ITR - (ASE + NHS) - (int): Intelligent Human-Machine Interface & Control for Highly Automated Chemical Screening Processes

1. Introduction

High-throughput, toxicity screening (testing) of dangerous chemical agents/compounds for effects on human cells and cell functions is a rapidly developing international biotechnology industry. Many countries, like the U.S., U.K. and Germany, currently have needs to test biological and chemical agents safely, quickly and accurately in order to develop new biotechnologies to mitigate potential effects of such agents on populations in, for example, terrorist acts. Considering this demand and the need to ensure safety in chemical screening, the nature of such processes has changed dramatically in the recent past. Toxicity tests that were once completed manually by human operators standing under a chemical hood and working with test plates of cellular material are now performed by advanced robotic systems integrated with lines of analytical measurement machines capable of handling cellular assays in order to establish human toxic potentials for hazardous substances. (We describe contemporary screening process lines in detail in the next section.)

This change in how screening processes are conducted has led to dramatic changes in the role of the lab technicians very similar to changes in the role of manufacturing line operators, which occurred with the advent of flexible manufacturing systems (FMS) and the need for supervisory control of such systems (Usher & Kaber, 2000). The new role of the chemical lab technician in toxicity screening includes monitoring the status, or mechanical "health", of robotic systems, detecting processing errors (e.g., mishandling of test plates or vials of hazardous/toxic agents) and failure modes, intervening to correct erroneous robot system states, and performing multiple data analysis tasks simultaneously including evaluating chemical test results and reporting results.

In this new screening process environment, operators are under high monitoring workload, high time stress in sequencing multiple simultaneous experiments and producing results in a timely manner. Operators must address competing goals of ensuring safety in robotic handling of dangerous chemicals and, at the same time, maintaining high productivity. This change in the role of the human operator in chemical screening has had implications in terms of the type of workload to which operators are subjected and their information requirements for effective task performance. Physical workload has been replaced by cognitive/mental load in supervisory control of multiple robotic systems. There is now, more than ever, a need for operators to achieve and maintain high levels of system/situation awareness (SA) in dangerous chemical handling operations to which other lab technicians may be exposed. Multiple operators (2) typically coordinate in feeding materials to screening process lines and controlling the robotic systems in testing. Consequently, the changes in the role of the human operator in contemporary screening processes have implications on communications for ensuring safety and processing efficiency. It is possible that all these changes have had a major affect on the stress level of operators and their work health.

Beyond the issue of change in the lab operator's role, there may be many developing countries or nations rebuilding from recent wars (e.g., Iraq, Afghanistan) that have the need for access to advanced chemical screening processes towards preventing future terrorist activities in their nations. Current barriers to access to such technology for these countries include the expense of lab automation and limited research resources to develop integrated systems for chemical screening processes. The barriers to high-throughput screening may be similar for new biotechnology "start-up" companies that have novel concepts for vaccines or medicines to remedy particular chemical agent exposures, but do not have the resources for advanced testing of compounds. This is an important issue because the biotechnology industry is very competitive. Those companies that have access to testing resources, in order to be the first to develop new vaccines, will be most profitable. Related to this, we know of no screening process systems that can currently be accessed or remotely controlled through network-based (Internet) communication to support specialized applications for developing companies and nations. It is possible that the existing barriers to screening processes may slow overall development of important biotechnologies for the world.

The major research needs that we currently see associated with changes in the way chemical screening processes are conducted and the limited access to advanced screening processes are given below. Each is addressed by specific research objectives.

- *Modeling supervisory control* **-** Developing an understanding of the new roles of screening process operators, the individual and shared SA requirements they may be for critical decision-making in dangerous chemical handling operations, and their resulting workload and stress levels. Our research objectives include developing a prototype supervisory control interface for screening processes that provides critical information needed at any given point in time (based on individual SA requirements); developing a shared SA display to support lab technician collaborative intelligence and coordination in managing a screening process; and integrating decision support features in these interfaces for effective process control. Our objectives also include developing specific physiological measurement and assessment methods for characterizing operator functional (workload, stress) states in near real-time and to relate these states to dynamic screening task allocations between the human and robots. This information on operator functional states and performance requirements will also be used as a basis for adapting the supervisory control interface content to promote effective screening control.

- *Monitoring* **-** Developing the capability for automated monitoring of the status of advanced robotic handling systems in chemical screening in order to: (a) reduce operator monitoring workload, (b) allow operators to focus on analyzing results of experiments for reporting to contracting companies, and (c) increase the number of processes that can be managed by a single operator (i.e., the overall productivity of testing facilities). Our objective related to this second research need is to develop an automated robot "health" status monitoring system, including identification of critical robot system state variables and failure modes. Supervisory controllers need this information as a basis for effectively managing the distribution of screening process workload across robots and maximizing the operational life of the automation.
- *Remote access* **-** Providing network-based access to advanced chemical screening processes (and integrated lab automation technologies) for developing nations and new biotechnology companies in order to promote the creation of medicines, vaccines, etc. to deal with biological and chemical threats by terrorists and to promote the effectiveness and efficiency of use of screening processes. Our objective related to this third research need is to develop new protocols for long-distance, network-based control of automated screening systems using the Internet (under potential communication delays). We want to develop a remote process control setup that is robust to time–varying, stochastic delays in the control loop of a non-linear system (Tipsuwan & Chow, 2003).

The *breakthrough information technology* that we expect to make through this ITR project is the development of an intelligent or adaptive human-machine interface to effectively support the new role of screening process supervisors in local and remote control of high time stress and high risk automated chemical and toxicity testing. The development of this technology will be based on cognitive modeling of supervisory controller behaviors during chemical screening processes and model predictions of operator performance with different interface design alternatives during the design phase and process run-time. An enhanced cognitive model will be developed to account for operator functional states (workload and stress levels), assessed in real-time in terms of physiological variables. Cognitive model predictions of operator behavior during different phases of the screening process will be made while chemical testing is occurring and supervisory controller interface content will be adapted based on these predictions. Beyond this, the intelligent interface content and the remote process control scenario will be adapted based on real-time assessment of robot system status or mechanical "health" states across multiple screening lines being supervised by a single operator.

2. Research Test-bed and Example Chemical Screening Processes for Study

This project will involve a large-scale research collaboration with the University of Rostock, Germany, and the Center for Life Sciences Automation (CELISCA) (see attached letters of intent to collaborate from Rostock and for matching funding of CELISCA by the German Ministry of Science). (We describe the international research team in detail in the Collaboration Plan at the end of the proposal. In general, we plan to bring together the research expertise of faculty at NCSU and CELISCA and to exploit unmatched research facilities at Rostock (see attached facilities description of CELISCA).) CELISCA is a world-class center for the study of high-throughput chemical screening processes and the use of advanced robotic systems in the life sciences (biohazard assessment and biotechnology development). CELSICA has screening process setups that are used for real operations as part of research and local biotechnology industry contracts. CELISCA is an excellent test-bed for studies of human-automation interaction in the biotechnology industry, design of interface technologies for human control of hazardous high-throughput screening processes, as well as distributed, network-based control of screening operations through the Internet. For example, CELISCA has already created on-line facilities for storing and retrieving experimental data from chemical screening processes (again, see attached facilities description for details on current CELISCA systems) and is prepared to expand these resources to an on-line laboratory for remote operation by companies and developing countries with limited access to sophisticated screening technologies.

There are two general types of screening processes currently conducted at CELISCA, including high-throughput chemical and toxicity screening. The chemical screening processes involve handling of dangerous toxic materials, primarily chlorinated solvents and carcinogenic, organometal compounds and acids. The purpose of this type of process is to determine whether organoarsenic/organosulfur compounds are present in solid material samples, like soils and tissues. (These compounds were widely used in chemical warfare agents in World War I and II (e.g., mustard gas, sulfur mustard) and still exist in numerous places in the world today, which are contaminated by the original agents, as well as their decomposition products (polychlorinated compounds – PCBs).) CELISCA's processes have been used to extract, derive and determine the presence of organoarsenic compounds in solids in, for example, site remediation (clean-up) efforts by burning methods.

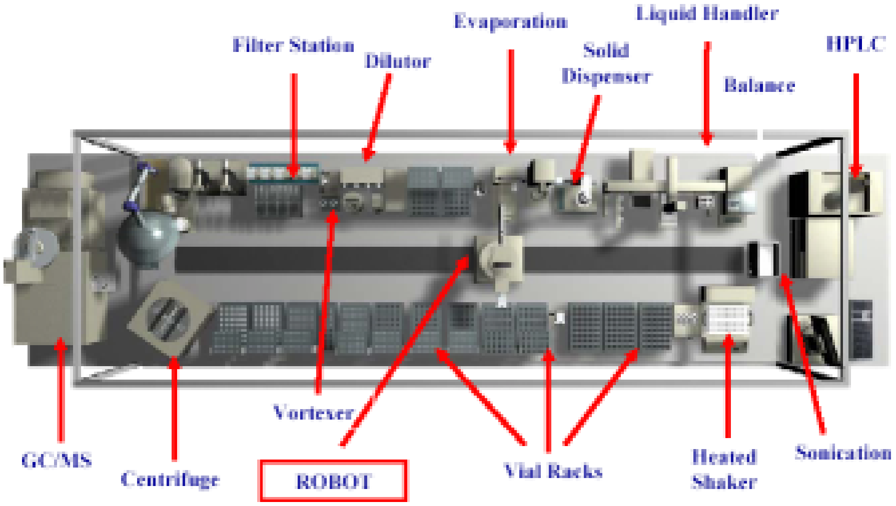

Figure 1. Robotic system for chemical screening of hazardous compounds.

