., Bainbridge, 1983; Nelson et al., 1995). This time, however, we anticipate automated system features that compensate for known and anticipated challenges in joint human-machine control. Future automation systems will:

- support human operators in assuming manual control (either of individual agents or of plant processes) during within-design basis operations,
- allow or rely on human operators to establish a strategy for automation, perhaps at several levels of control,
- provide methods for human interaction with automated reasoning processes, including processes that are extensions of tasks not previously performed by human operators, and
- support human operators in testing hypotheses regarding control actions (or action omissions) taken by the operator, other operators, or automated agents.

Are these features evolutionary or revolutionary advances in automation technology? We argue that they are evolutionary advances, but via a process more akin to *punctuated equilibrium* than phyletic gradualism. That is, the advances are anticipated to come in significant discontinuous jumps rather than gradual incremental developments. This perspective allows us to envision short leaps in automation capability without having to contend with gulfs in technology.

3.2.3 Types of Automation

Given the assumptions above, we can begin to establish some priorities for types or varieties of automated systems to include in our vision of the future NPP control room. The goals of this exercise are to narrow the design space and to recognize potential matches between automation types and HSI concepts. Table 1 list several automation systems that we believe would lend themselves to exploration of design concepts.

Table 1: Likely candidate automation systems for HSI concept development

Automation/Technology	Automation Characteristics	Interaction Characteristics
Computerized Operator (and Decision) Support Systems	Employ model-based and probabilistic reasoning Conducive to shared human-machine problem solving Capitalize on IFE experience base	Strong sense of agency Options for integration/separation from process representations Options for allocation to single or multiple operators
Virtual sensor technologies	Employ model-based and probabilistic reasoning engines Capitalize on IFE experience base Temptation to implement below level of operator purview	Weak sense of agency No known precedent for operator interaction
Task execution engines (e.g., automated start-up procedures)	Capitalize on recent HRP developments Highly conducive to shared task execution	Risk of anchoring to existing HSI concept
Model-based predictive control	Employs model-based reasoning engine Performs multiple simultaneous control actions Includes optimization	Human operator challenged with assessing health of controller Discontinuous workload transitions when automation becomes over-constrained Sense of hidden agency
Safety systems (Reactor Protection Systems, Emergency Core Cooling Systems)	High level of automation autonomy Well-established in existing plants	Primarily monitoring and verification
Process optimization	Relies on advanced algorithms and extensive computation Not prevalent in NPP, perhaps due to emphasis on production	Operator sets objectives for automation to achieve Operator attempts to identify and remove barriers to optimization
Process models and simulations (e.g., TEMPO).	Presently used off-line	Unknown – an opportunity to anticipate interaction requirements

3.2.4 Unity of Automation

Automation in future NPP control rooms will likely be comprised of a set of automated systems fronted by agents with which human operators share control. A fundamental design decision for human-automation interaction is whether the operators will interact with each agent independently, or through a coordinated/coordinating agent. Each approach invites a challenging set of problems. If we subscribe to the notion of multiple independent agents, then we might expect that some agents will have overlapping scopes of view or spans of control. Similarly, there will likely be gaps in automation coverage. Further complicating the situation, it is likely that not all agents will be fully cognizant of the others. Human operators will presumably be tasked with detecting and managing conflicts between agents and filling in gaps to achieve coherent control. If, instead, we subscribe to the notion of a coordinated/coordinating agent, the problems above may be hidden from the human operator – at least until the coordinating agent is unable to resolve the conflicts. In such a case, the human-automation interaction problem may become one of assuming control of unfamiliar agents under difficult operating scenarios.

4. A DESIGN SPACE FOR FUTURE NPP HUMAN-AUTOMATION INTERACTION

In this final section, we introduce three design dimensions that are emerging as design challenges for our iterative prototyping and evaluation approach. Note that these are merely initial dimensions. The full set of design dimensions will grow throughout the course of the project.