Complete automation of this type of process is necessary to prevent laboratory personnel contact with original agents. The current chemical screening processes at CELISCA are manned by distributed multi-station master robots, which are controlled through a local process control system (PCS). The robots are custom designed for the screening processes and can be configured on demand for specific experiments, including being equipped with different kinds of liquid and solid handlers and vial racks. The robots are integrated with analytical measurement systems in a process control line (see Figure 1). The PCS manages the robot as well as the machines (controlled by their own local controllers). A single line is approximately 6m in length by 2.5m in width and 2m in height. The master robot is mounted on a conveyor and delivers and moves materials for 10-15 machines. Each line has the capacity to process several hundred samples of contaminated material, as part of a single experiment (job). Typical production volumes include tens of thousands of samples processed over 2-3 day periods.

One supervisory controller, planning and programming the robotic tasks, typically operates this chemical screening process. An additional lab technician works on hazardous operations including the delivery of solvents, vials, plates, etc. to the process line. Technicians currently handle these operations because existing automated guided vehicle technologies are not considered to be reliable or accurate enough for such material handling. This situation does pose a substantial, “unavoidable” risk for technicians. (The periodic need for lab technicians to attend to screening processes is a critical issue in facilitating any distributed control of screening lines.)

The toxicity screening processes at CELISCA are designed to establish human toxic potentials of hazardous compounds identified by the chemical screening processes. Cellular assays are used to analyze reactions due to different concentrations of toxins. The assays are monitored by vision systems in screening. The process includes different steps such as cell seeding, incubation, addition of compounds, and measurement of cell activity.

As in the chemical screening process, complete automation of the toxicity screening process is necessary to prevent dangerous situations for lab technicians. The setup of the robotic system for this operation is designed to facilitate parallel processes across various machine systems. The robot essentially works as a systems integrator. It transports sample plates between the different machines, such as a liquid handler, plate reader, incubator, barcode labeler, MTP shaker, etc. (See the facilities description for additional information on the toxicity line machinery). The duration of the toxicity screening process depends on the number of samples, the time required for the different steps in the process, and the availability of the analytical measurement systems at any given point in time. It can range from 15 min. for a few assays to 100 hours for large, complex experiments. An integrated static job scheduler is designed to optimize the time for any process.

Like the chemical screening line, one supervisory controller manages the toxicity screening process by planning and programming robot tasks. However, robot errors may occur in the screening process or chemical reactions may not progress as planned. Therefore, operators may need to periodically intervene in the master robot control. This is a critical point because screening processes cannot be entirely managed by off-line programming in advance of experiments. There must be the capability for near real-time, closed loop programming of the activities of the master robot based on the progress of an experiment. (We will say more about this in the next section.) The cytotoxicity screening process also requires an additional lab technician to deliver the solvents, vials, plates, etc. to the line.

Currently biotechnology companies contracting CELISCA for toxicity screening anxiously wait for lab chemists to become available to report results of their screening processes. Although CELISCA has developed web access to some of the experimental data output, this information is currently only accessible by internal users. Contracting companies may have “in-house” chemists that could use this system and interpret results themselves. Furthermore, companies do not have direct access to control over their experiments in the event screening does not progress as planned. For example, they cannot directly observe absorbance results and adjust compound concentration levels in real-time for toxicity testing; therefore, the screening is an open-loop process for these customers. These issues seriously compromise the efficiency of contracted screening operations.

3. Research Plan

The objectives that we've established for this project will involve using the screening facilities at CELISCA as a research test-bed. They will represent a major expansion of the screening technologies/capabilities currently being investigated. In this section, we describe the specific research tasks to be completed in order to achieve the breakthrough information technology of an intelligent human-machine interface and remote process control system for effective management of highly automated chemical screening processes. The chemical and toxicity screening processes described above will be the focus of our work. Although there are many other types of processes that CELISCA conducts, and that occur in chemical screening, in order to constrain the research problem and make the intelligent interface development manageable, we have selected these processes. Each major subsection represents one year of research for the project team. We expect the work to take approximately 4 years to complete (see the project timeline included in the Collaboration plan).

3.1. Defining Operator Information Processing and Modeling the Chemical Screening Process

In the first year of the project we will concentrate on the major research need of developing a comprehensive understanding of the contemporary role of human operators in advanced chemical screening operations. To our knowledge, cognitive task analyses (CTAs) have never been conducted on such processes and they are needed to establish dynamic goals and process SA requirements of line supervisors. We will also develop the first cognitive model of chemical screening supervisory controllers, based on the results of the CTA. Once we've described the operator's role in local control of screening processes, we will define a new process model for remote operation of the advanced screening automation at CELISCA.

3.1.1. Goal-directed (cognitive) task analyses of chemical and toxicity screening processes

Here we detail our current knowledge of operator roles in chemical screening processes and our plan to do formal CTAs. At present, screening process operators (in the supervisory control role) must plan chemical experiments and program test procedures with software specifically developed for CELISCA systems. The supervisors setup a batch process for each experiment and lab technicians stock the screening lines. Once chemical screening is initiated, the supervisor or chemist must watch the process to detect for hazardous states and to determine whether the process should be interrupted; that is, they perform passive-decision-making, a role for which human operators of complex systems have been found to be ill-suited because of the potential for complacency and vigilance decrements (Endsley & Kiris, 1995; Parasuraman & Riley, 1997). (We mention this because it has implications for the interface design effort.) The supervisors must also study the results of the analytical measurement processes in order to decide whether an experiment is running as planned. In many experiments, the chemical screening process must be completed in order to establish success or failure (i.e., identification of a toxic agent and the concentration required for toxic effects). If an operator must make an assessment of the results of an experiment while the process is running, they have the capability to change process parameters or settings of a specific measurement station through the PCS. This current local control capability has implications for the remote process model we will develop.

Any errors that may occur in a process, or with the robot or analytical measurement systems, are presented to the supervisory controller through the control software as error messages on a display screen. They may also be revealed through a video window as part of the operator display presenting images from Internet Protocol (IP)-based cameras mounted above the process line (typically two cameras per line). Thus, operators need to monitor visual system displays to ensure proper operation of the system and to control the process through a computer workstation. Although operators may be located in the CELISCA facilities while controlling a screening line, they typically do not have a direct view of the process.

Typical errors in a screening process include the following: a robot crashing into a measurement station or work piece; a robot dropping materials (vials, test plates, solid samples, etc.); improper threading or screwing of lids on chemical containers by a robot; centrifuge failures; and leaking chemicals. With respect to the last type of error, chemical spills are controlled by lab technicians based on warnings from electronic "sniffer" systems along the process line able to "smell"(detect) the presence of chemicals in air and identify hazardous states of a process.

It is usually possible for one operator to resolve an error condition. A lab technician must be able to move about a line and examine the master robot's work and determine where the error occurred. The technician must also be able to move materials, racks, etc. to, or from, a machine. Resolving error conditions remotely requires the capability to intervene in the process control and reprogram near-term move sequences of a master robot to, for example, clear damaged materials from a line, etc. (Otherwise, the process line can function under open-loop control.) If there are serious problems with a process, such as a chemical spill, a lab supervisor must be consulted. The line supervisor, lab technician and group leader communicate directly, or via telephone or computer (instant messaging). Operator and technician skills vary and they play an important role in the capability to plan and manage a screening process. For this reason, it may be necessary that a group leader is contacted to resolve errors. Typical causes of errors in a process include uncertainties about the properties of a material provided by a client (contracting company), and failures of clients to conform to screening process tolerances in preparing physical samples, etc. Unfortunately, CELISCA has limited control over these issues and, therefore, errors do occur.

Using CTA, we will develop information on operator perception, planning, decision-making, and interface actions occurring during screening operations in order to describe how specific screening tasks are accomplished. We've previously applied goal-directed task analysis (GDTA; Endsley, 1993) to telerobot applications in nuclear materials handling and for defining supervisory controller information requirements in FMS operations (Kaber, Onal et al., 2000; Usher & Kaber, 2000). We've related operator information requirements for various tasks to system interface design, specifically developing desktop display/control guidelines for operator SA and performance.

For the present CTA, we will elicit knowledge from expert screening operators to identify task principles, goals, strategies, plans, their perceptual skills, mental model structures and common problems encountered by operators (Gordon & Gill, 1994). In a CTA, the focus is on breaking-down operator goals and not describing the procedures of specific task steps by using particular interface technologies. The analysis is intended to be "technology-independent" so that the results may be applicable to many forms of chemical screening processes and for prescribing appropriate human interface information content for many systems. There are many methods that exist for CTA, including expert interviews, verbal protocol analysis, concept mapping, and critical incident or contrived case analysis (Klein, Calderwood et al., 1989). Because of the hazardous nature of the chemical screening processes, it is not possible for us to use verbal protocol analysis, for example, during actual operations.

In this work, we will recruit a small sample of CELISCA operators, which may include process supervisory controllers (or job schedulers), lab technicians, and chemists monitoring the results of the screening process, to view videos of pre-recorded chemical screening experiments. This will ensure that we capture a range of opinions on process control. (This part of the research will be conducted at CELISCA. All participants will be paid through CELISCA's grant from the German Ministry of Science.) The videos will be structured based on analyses of process workflows and will include footage of the actual process lines in operation as well as the PCS output at the existing operator interfaces. As the screening process operators view the videos, we will ask for their opinions on how the taped experiment is being programmed and executed with the advanced lab automation. In general, the videotaped processes will be simplistic chemical and toxicity experiments and are expected to motivate comments from operators in the CTA. Hoffman et al. (1989) have advocated this type of approach to CTA, presenting contrived operating circumstances to participants, in order to generate questions in their minds. The rationale here is that if a participant views a familiar operating scenario, this may not allow for critical insight into their cognitive processes.

We will ask the participants in the CTA to make comparisons of the videotaped operating procedures with their typical approaches to controlling screening processes. We will also ask them to answer questions on how they would address similar experiment planning or conduct process interventions in order to deal with automation errors.

The data that we capture through the CTA will be used to construct lists of operator process strategies and their perceived information, or SA, requirements for various phases of the chemical screening process. The data from the CTA will also be used to describe typical chemical experiment plans and operator decision rules and we will represent these as productions to ultimately be used as a basis for the cognitive model development (the next step of the research). The CTA data is expected to serve as a basis for defining the content of the initial supervisory control interface prototype to be developed during the second project year. The lists of individual operator information requirements will also be used to identify knowledge shared by the chemists, lab technicians, etc. we survey, or the "common body of knowledge" required for coordination of these operators. We expect this to be a subset of the collective requirements of all operators and the information that would ultimately be used to support the prototyping of a shared SA display, as part of the overall process control interface. The results of the CTA will be verified through assessments of the effectiveness of various supervisory control interface design alternatives for supporting operator SA by using the cognitive model. We also plan to use the same group of operators, who participate in the CTA, to evaluate the interface prototypes. This will occur through informal, cooperative usability evaluations.

3.1.2. Cognitive modeling of supervisory controller performance

The information produced by our CTAs will feed the construction of detailed computational cognitive models. Cognitive task analysis and cognitive modeling are part of a common paradigm (John, 2003; Kieras, 1999), in that research and practice in both areas rely on an explicit representation of human cognitive processing. Cognitive modeling techniques have been used to model complex decision-making tasks with considerable success, in some cases resulting in millions of dollars of savings in human resources (Gray, John et al., 1993; Rosenbloom, Laird et al., 1994). By building cognitive models that represent information processing and decision-making in the chemical screening process domain, we will lay the foundation for developing user interfaces that adapt effectively to user needs and changing environmental conditions.

Cognitive modeling for decision-making tasks generally relies on the concept of a unified cognitive architecture, such as ACT-R (Anderson & Lebiere, 1998) and Soar (Newell, 1990). A cognitive architecture can be viewed as a computational architecture that is constrained by known limitations of human cognition, perception, and action in its representation of knowledge and decision-making; in this view, cognitive models are the equivalent of programs that execute in the architecture. Operations supported by a cognitive architecture may be external, representing perceptual input to the decision-making process and actions taken to modify the environment, or internal, representing memory accesses and decisions. Within the past few years cognitive modeling architectures have become powerful and sophisticated enough to interact with real (though simple) environments, rather than abstract simulations; that is, some models have been used for control purposes as substitutes to human operators.

Our goal is to build cognitive models, with extensions to the ACT-R architecture where necessary, that can produce detailed, accurate predictions of human performance in carrying out the information processing tasks associated with chemical screening and robot job scheduling activities, as described above. These models will represent the knowledge operators bring to bear, the decisions they make in different situations, their perceptual processing of available information, and the actions that they carry out, including limited interaction with others (e.g., instructions or information from the laboratory group leader.) The level of representation of operators within the models will be on the order of *Start subsystem X* or *Initiate process P*; the models will be able to process specific items of information and basic spatial information layouts. Because these models are computational, they can be integrated into an intelligent user interface to provide predictions about user performance, based on the models' predictions about operators' capacity to interpret and process information, given the context of specific, dynamic decision-making tasks. This aspect of the research is described in more detail in Section 3.2.3.

Our proposed research will make several unique contributions to cognitive modeling. The models we develop will be at least as complex as any in the literature, and they will address important real-world problems in supervisory control. We also expect our results to generalize to other domains in two ways:

- The laboratory environment poses significant challenges to current state-of-the-art cognitive modeling: the physical environment is more detailed and complex than most environments into which existing architectures have been integrated; more sophisticated visual processing of information is called for than architectures commonly support; and few complex models are required to run faster than real-time in generating predictions of user behavior. This capability will be necessary in the CELISCA project in order to predict operator behavior with various control interface configurations during specific screening tasks just in advance of them actually occurring. We expect to develop novel architecture extensions for model-environment interaction, building on our past work (St. Amant & Riedl, 2001; Shah, Rajyaguru et al., 2002; St. Amant, Horton et al., 2004).
- Developing and testing development tools that support the semi-automated generation of detailed cognitive models from high-level task specifications, again drawing on our past experience (Ritter, Van Rooy et al., 2002). Recent progress has been made in model generation (Salvucci & Lee, 2003), but existing techniques are inflexible and produce only very simple models. We will apply AI search and optimization techniques to drive a much more robust and powerful model generation process. We expect to be able to significantly reduce the effort and expertise needed to produce high-quality models.

Development and refinement of the cognitive models will take place through the first year of the project, with an empirical validation phase scheduled for the end of the period. Validation experiments will involve measuring CELISCA operator performance when using specific interaction techniques, in specific interface configurations, and comparing the data against model predictions, as is common practice in cognitive modeling research (St. Amant, Horton et al., 2004). (Again, the German Ministry of Science will fund the participation of CELISCA operators in this step of our research and CELISCA researchers will recruit the sample of job schedulers, lab technicians, etc.) Measures based on existing interfaces have been shown effective for predicting performance on improved interfaces in the same domain (Gray, John et al., 1993).

3.1.3. Framing the (remote) process control problem

The chemical screening processes at CELISCA can be generally considered as a high-level form of human-robot interaction (HRI), as compared to, for example, human direct telemanipulation of one of the robot arms on the International Space Station in maintenance operations (the environment is also complex and structured, but the technology is not sufficient for fully autonomous operations). Many complex military and civilian applications of remote robotic systems require multiple human operators to control a single machine (e.g., the US Air Force

Predator Unmanned Aerial Vehicle) or, at best, multiple operators controlling multiple machines. Current HRI research interests include developing systems that permit a single human operator to effectively control multiple systems/robots simultaneously (MacMillian, 2004). This is the general operating scenario for chemical screening supervisory controllers at CELISCA, who must carryout multiple experiments, simultaneously, across process lines. Unfortunately, there are no process models of single-operator, supervisory control of multiple robots or machine systems available in the literature, such as a CELISCA operator managing an entire chemical screening process.

The final step of the first project year will be to define a detailed concept of remote, closed-loop control of the CELISCA chemical screening process. Our preliminary concept of remote control of master robots in screening lines from an NCSU control center is presented in Figure 2. Our intent here is to demonstrate the ability to formulate the control problem, as a basis for formal process modeling.

We divide the teleoperation scenario into three separate units, including: (1) the Robot Unit (which includes the robotic system and its on-board robot controller) at CELISCA; (2) the Communication Unit, reflecting the forward- and return-link delay conditions; and (3) the Control Unit at NCSU.

In this concept, the commands for the CELISCA robot system are represented by $r\ (t)$. Looking backward in the control loop, an estimation of the robot commands (or input) $\hat{r}\left(t - \tau_R\right)$ (given the state of robot system and objective) is made by the Central Control Unit at NCSU. This estimation considers the return-link time delay. The operator at the Central Control Unit using the supervisory control display formulates robot commands. The information presented to operators through the display will be based, in part, on a process model to be developed and investigated in this project. The display will allow for operator prediction of actual master robot states in light of the communication delays (to be described in Section 3.2.1). The projected robot commands can be represented as $\hat{r}\ (t)$ once they are sent from the central control unit.

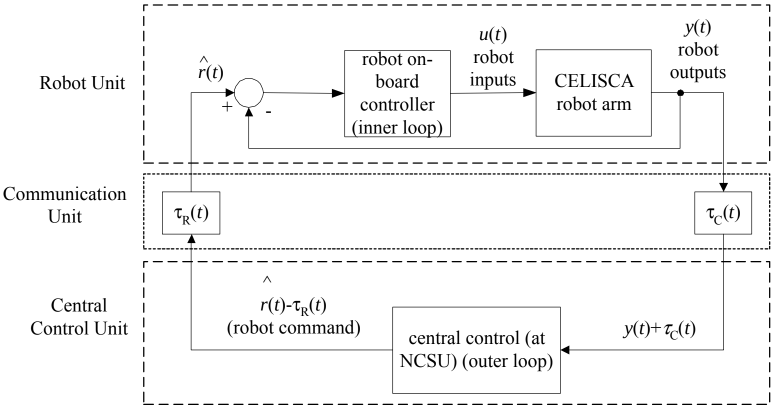

Figure 2. Schematic diagram of overall remote-control process concept.

Looking forward in the control loop, $u\ (t)$ represents the control commands from the on-station robot controller to the robot arm to execute the command $r\ (t)$. The output of the control loop, or the actual state of the robot system, can be represented as $y\ (t)$.

With respect to the Communications Unit of the concept, τ_R represents the time delay in transmitting a signal from the Central Control Unit to the Robot Unit, and τ_C is the time delay in transmitting a signal from the Robot Unit to the Central Control Unit.