4.1 Agency and Dialogue in the HSI

Much contemporary automation is “silent” in the sense that it performs functions with only minimal communication with operators (Sarter, Woods & Billings, 1997). A silent partner is welcome when its performance is effective and reliable. In fact, as automation becomes more effective and reliable, our manner of referring to it tends to migrate away from the language of automation towards the language of functionality. For instance, how many readers would say that they have an “automated dishwasher”?

In the context of process automation, we can apply this logic to highly reliable closed loop regulatory control. Should NPP operators be encouraged to think about PID controllers as automation or alternatively as part of the plant? Should interaction designers create HSIs to establish communication between operators and such controllers?

At the opposite end of the spectrum, advances in automation technology will result in automation being introduced into the control room that, while powerful and efficient, will have periods of varying effectiveness and reliability. In part, this can be attributed to the increased use of probabilistic and model-based reasoning methods over more deterministic methods. Consequently, future operators will interact with automation that relies on less concrete processes and appears less predictable. In addition, the operators may be expected to judge the suitability of the automation to deal with specific plant situations, or to direct its selection of data, processing methods, or responses.

Process operators interacting with advanced model-based automation have been observed to ask, “What is it doing?”, “Why is it doing that?”, and “What will it do next?” (Jamieson & Guerlain, 2000). These questions point to the operator’s desire for a dialogue with the machine controller that appears increasingly agent-like as its power increases. Moreover, automation that takes initiative, works independently, judges the plant state, and performs complex control tasks and generally seems more intelligent also encourages agency. The anticipated shift in automation capability and the resulting demands on human operators suggests an increasing reliance on the agency metaphor in human-automation interaction. It suggests that an important design dimension will be the techniques for embodying that agency and establishing a dialogue with it. Thus, we will explore HSI concepts to foster and exploit the agent metaphor for future NPP control room automation.

4.2 Agent Distribution and Allocation to Crew

Drawing from the assumption that future automation will be implemented as a suite of agents, a key design decision will be whether the representations of those agents are integrated with, or separated from, process representations:

- Integrated agent/process representation means that the agent representations are dispersed through the display space such that they are proximal to related process representations.

- Separated agent/process representation is taken to mean that all agent representations are co-located in the display space and distinct from process representations.

Drawing from the assumption that future NPP control rooms will be staffed by multiple operators, a second key design decision will be whether the agent interaction tasks will be allocated to a single individual or shared amongst multiple crewmembers.

Taken together, the Unity and Allocation axes outline a potential design sub-space. Separated agent/process representations would presumably align with an organizational structure that affords allocation of agent interaction tasks to a single crewmember. Integrated agent/process representations would presumably align with an organizational structure that affords allocation of agent interactions tasks to multiple operators. However, multiple operators could conceivably employ the separated agent/process representations and a single operator could employ the integrated agent/process representation. The effectiveness of these alignments is an empirical question.

Nested within the task allocation to a single operator are incremental levels of access to agent information by unassigned crewmembers. Thus, a crewmember that is not responsible for interacting with the agents might have varying degrees of access to either an integrated or separated agent representation. Limiting access would presumably reduce the supervisory and control task load for each crewmember, but could also increase communication task requirements between operators. Increasing access would expose operators to more data, but could generate less signal than noise if the data does not fit the operator’s problem solving context.

4.2.1 Insights from 2009 Coping with Automation Experiment

The 2009 Coping with Automation (HWR-937) experiment implicitly explored a subset of this design space. Agent representations in so-called transparent automation displays were separated from process representations and responsibility for the agents was shared amongst the crew. This condition was contrasted against an opaque condition wherein no explicit representation of the automation was provided. The results of the experiment were surprising. Transparent automation displays were associated with inferior performance on disturbance detection tasks; and offered no advantage in terms of overall task performance or workload. They were, however, associated with greater trust in the automation.

Five explanations for these observations follow.