This overall concept will be expanded and refined as part of the project and will allow us to develop a detailed process model at the beginning of the second year. It is important to note that the Internet-based control of the CELISCA lab automation that we propose will not necessarily be hard, real-time control.

3.2. Simulating the Remote Process Control System and Prototyping the Intelligent Supervisory Control Interface

During the second year of the project, we will concentrate on the major research need of providing network-based access of the advanced chemical screening processes (and integrated lab automation technologies) at CELISCA for distributed users. We will also focus on the prototyping the initial supervisory control interface to meet operator SA requirements in their new roles and to support critical decision-making in chemical screening processes. Finally, we will establish how the interface content will be adapted in real-time to operator performance requirements based on cognitive model performance predictions.

3.2.1. Development of process model

This task will be a direct extension of the process concept development in Task 3.1.3. Here we will focus on the design and development of the process model, including the Robot Unit combined with the Communication Unit. The characteristics of the Communication Unit are relevant to the major research task of monitoring and parameterizing the communications delays and we will have more to say about this later.

With respect to the Robot Unit, it has its own characteristics; however, for the purposes of this work we are primarily concerned with the input (the robot commands) and output (actual Robot Unit performance) of the unit. The overall model (Figure 3) is an adaptation of the process concept presented in Figure 2.

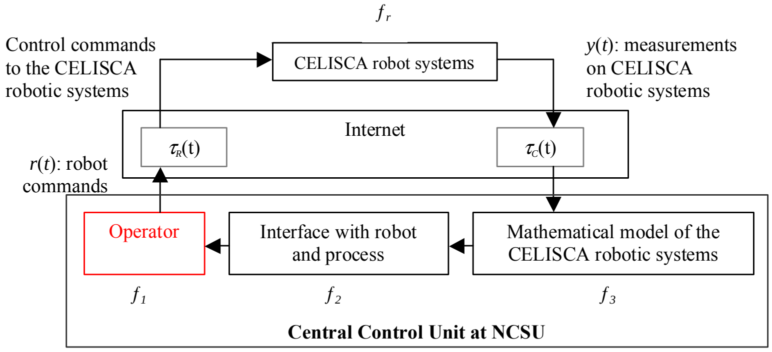

Figure 3. Schematic diagram of teleoperation of robotic system at CELISCA from NCSU.

The variables in this figure can be defined as follows:

f_r - the actual open loop robotic system in CELISCA.

f_1 - the mathematical model of the robotic systems kinematics used to predict the robot system dynamics.

f_2- the mathematical model and display of the graphical model of the robotic systems to predict arm dynamics under the time delay of τ_C and taking τ_R into consideration.

f_3 - the cognitive model of the human operator with output commands sent to the robot system based on operator (or cognitive model) perceptions of the robot/process model displays and projections of the actual state of the Robot Unit.

In this project, we will model the overall teleoperation system into two main models. The first model is the process model f_G, which is a composite mapping of f_1 and f_2: $f_G = f_1 \circ f_2$. The second model is the cognitive model f_3 (development discussed in Section 3.1.2).

With respect to the process model development, the first step in this effort will involve mathematically formulating a generic description of the CELISCA robotic systems using differential (or difference) equations. Appropriate parameterizations will be developed for the robot arm dynamics, the communication profile, and NCSU teleoperation dynamics in order to support the integration of the models.

Subsequently, we will investigate and develop accurate mappings for f_1 and f_2. For example, we will develop f_1 so that $\|f_1 - f_r\| \leq \varepsilon$; where ε is a preset modeling accuracy for the Robot Unit kinematics, and f_r is the actual dynamics of the Robot Unit. The mappings will support our development of strategies to the integration of the various models.

We will create a simulation (time-domain based representation) of the dynamics of the robotics system (under varying load conditions) integrated with the Communication Unit using MATLab/SIMULINK/Stateflow (MathWorks, 2001). This simulation will allow us to investigate the effectiveness of the cognitive model (f_3) to account for delay conditions and to assess the safety of potential control actions prescribed by human operators relative to the most current information on the remote robotic systems (this will addressed in Section 3.4.3). In general, we will describe the relationship between the overall closed-loop control and the system stability region.

3.2.2. Development of operator interface displays

The interface prototyping effort will be constrained by the specific chemical screening process to be studied. We will focus on the supervisory control role, developing an interface to allow a single remote operator to supervise an entire screening process line. (The methods we formalize as part of this research and the resulting intelligent interface technology could serve as bases for future development of adaptive interfaces for other operator roles.)

CELISCA currently has operator interfaces for configuring and programming the robotic systems integrated in the chemical and toxicity screening processes (see Figure 4, left, for an example for chemical screening). The interfaces also allow for the parameters of the different analytical measurement systems along the screening lines to be set for specific applications. The control screens and measurement system data interfaces are currently presented with frame sizes of 1024×768. The camera/video windows as part of the operator control interface (mentioned above) are currently presented with frame sizes of 160×120, 320×240, or 640×480 pixels.

Beyond the control interfaces, operators currently have access to output displays for the static scheduler integrated in the PCS (see Figure 4, right). This interface and the control displays were developed from an "engineering" perspective; that is, all the functionality to control the master robots and the slave measurement machines is provided through the interfaces, but the displays were not designed to address dynamic operator goals and SA requirements nor were they designed to address specific usability goals (visibility of functions, ease of use, error recovery, modeless dialogs, etc). Consequently, the displays only weakly exploit human perceptual and attentional capabilities (Healey, Booth et al., 1996). Beyond this, the displays are not integrated, in the sense that

Woods and Roth (1988) provide; that is, in integral displays, higher order properties are represented by depicting the relationships among the lower order data that define the property. Lacking this, it is difficult for CELISCA operators to maintain knowledge of situation contexts in process control.

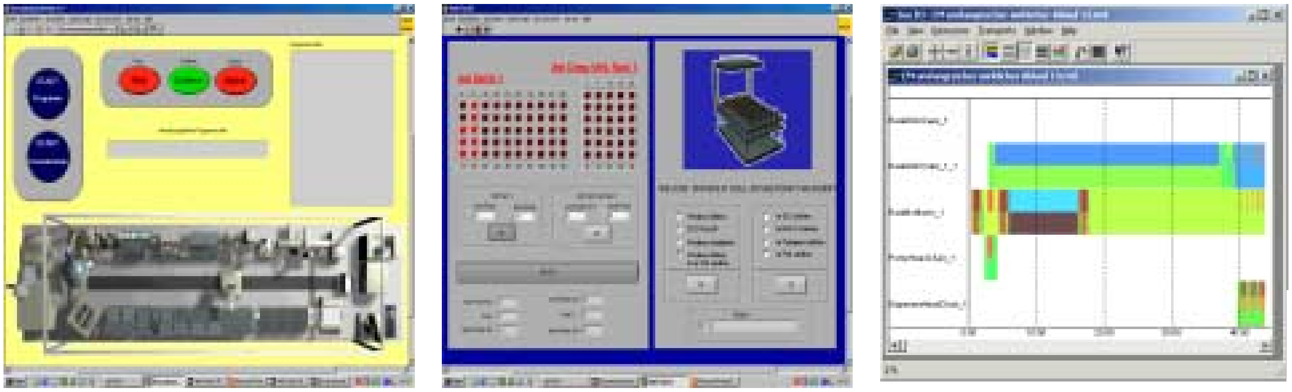

Figure 4. Existing user interfaces for robot control, and setting measurement system parameters and schedules.

Based on results of cognitive task analysis (Tasks 3.1.1), we will develop interactive information displays to address the information requirements of remote and local operators in management of chemical screening processes, for example, an experiment planner/job scheduler at NCSU or at CELISCA (working directly with a lab technician). (In general, we expect the information needs of the local operator to be a subset of those of the remote operator.) We will focus on designing prototype displays for the process supervisory controller to facilitate basic toxicity screening steps (cell seeding, incubation, addition of compounds, and measurement of cell activity) through planning of master robot motion sequences.

Operators need certain visuals of screening processes to effectively monitor robot states. For remote operators, communication bandwidth limitations may be an issue and, therefore, we will carefully consider the results of the CTA to identify exactly what visuals are needed, and when, in order to support performance and safety. Other data that operators need for control may include smells to assess the progress of an experiment and ensure safety (detect chemical leaks). This information could be helpful for a remote chemist running an experiment to develop good process SA and make effective decisions about re-planning tests. It may be possible to transmit the electronic “sniffer” data already captured at CELISCA and present this to remote operators through different display modalities (e.g., visualization or audition of smells).

The data that operators need may span across processes, systems and task materials, but they do not necessarily need all this information at once. CELISCA currently uses multiple display operator “watch stations” for chemical screening control and experiment analysis. Given operator workload and attentional limitations, we think a single, adaptive display device is what is needed and would allow for the optimization of information delivery for supporting various phases of screening processes, meeting operator task priorities, and near-term material needs of robotic system. (The adaptive interface technology described in the next section will address this issue.)

In order to develop information display prototypes that contribute to effective chemical screening process control, there is a need to consider the characteristics of the lab operating environment. User interaction with interactive systems is strongly constrained by the CELISCA environment. Ambient noise reaches 70 dB, which makes voice input and sonification techniques impractical. We also need to consider the level of robot autonomy (in terms of off-loading specific screening functions to hardware). Lab technicians must occasionally move about to watch robot operations, to deliver materials to machines, and to load or unload samples. Consequently, even advanced forms of interaction technology, including multimodal devices, and standard approaches to virtual and augmented reality that involve tethered devices or mobile backpacks are infeasible. Some of these issues are only relevant for local operators, for example, noise in the control environment and may not be issues for remote operator. In fact, this might be one advantage of the remote control scenario for promoting interaction flexibility.

Touch input and mobile devices could reasonably fit into the environment, however; we plan to pursue the possibilities provided by current tablet PC technology. We will conceptualize touch input devices providing multi-finger input. For example, users may view a graphical representation of the chemical screening process on the tablet PC display (like Figure 1) and point to icons with one finger while selecting commands from a co-located pop-up window with another finger in order to obtain data on a specific process element or to change measurement system parameter settings in real time. We realize that the content and functions of such an interface needs to be carefully defined, as it will constrain the user interaction. We will consider the functionality underlying the existing

CELISCA interfaces and evaluate it relative to the critical decisions and information requirements of operators identified through the CTAs, as a starting point for our display design efforts.

Computer science (CS) and industrial engineering (IE) research assistants on project will work in teams to develop rapid prototypes of supervisory control interfaces using SIMULTEK RAPID or Macromedia Director. They will also work on concepts of the shared SA display to be used by all operators to develop collaborative intelligence in the screening process control. Individual operators have knowledge requirements relevant to their specific duties. They may also have knowledge that is commonly held by other operators. In addition, certain operators may need to collaborate with each other to effectively complete tasks (supervisory controller and lab technician in resolving process errors and recovering experiments). They may require specific pieces of information that other operators have. The primary control interfaces can be designed and customized to individual operator needs, and SA displays will be developed within these interfaces to share common knowledge among distributed operators or to present critical information that must be shared between operators for effective performance. For example, we may need to present lab technicians with information from the supervisory controller's display that is needed as a basis for re-stocking screening lines, or we may need to present information from a lab technician display to supervisors that is needed for tracking experiment progress (e.g., vials loaded on the robot, etc.).

We will prototype a number of control interface design alternatives - a collection of interactive information displays - each of which may better support particular phases of chemical screening than others, or that uphold certain usability principles to greater extents. This collection of displays will be organized in a graph to be used in the next major research step, the adaptive interface system development.

3.2.3. Adapting interface content based on cognitive model performance predictions

A promising area of research in intelligent user interfaces focuses on the automated adaptation of interaction mechanisms to user needs. Adaptation is not appropriate in all situations; for example, when users have strong expectations about system behavior, based on past experience, the reduction in predictability produced by automatic adaptation can cause significant frustration and impairment of performance. In other situations, however, adaptation can produce improvements in the responsiveness of the system to the user's current information requirements. The CELISCA environment is well-suited to an adaptive approach for several reasons: potentially large amounts of changing information must be handled; complex, unexpected interactions between processes may arise; decisions may be needed under time pressure. A system that can adapt to changing task requirements, taking into account cognitive considerations, can significantly influence performance.

Some existing systems integrate cognitive models into their processing, but these are found mainly in computer-based education research, such as intelligent tutoring systems. In contrast to existing domains for the application of cognitive modeling, supervisory control has several novel features. The operator's decision-making process relies on detailed and potentially changing information about a real (rather than simulated) system, the operator acts under changing time constraints, and the operator must attend to information in the physical environment and from co-workers as well as computer-supplied information. To facilitate the operator's activities, we propose to develop a user interface management system (UIMS) in which cognitive models, as described in Section 3.1.2, drive the dynamic reconfiguration of the interface with which the operator interacts.

To illustrate processing in the UIMS, let's assume that the operator is constructing an experiment schedule in an interactive visualization environment. The UIMS maintains a graph of interactive information displays with specific paths through the graph that represent default responses to operator actions and requests, under standard conditions. Evaluation of analytical measurements for a running process raises a flag that requires operator intervention. The intervention will require several steps in a decision process, captured by a cognitive model, with different information to be examined during each step. The UIMS simulates the intervention process multiple times, running the appropriate models, based on alternative paths through the graph of displays. Some paths will suspend the scheduling process to focus on the intervention task; some will bring the intervention to the operator's attention but delay processing until later; some will interleave the two processes. The performance of the models will differ based on the attentional and cognitive demands of the tasks and known time constraints on their completion. The UIMS will select the most efficient sequence of presentations that lead to highest quality results. Quality in this context is defined by empirical measures of operator performance, as discussed in Section 3.3.2.

The adaptive UIMS development will commence in the second year of the project and is expected to continue into the third year, relying on formative evaluation during the process. As with the initial supervisory control interface prototyping effort, CELISCA operators will be recruited for usability evaluations of the adaptive interface technology. The UIMS will be subject to a formal evaluation in the fourth year, using standard summative evaluation techniques (Dix, Finlay et al., 1999).

3.3. Robot "Health" Status and Operator Functional State Monitoring

In the third year of the project, we will focus on developing the capability for automated monitoring of robotic handling system states in the chemical screening process in order to reduce operator workload and stress levels. We will also develop the capability to monitor operator functional states in real-time through physiological variables.

3.3.1. Identifying robot system state variables for "health" monitoring

The most important information for screening process operators to have from moment-to-moment in supervising multiple simultaneous chemical experiments is the task status and mechanical "health" state of the master robots on the chemical lines. Currently, significant portions of operator time are consumed by robot monitoring, and in order to automate this task we must develop a full understanding of the CELISCA actuator systems. This step of the research will identify appropriate system state measures to be monitored for automated fault detection and diagnosis.

As an example, the noise (or sound waves) generated by robots dropping trays of chemicals or breaking trays in screening processes could be a critical cue to operators or lab technicians that there has been a chemical spill. With this in mind, we may consider placing microphones in specific locations along process lines in order to capture specific audio frequencies and amplitudes for automated fault detection. Another example of robotic system state variables that could be used for automated monitoring, include actuator parameters/settings. The nominal settings for proper operation of CELISCA actuators include: a linear speed of 1m/s; an angular speed of 360 degrees/6s; and a data sampling rate/control rate of 10Hz. When an actuator starts to develop an incipient fault, such as friction degradation, the actuator temperature will rise; it will consume more current; and move slower than normal, even when the input voltage remains constant. We may monitor, for example, the temperature, speed, current, and input voltage of CELISCA actuators in real-time, and compare our observations with nominal data for specific actuator dynamics. This will provide us with the capability to automatically detect and diagnose potential robot faults.

In this step of the project, the PI and co-PIs at NCSU will collaborate closely with the researchers at CELISCA through frequent visits to the University of Rostock (e.g., two visits/year) in order to establish the necessary domain expertise on the robot system, including design specifications and operation practice, and to properly identify the parameters and variables for accurate, automated robot system "health" monitoring.

3.3.2. Physiological variables for quantifying operator functional states

The objective of this task is to develop measures and indices of screening operator workload that could be used in real-time to identify potential under-load and overload conditions depending upon, for example, the number of chemical experiments being supervised, the number of robots being monitored, etc. Our strategy is to do this with non-invasive physiological parameters.

CELISCA researchers (R. Stoll and N. Stoll) have conducted several studies with screening process operators controlling advanced lab automation to establish their physiological states in the use of existing human-machine interfaces, as compared to resting physiological states in controlled (medical) lab environments. The general procedure CELISCA has used involves medical examinations of operator health and ability status and assessment of operator physiological states under standardized load conditions (e.g., increasing physical workload on an ergometer). For these studies, cardio-circulatory responses (e.g., heart rate, heart rate variability, blood pressure) and metabolic parameters (e.g., oxygen consumption) of relatively homogenous populations of operators have been measured. Each individual operator's physical fitness and selected physiological response parameter's are compared with existing physiological databases on normal, healthy operators.

As part of the present research, we will conduct investigations of screening operator physiological responses under manual and automated workflow conditions in order to establish the impact of operator role changes on workload, stress and overall work health. We will study operators under various working conditions in an authentic screening process. (As in the previous tasks, CELISCA and the University of Rostock will recruit all operators for this research and they will be paid for their participation through the German Ministry of Science grant to CELISCA.) The variables of physiological response to be observed in this study will include heart rate, heart rate variability, blood pressure, and oxygen consumption. In order to develop indices of operator (physiological) stress, we will manipulate the type of work tasks to which operators are exposed (classified using "chronometrage") and workload levels for both manual and automated screening processes (number of simultaneous experiments, number of machines under operator control). Average physiological responses will be determined for each workload manipulation. (Operator performance measures, including time-to-task completion and errors, will also be collected during the study for correlation with physiological data and use in enhancing the cognitive model (Task 3.1.2).)

Indices of stress based on cardio-circulatory parameters will be validated through post-trial interviews with operators and solicitation of subjective impressions on strain level in different process phases (using the Borg scale). It is expected that the physiological load associated with the manual screening procedures will be more evident through metabolic parameters, such as oxygen consumption, and the cognitive stress associated with operator supervision of robot-assisted screening will be more evident in the cardio-circulatory range of measures.

3.4. Intelligent Interface and Control System Prototyping (based on Cognitive Model, Physiological Data Model, and Robotic System State Model Integration)

During the fourth year of the project, we will focus on developing computational tools for automated classification of operator functional states and robotic system "health" status in chemical screening processes by using neural network technologies. We will integrate the physiological data model with the supervisory controller cognitive model for highly accurate operator performance predictions. The robot "health" monitoring and state classification system will be integrated with the overall process control model to provide remote operators with highly accurate process state information in order to promote effective and efficient planning and programming of screening experiments under potential communication delay conditions.