1. Incongruent Cognitive Tasks: The detection task and the automation supervision tasks may have been incongruent, perhaps because they draw on different processing capacities that cannot be employed in parallel.
2. Process-Display Incompatibility: The incongruent tasks may not have been effectively supported by the separated agent/process representation (i.e., a design shortcoming as opposed to a fundamental cognitive limitation).
3. Novel displays: The crew’s attention may have been drawn away from process displays to the novel information displays. Note that this effect would tend to be short-lived.
4. Task-Display Incompatibility: The recently developed agent representations may have been better suited to the agent supervising task than the established process representations were to the process monitoring task. Thus, when presented with both displays (as in the transparent automation condition), the operators’ attention may have been drawn to the better display. Although the cognitive effect (i.e., attentional focus) is similar to the novel displays explanation, both the cause and effect would tend to be more persistent.

5. Unforeseen benefits of opaque automation – the need to survey process displays to track the actions of automation may have directed operator attention to information revealing of process disturbances.

How do these explanations bear on the integration of agent/process representations and the allocation of agent supervision and process monitoring tasks? The first attribution would tend to favor allocation of the agent and process supervision tasks to different operators. The second and third attributions would tend to favour integrated agent/process representations (although the anticipated effects of novelty may not constitute a strong design motivation). The fourth explanation could support either a re-design of the process representation in a separated agent/process representation scheme, or an integration of the representations. The fifth explanation would also favor integration of the agent-process representations.

The results of the 2009 Coping with Automation Study suggest that a broader exploration of the agent/process representation and task allocation design space is needed. At minimum, this would require the prototyping of a new integrated agent/process representation. Further development of the separated representation prototype is warranted by qualitative feedback from operators.

4.3 Observabililty and Directability

The surprising results of the 2009 Coping with Automation experiment (HWR-937) suggest two additional dimensions of the design space: *observability* and *directability* of the agent (Christoffereson & Woods, 2002). Observability refers to the establishing of a shared problem representation. That is, a common understanding of the control requirements and objectives held by both the agent and the operator. Note that observability extends beyond making the behaviour of the agent visible (i.e., transparent) toward providing a rationale for the agent that is accessible to the operator. Perhaps the transparent displays, while sufficient for establishing information availability, failed to establish a shared problem representation. That is, the metaphor used in the transparent automation displays may not have matched, or been amenable to, the problem representations employed by operators. The difficulty in using the representation may have drawn the operators' attention to the automation display and away from the process monitoring task.

Directability refers to the degrees of freedom that the operator has in determining the behaviour of the agent. At a gross level, this can be reduced to granting the operator the authority to turn the agent off and on. To exploit the power of advanced automation, however, operators may need to have greater resolution of control over agents. In particular, operators who are sensitive to changes in operating context may be able to keep automated agents working through beyond design basis events – rather than surrendering control to the overloaded operators. It is noteworthy that the transparent automation displays used in the 2009 experiment provided operators with no direct control over the automation. One might conjecture that the operators' inability to direct the agent through the display led to increased attention to control actions and reduced monitoring of the process.

We should be cautious in applying familiar distinctions to experimental results as it is likely that we can find a potential explanation in any one of them. Regardless, intuition draws us to include the observability and directability dimensions in our design exploration. We recognize the need to tell the operator more than just the behaviour of the automation (i.e., transparency), but also to explore new metaphors for establishing a shared problems representation. The most effective representations will be those that encourage effective interaction with the agents.

5. CONCLUSION

The potential design space under a project entitled “Human-System Interfaces for Highly Automated Plants” is immense. In such a large space, an exploratory design project runs the contrasting risks of a) getting lost, or for fear of getting lost, b) failing to venture far from familiar territory. The aim of this Project Profile has been to establish some boundaries for the automation and HSI space, and to describe a means of exploring the space without falling victim to either hazard.

As the title suggests, this profile is merely a first description of the project’s goals, constraints and methods. Future reports will further develop these topics as well as introduce new HSI ideas and describe their development.

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