3.4.1. Neural network for operator functional state classification in screening process control

This task will involve four steps including: development of an artificial neural network (ANN) for classifying screening process operator functional states based on the physiological variables investigated in Task 3.3.1 and operator task performance; training of the network for classifying operator states in terms of actual screening process workload levels; validation of the network; and relation of NN outputs to instances of the cognitive model developed in Task 3.1.2 for making highly accurate predictions of operator performance in various phases of screening processes. With respect to the last step, there may be unique sets of productions/parameter specifications as part of the cognitive model of the supervisory controller depending upon the operator's functional state.

Many prior studies have explored the use of physiological measures as a basis for operator functional state classification using NNs, including cardiovascular activity (e.g., heart rate, heart rate variability) as indicators of cognitive load or cognitive task involvement (Wilson, Monett et al., 1997; Wilson, Lambert et al., 2000; Wilson, 2001). According to Scerbo et al. (2002), cardiovascular activity is the most commonly used physiological index of cognitive workload. Heart rate has been observed to increase as cognitive load increases (Wilson, 1992). Scerbo et al. (2002) observed that such cardiovascular activity measures had good sensitivity and diagnosticity for assessing workload and that the measures could serve as bases for classifying overall operator functional states and driving appropriate modes of control in complex human-machine systems.

We will develop a feedforward neural network (FNN) for classification of screening process operator functional states during real screening operations. The network will include multiple inputs representing various physiological and performance measures. We will define a parsimonious network architecture, including a single layer of hidden neurons and multiple output neurons representing several actual levels of screening workload to which operators may be exposed. The hidden neuron layer will be defined based on Masters' (1993) equation: $h = \mathrm{Int}\,(n \times m)^{1/2}$. The number of hidden nodes (h) is determined based on the number of inputs (n) and outputs (m) as part of the network. In general, this equation has been found to define parsimonious network architectures with good predictive accuracy (Chen, Kaber et al., 2000; Chen, Kaber et al., 2004). Chen et al. (2000) also demonstrated use of this equation to prevent over-specification of a NN, over learning of training data patterns by the NN, and, consequently, degradations in network validation performance.

In this research, in order to develop the NN we plan to explore two to three different variations of the chemical screening process task involving operator supervision of one screening line and one experiment, one screening line with multiple experiments, two screening lines with one experiment each, etc. Therefore, the initial NN architecture will include at least 3 inputs (heart rate, heart rate variability, operator task errors), 3 outputs, and the number of hidden neurons may be as few as three, on the basis of Masters' equation. Given the differences in operator tasks in the chemical and toxicity screening processes, it may be necessary for us to develop multiple networks for application to each type of process.

In training the NN, we will use actual physiological and performance data collected on the screening operators during real processes. As in Task 3.3.1, the CELISCA researchers will recruit the participants for this study and they will be paid through the grant to CELISCA from the German Ministry of Science. During experimental trials, we will record operator heart rate and task errors in planning and programming toxicity testing (cell seeding, incubation, etc.). We will analyze both types of data in 1 min. time blocks with 50% overlap to compute moving averages for various measures to be used as inputs to the NN. We will aggregate the heart data in real-time. The time blocks for data collection may vary in order to allow for a sufficient number of observations on operator performance. We expect these measures to allow for accurate assessment of operator functional states. The number and timing of observations on the physiological and performance measures needs to coincide in order for the NN to make regular classifications or predictions of operator states on the basis of all inputs.

The connection weights among the input, hidden and output neurons will be established by allowing the NN to relate the physiological and operator performance data to the actual screening task workload levels that we manipulate during the experiment. We will use an error back propagation (EBP) algorithm for determining the various weights in order to minimize classification error and we will establish a rigid error criterion for the network training (e.g., MSE = 0.02). We will use between 50-80% of the data collected during the test trials with the screening operators to train the NN. Training observations will be selected from the entire data set on a random basis. The overall objective of the training will be to identify characteristics of operator functional states under "low", "medium" and "high" levels of screening process workload.

Once the NN is trained, we will use the remaining 20-50% of the operator physiological and performance data collected during the experiment to assess the classification accuracy of the NN (i.e., validate the network connection weights). We will use the NN to classify operator functional states in terms of screening process workload. We will also study the relationships between the various physiological and performance measures using correlation analyses. This information will be used in enhancing the cognitive model in the last step of the research (3.4.3) for facilitating highly accurate predictions of screening operator performance by considering their physiological states.

3.4.2. Neural network for CELISCA robotic system "health" classification

Since the Robot Unit in CELISCA is a non-linear, stochastic system with unexpected disturbances occurring during operations, we need an automated "health" monitoring system that is able to detect and diagnosis potential faults and to aid operators in making the best process control decisions. Many system variables (e.g., robot loading conditions) are important to assessing the Robot Unit "health" conditions. Those system parameters discussed in Task 3.3.1 will be considered in this part of our research.

It is important to note that system "health" monitoring is different from system protection. For example, a robot arm in the Robot Unit may become jammed in placing a chemical tray and may consequently draw a large "in-rush" electrical current that could burn/destroy the actuator system. This situation may require immediate attention by a local lab technician and it can therefore be classified as a system protection case. In this proposed task, we will focus on "health" monitoring, which has a longer time constant than system protection cases and requires a higher level of automation intelligence and information, such as historical performance data, maintenance schedules of the robotic systems, etc. in order for proper decisions to be made by operators from the Central Control Unit at NCSU.

In Task 3.3.1, we discussed using different sensor technologies on screening lines/robots in order to collect data on critical process states or robot errors (e.g., dropping trays). Many different sensor fusion techniques for systems "health" monitoring have been proposed, developed and investigated in the last several decades. These techniques include parametric approaches such as model-based approaches (Kozlowski, Byington et al., 2001; Wang & Spanos, 2002), residual analyses (Magrabi & Gibbens, 2000; Spina, 2000), non-parametric approaches such as statistical analyses (Roemer, Kacprzynski et al., 2001; Brotherton, Grabill et al., 2002; Ayhan, Chow et al., 2003), expert systems (Liu, Lee et al., 1987; Roemer, Nwadiogbu et al., 2001; Liu & Schulz, 2002), ANNs (Brownell, 1992; Chow, Sharpe et al., 1993; Greitzer, Kangas et al., 1999; Brotherton & Mackey, 2001; Sun, 2002), fuzzy logic (Park & Lee, 1993; Hernandez, Basset et al., 1996; Chow, 1998; Altug, Chow et al., 1999; Fu, Shen et al., 2001; Mahajan, Wang et al., 2001; Dempsey, Handschuh et al., 2003), and a combination of these technologies.

The proposed CELISCA Robot Unit "health" monitoring system must be capable of functioning under a broad range of operating conditions and it must be capable of fast sensor fusion response times for real-time applications. It is difficult to find an exact parameterized mathematical model for application to such a highly non-linear stochastic system. As a result, many techniques such as linear discriminant analyses (Montgomery, Runger et al., 2000; Montgomery, 2001) and model-based approaches will not be suitable in this task. Among all the techniques that have been developed, ANNs are one of the most suitable technologies for use in this task to facilitate rapid sensor fusion and health monitoring. The ANN can learn sensor fusion by using actual system data for training, which can be collected on the actual Robot Unit in CELISCA, without relying on a parametric mathematical model. Since the structure of the ANN is inherently parallel, it allows for parallel processing of data and short computation times for the network to classify robot system states based on sensor fusion. The computational time for a network can be determined as $T_{network} \approx n_{layer} \cdot T_{neuron}$, where n_{layer} is the number of layers in the network (usually ranges from two to five, depending on the architecture used), and T_{neuron} is the computational time required to process one neuron (because all the neurons are processed in parallel in each layer). Thus, the ANN can make quick decisions and perform real-time Robot Unit "health" monitoring after training.

In the overall (remote control) process model (see Figure 3), the ANN will link the feedback control loop with the feedforward loop within the Central Control Unit. The ANN will have inputs from the Robot Unit and the commands made by the operator. The Communication Unit will delay the measurements on the Robot Unit, and it will delay the commands sent from the Central Control Unit to the Robot Unit. The output of the ANN will be fed to the Operator (or the cognitive model) in order to handle any faulty conditions of the Robot Unit, and to modify the process model parameters to correctly reflect the corresponding change in system "health" conditions. As part of the remote robot monitoring system development, we will investigate the impact of communication time delays on the overall system monitoring performance.

In this task, like Task 3.4.1 we will use a FNN trained through an EBP paradigm (McCulloch & Pitts, 1943; Rumelhart & McClelland, 1986; Werbos, 1990; Zurada, 1992; Haykin, 1999; Chow, 2001). We will investigate, identify and design: an appropriate NN configuration (i.e., number of layers, number of neurons per layer); the required input-output training and testing patterns; total number of training patterns and testing patterns required in order to draw statistical conclusions on the designed NN performance; training "stopping" criteria (e.g., mean-square error or cross validation); training algorithms (e.g., gradient descent; steepest descent or Levenberg-Marquardt algorithm) and training rates settings.

3.4.3. Integration of operator and robot functional state classification information with enhanced cognitive model

The outputs of the NN developed in Task 3.4.1 will be considered in developing an enhanced version of the process/supervisory controller cognitive model. In order to consider operator functional (physiological) states in the cognitive model we develop, the results of the correlation analyses of, for example, operator heart rate and performance errors in toxicity screening tasks, will be used as a basis for modifying parameters of the cognitive model, including rule sets, error productions, and times to completion of information processing tasks. The cognitive model will be constructed to use different rule sets for predicting operator performance, based on physiological states. For example, high workload and high stress may be associated with great error rates and longer task completion times being predicted by the model. To our knowledge this will be a unique integration of a physiological data model and a cognitive model.

The final steps of this research will include: a sensitivity analysis of the cognitive models and the user interface (which is rare in cognitive modeling and intelligent user interfaces research); and developing a "blueprint" for the next generation of supervisory process control systems in the chemical screening domain. Ideally, the results of our work should indicate how future systems can be made less expensive, more efficient, and much more usable.

The CELISCA laboratory environment is a state-of-the-art facility, engineered in order to reduce or eliminate sources of disturbances and variability in the chemical and toxicity screening processes, and to support a high level of efficiency and safety in these activities. As such, it can be viewed as a model for other laboratories that may be built or operated under different conditions: reduced or increased capacity, higher or lower quality equipment, differences in procedures, or variations in operator knowledge and training. The research that we've proposed will allow us to explore the effects of such differences on human performance.

One of the most important benefits of building cognitive models to understand human performance is that models can be tested under conditions that may be difficult or impossible to realistically produce in practice. For example, we might ask whether a single operator could manage an additional robot line, with the resulting increase in output, without degradations in the quality of results. Making such an addition to the actual physical environment would be prohibitively expensive but can be done trivially in software. Similarly, we might ask whether a single operator would be able to produce comparable results in a less reliable (and thus less costly) installation. Again this is straightforward to test, via the predictions of cognitive models, in simulation.

We propose to perform such testing on variations of the number of robot lines; on variations in the frequency and duration of required human interventions (robot errors, e.g., robot collisions with stations, robot loss of materials, etc.); and on variations in multi-tasking requirements (e.g., the number and ordering of active processes.)

Variation in these factors defines a multi-dimensional space of laboratory configurations against which we can test human performance. We propose to run extensive simulation testing over these dimensions, using the cognitive models and the adaptive interface we've developed. The quality measures, as discussed earlier will allow us to rank different configurations, and to identify cases in which the quality of results decreases to unacceptable levels, or the burden on the operator's cognitive processing becomes too great. Lets say that the mechanical "health" status of a robot is compromised because of many repeated actuator jams. If data from process sensors causes the NN, as part of the robot "health" monitoring system, to decide that a robot fault exists and diagnosis of the Robot Unit is necessary, this NN output will be used to adapt the process model (f_1 in Figure 3) to reflect its faulty conditions. The overall process model will essentially change and the manner in which the human controller interacts with the system must change to more closely resemble a closed-loop control process. The robots state will affect our simulated system performance and should affect the cognitive model output (human operator decisions), modeled as f_3 in the overall process model. This type of scenario will allow us to assess the adaptability of the cognitive model to a range of chemical screening process conditions, as well as the effectiveness of our intelligent interface technology for supporting supervisory controller SA and critical process decision-making.

4. Summary of Intellectual Merits and Broader impacts

The *intellectual merits* of this research include the following:

(1) Cognitive task analysis of human control of highly automated chemical screening processes - To our knowledge cognitive task analysis has not previously been applied to life sciences automation and is critical for understanding potential negative human performance consequences of automating such processes.

(2) Cognitive modeling of chemical screening process, supervisory controller performance - To our knowledge cognitive models have not been used in real-time (during screening processes) to make predictions of human behaviors and to serve as a basis for prescribing dynamic control interface configurations in order to support operator SA and effective complex, decision-making.

(3) Process models of single user (remote) control of multiple robots - There has been considerable interest in the HRI community in gaining a better understanding of how a single user can simultaneously control more than one robot. The project will yield a detailed model for single supervisor and multiple robot control scenarios in screening processes, and the results are expected to generalize to problems in other domains.

(4) Internet-based (long-distance) teleoperation of screening processes and effective experimental data analysis - This research will be one of the first efforts to facilitate on-line control of lab automation for screening tasks and output/data analysis.

(5) Automated robot "health" monitoring system – Substantial research has been conducted on automated system "health" monitoring technologies, but this work has been limited to local control scenarios. To our knowledge, this will be the first research effort to develop robot "health" monitoring capability (using NNs) in a teleoperation/remote-control scenario for facilitating chemical screening processes. The work will also involve assessment of the impact of communication delays in the teleoperation scenario on the effectiveness of automated "health" monitoring system fault detection and diagnosis.

(6) Neural-network based classification of operator functional states in screening process control (in real-time) and prediction of information requirements (interface content) for screening tasks - Recent research in military contexts has developed experimental tactical command and control systems relating measures of operator physiology to modes, or levels, of computer assistance in order to manage operator workload. To date, no work has considered the integration of information on operator physiological states and performance in real-time, as bases for prescribing modes of human-machine interaction in complex systems.

The main *broader impact* of this research will be the enhancement of safety and effectiveness of high-throughput, chemical and toxicity screening processes in the U.S. and Germany. There will be a direct impact on use of life sciences automation in Germany (at CELISCA). We also expect an impact on the US biotechnology industry through scholarly publications on screening process control and human interface design, which we will develop based on the results of the research. Papers will be published in human factors, human-computer interaction (HCI), and controls systems journals.

The research will also result in network-based (Internet) access to highly specialized and expensive automated, chemical screening technologies for new biotechnology companies and "third-world" countries. This outcome is expected to accelerate the development of new biotechnologies for mitigating the effects of, for example, terrorists' acts, and for advancing medical science.

The research project is also expected to provide highly specialized training to both US and German graduate students in the areas of automation design, ergonomics and HCI, and network control systems (see Budget Justification for further information on student involvement in the research project). This will occur through direct student involvement in the proposed research tasks and through faculty development of new course modules, based on the results of the project, for integration in existing courses in CS, electrical engineering, and IE at NCSU. We will actively seek to recruit women and minority students for research assistantships funded through this project.

5. Results from Prior NSF support and Project Related Research Support

All of the co-PIs on this project (save R. Stoll) have had prior NSF support (through either the HCI or ECS programs) for research on web-based access to remote systems, intelligent interfaces, and virtual reality systems. However, because of space limitations and the need to present a complete research plan, we are only able to provide information on this support through the Biographical Sketches and Current and Pending Support documents.

Research Coordination Plan

The proposed tasks will be jointly addressed by researchers at NCSU and the University of Rostock, working in the fields of automation, CS, electrical and computer engineering (ECE), IE and human factors, and medicine and occupational physiology. Drs. Kaber, Chow and St. Amant will be supported through NSF funding. Regina Stoll, who is also a co-principal investigator (PI) on this proposal, and Norbert Stoll and Kerstin Thurow (senior personnel) will be supported through funding from the German Ministry of Science - Mecklenburg-Vorpommern, providing matching funds to CELISCA of approximately 1.6M Euro (see supporting documents for a letter of intent from the German State) and industry matching to CELISCA amounting to 325K Euro. A new center for "Human-Automation Interaction" (HaI-C) is being planned at NCSU through the integration of the CS Media Lab, the ECE Advanced Diagnostic, Automation and Control Lab and the IE Cognitive Ergonomics Lab (see attached letter of support from NCSU College of Engineering, Associate Dean for Research). These facilities, the research instrumentation and faculty working through the labs (Chow, Kaber and St. Amant) uniquely complement each other in terms of addressing research problems in intelligent/adaptive interface design, control of network/distributed systems, and automated system state and "health" monitoring. The planned NCSU center will support the proposed research and will be linked to CELISCA through a structured research relationship.

Kaber will serve as the PI for the proposed NSF ITR project. He will be responsible for ensuring that each of the research tasks is carried-out according to the project timeline (see table below) by coordinating the work of the co-PIs, including St. Amant, Chow and R. Stoll, and the research assistants. The major tasks for the project include:

- conducting the cognitive task analysis with current chemical screening process operators at CELISCA;
- developing the process model to describe remote, closed-loop control of the screening process;
- developing the cognitive model of supervisory control of the chemical and toxicity screening processes in order to make predictions of operator task performance under various operating circumstances;
- prototyping a supervisory controller interface considering operator information requirements and usability;
- linking cognitive model predictions of operator performance to adaptive interface content to optimize operator perceptual knowledge and process SA;
- identifying screening robot system-state variables and operator physiological variables for classification of overall robot system “health” (physical integrity of the system) and classification of operator functional states;
- developing neural networks to automate robot system monitoring and operator state classifications; and
- integrating the supervisory controller cognitive model with the operator physiological data model and the robot “health” monitoring system as a basis for making accurate predictions of operator performance in screening processes under low/high workload conditions, or when robotic system “health” may be “poor”, etc.

(The specific steps to each of these tasks will be executed according to the timeline presented in the table.)

Year	Semester	Task
2004	Fall	*Conduct goal-directed (cognitive) task analysis* of chemical and toxicity screening processes using videos of simple chemical experiment procedures presented to expert process supervisory controllers, lab technicians, and chemists. Identify operator information requirements for phases and specific tasks of chemical screening.
2005	Spring	*Develop cognitive model of supervisory controller behavior* based on results of CTA – develop extensions to ACT-R cognitive architecture for modeling touch input devices (with portability), including tablet PC.
2005	Summer	*Conduct cognitive model validation* experiments with CELISCA operators. *Develop detailed concept of remote, closed-loop control* of the CELISCA chemical screening process, specifically master (line) robots.
2005	Fall	*Develop mathematical model of process control scenario* involving single user direction of multiple, remote robot actuators at CELISCA. *Simulate CELISCA Robot Unit and Communications Unit in process model* (using time-domain based representations) to *investigate effectiveness of cognitive model in accounting for communication delay conditions in predicting human operator robot control actions*.
2006	Spring	*Prototype interactive information displays* to address information requirements of supervisory controllers. *Design interface content and formatting for control interfaces and shared SA display* for basic toxicity test tasks. Use CELISCA operators for informal usability tests. *Assemble collection of prototypes in graph for use in adaptive interface development*.
2006	Summer	*Develop UIMS* in which cognitive models drive dynamic reconfiguration of interface for screening process operators. *Create prototype of intelligent interface* on tablet PC.

2006	Fall	*Conduct formative evaluation of adaptive UIMS*. *Conduct usability evaluation of UIMS with CELISCA operators* and formal summative evaluation.
2007	Spring	*Identify appropriate robot system-state measures to be monitored for automated fault detection* and diagnosis in chemical screening processes. Work with CELISCA researchers to *develop domain expertise on master robot systems*, and to *equip chemical screening lines with data sensors for remote system fault detection*.
2007	Summer	*Develop measures and indices of screening operator workload* using non-invasive physiological parameters. *Conduct experiments in Rostock medical lab and in real screening process facilities to describe characteristics of operator physiological states* under various process workload conditions.
2007	Fall	*Develop NN for operator functional state classification in screening process control based on physiological variables* and operator task performance. *Conduct experiment at CELISCA to collect data on operators under various workload conditions for training/validating network.*
2008	Spring	*Develop CELISCA Robot Unit "health" monitoring system using NN technology*. *Use historical robot performance data and system-state variable information for training and validating NN.* *Integrate NN for classifying robotic system states into overall process control model* and simulation.
2008	Summer	*Develop final cognitive model considering physiological states of operator* during various phases of chemical screening process. *Conduct sensitivity analysis of cognitive models and user interface* for adaptation to range of screening process conditions and effectiveness of interface for supporting controller SA & performance.

It is expected that Rob St. Amant will devote 1.75 months of his time to the proposed research during the first project year. He will commit 2.75 months of time to the research in each subsequent project year. Dr. St. Amant will work with Dr. Kaber on the cognitive task analysis in order to identify the goals, tasks, critical decisions and process situation awareness requirements of operators in supervising multiple chemical screening operations simultaneously. Dr. St. Amant's expertise in HCI will be critical to the supervisory control interface prototyping effort and development of the adaptive interface technology. He will apply his experience in developing cognitive models for describing human-robot interaction to developing a new cognitive model of chemical screening process operator performance. On the basis of this work, he will direct CS graduate students in using cognitive model outputs as a basis for defining appropriate operator interface content and configuration for performance of various tasks as part of screening processes. Dr. St. Amant will also apply his expertise in cognitive modeling to developing enhanced ACT-R models that consider operator physiological data in making predictions of screening operator information processing performance.

The proposed budget will allow Mo-yuen Chow to devote 2.5 calendar months of his time per project year to the various research tasks. Dr. Chow's expertise in control systems will be critical to describing the remote process control problem and to prototyping the proposed process control model in order to facilitate remote access of CELISCA's chemical screening processes from NCSU. Dr. Chow will apply his experience in automated systems fault detection and diagnosis to developing the CELISCA robot system "health" monitoring capability. He will work with Drs. Kaber and St. Amant to use data from the robot "health" monitoring system to adapt the process model for specific remote control conditions. The systems "health" monitoring data will also be integrated into the cognitive model and used for promoting accurate operator performance predictions given various system states.

Regina Stoll is included as a co-PI on this proposal in order to facilitate the research collaboration between NSCU and CELISCA. (Dr. Stoll currently holds an adjunct associate professor appointment in the Department of Industrial Engineering at NCSU. This formal affiliation with the University permits her to serve as a co-PI on the proposed project.) The proposed budget presents Dr. Stoll's academic year and summer time commitments to the project as 1 and 2 months, respectively. (There are no salary figures included in the NSF budget request for Dr. Stoll because of her support through the matching grant from the German Ministry of Science.) She will devote her time and expertise in occupational medicine to the ITR project tasks, including identifying specific operator physiological variables for establishing stress and workload states in real-time. She will work with Dr. Kaber to define indices of screening process operator stress in terms of physiological variables. She will also apply her experience in developing neural and fuzzy models and systems to development of the neural network for operator functional state classification. Beyond this, Dr. Stoll will work with Drs. Kaber and St. Amant to define an approach for considering operator physiological data in the cognitive model structure and to influence operator performance predictions.

David Kaber will devote 3 months of his time to the proposed research tasks during each project year. His expertise in human factors will be critical to the cognitive task analysis and the supervisory control interface prototyping. He will also apply experience in cognitive modeling to work with Dr. St. Amant on developing the new model of chemical screening operator performance. Dr. Kaber will work with Dr. St. Amant to define different alternatives of the prototype supervisory control interface to be analyzed by the cognitive model in attempting to identify superior interface configurations (during screening process run-time) for supporting supervisory controller performance in different phases of operations or tasks. Dr. Kaber will also apply his expertise in neural network development to developing a computational tool for classifying operator functional states based on physiological data inputs (with Dr. Stoll).

Kaber, Chow and St. Amant will collaborate with the other researchers at CELISCA (N. Stoll and K. Thurow), who will be conducting a parallel research project complementing the proposed ITR work. This interaction will occur directly through international travel by the co-PIs and students (see travel costs included in budget for extended stays by Kaber, Chow, St. Amant and IE, ECE and CS graduate students at the University of Rostock). In addition, R. Stoll will serve as a liaison between NCSU and CELISCA for remote interactions. In general, the faculty at NCSU and CELISCA will collaborate on the development of an intelligent human-machine interface for chemical screening process control and physiological-based assessment of supervisory controller workload levels in high time stress and high risk screening operations. (The specific research tasks of CELISCA are listed below.)

The faculty participating in CELISCA (besides R. Stoll), including N. Stoll and Thurow are internationally recognized for their expertise in laboratory automation, complex robotic systems development, operator functional state assessment and monitoring, and network control systems integration. Norbert Stoll is currently Professor of Informatics and Electrical Engineering at the University of Rostock (previously Dean of the College of Engineering). He will serve as the PI on the CELISCA research project supported by the German Ministry of Science. He will be responsible for ensuring that each of the following major research tasks is carried-out according to CELISCA's project timeline by coordinating the work of the co-PIs, including R. Stoll and K. Thurow and University of Rostock graduate research assistants:

- investigation of human physiological load/strain in use of highly automated life science processes;
- development of effective data analysis interfaces for web-based access of screening processes data and data on operator physiological responses; and
- technical optimization of human-machine interaction for high-throughput screening systems.

Kerstin Thurow is currently Professor of Informatics and Electrical Engineering at the University of Rostock. Dr. Thurow is a researcher at CELISCA and her expertise is in lab automation and chemical screening. She will devote approximately 3 months of her time to the second and third major tasks listed above.

Regina Stoll's time commitment to the above research tasks, as reflected in CELISCA's budget to the German Ministry of Science, is identical to the time shown in the attached ITR budget; however, there are actual salary figures for her in the CELISCA budget. She will be primarily involved in addressing the first research task on investigating human physiological strain in use of automated screening processes, as part of the CELISCA project.

Norbert Stoll will devote 3 months of his time to the parallel research project at CELISCA. His expertise in soft real-time control systems will be critical to CELISCA's development of web-based applications to allow distributed users to access screening process output. He will also collaborate with Dr. Regina Stoll and the NCSU researchers (Kaber and St. Amant) in developing human-machine interfaces for high-throughput screening.

As N. Stoll and K. Thurow are included as senior personnel on this ITR proposal, Kaber, Chow and St. Amant have all been included as senior personnel on CELISCA's proposal to the German Ministry of Science. The evidence that we provide of this proposal is the letter of intent from Mr. Thilo Streit at the German Ministry of Science to fund CELISCA's research effort in parallel to the proposed ITR project. The time commitments of Kaber, Chow and St. Amant reflected in CELISCA's research proposal are identical to the time commitments shown in the attached budget; however, there are no salary figures for NCSU research support in CELISCA's budget. The grant to CELISCA from the German Ministry of Science will also include funds for U.S. faculty room and board in visiting the University of Rostock for extended periods of time during the course of the ITR project.

The efforts and expertise of the faculty at CELISCA will be combined with the expertise of the NCSU researchers in human-robot interaction, cognitive task analysis and modeling for intelligent interface design, human factors analysis and systems design, and network control systems development and fault diagnosis. International, multidisciplinary project teams will be formed to address each of the major proposed objectives. Specific, U.S. and German faculty partnerships (or pairings) will be established on the basis of expertise and research interests in automation design, ergonomics and HCI, and network control systems. It is expected that such a structured link of the planned NCSU HaI-Center and CELISCA will result in a "true" research collaboration for creating the new intelligent/adaptive human-interface technologies for chemical screening process control and developing approaches to long-distance, network-based control of CELISCA's lab automation.