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FINAL REPORTING--FEBRUARY 2015
1. Project aims

This project investigates the hypothesis that selecting units of work to automate based on human procedures will improve human-automation designs. The structured actions sets within procedures, such as steps, can be used as the basis for meaningful, sharable organization of what is automated and how information should be passed between humans and automation. Investigators hypothesize that human-automation interaction organized this way will provide several benefits, relative both to manual operations and to less user-centric automation, including effective execution and more adaptable use with flexible levels of automation. To test this hypothesis, we are (i) developing strategies for using procedures to identify units of work for adjustable automation, (ii) building a test environment with software for manual or partially automated execution of procedures, and (iii) using this environment to evaluate the effectiveness of

alternative strategies for automating procedures.

2. Key findings

The analysis was completed on data from the Year 2 study investigating whether procedure automation could be used effectively in situations where procedure preconditions do not hold (a type of problem-solving). Recovering from or preventing failures threatened by these unmet conditions can be difficult, and software designed for fluent execution of nominal tasks may not facilitate problem solving. However, all 12 participants solved the problem posed by an unmet procedure precondition in two sessions. Specifically, they found a procedure that could make the required condition true then resumed the original procedure. They did this with no prior encounter or training for problem solving when conditions assumed in a procedure are not met. By the second session 11 of 12 participants were able to prevent rather than recover from the failure [Billman, et al., 2015].

A study was completed in the Human Exploration Research Analog (HERA) Campaign 2 evaluating PRIDE electronic procedure software. 16 subjects participated, 4 per mission. Each subject was trained for 2 hours prior to the 2-week mission, then performed seven 1-hour sessions during the mission. We embedded two study-designs within the larger 7-session activities. The Step-List Study tested the hypothesis that performance using procedures with actions grouped into functional units of work called steps (Step Format) would be better than using procedures without this grouping (List Format). The Problem-Solving Study investigated 1) the effects of repetition on problem solving, 2) the effects of a secondary manual task done in conjunction with the primary habitat task where problem occurs, and 3) the effects of encouragement to plan in advance on subsequent execution. Several exploratory tasks were distributed over the mission as well, including the Automation-Manual Investigation comparing human performance with an electronic procedure to the same procedure done using as much automation as possible.

HERA Step-List Study: We found significant effects of format on both markup errors and mode-execution errors given a correct markup. This suggests the Step Format made it somewhat easier to assign execution mode (Manual or Automated) and execute from those assignments; there was no influence of Format on time measures. These results suggest that the Step format reduces errors in setting function allocation relative to List format and they merit further investigation.

HERA Problem Solving Study. Behavior across users and days for the HERA experiment is both less successful in accomplishing the task-specified goals and more variable in the strategies adopted, than in the earlier Year 2 study of problem-solving behavior. The most striking result is the degree of variation in strategy and outcome across this user group. Some users were successful in using electronic procedure software to recover from an unexpected situation where the procedure could not be executed directly and normally. Other users were not, and their difficulties included an assumption that automation would prevent any harmful action, reluctance to do anything not directly specified in their daily tasks, and uncertainty about what might be causing the specific value or its importance. There are many possible contributors to the reduced likelihood of accomplishing the task goal in HERA over that in the Year 2 study. The task was structurally more complex in HERA, because the user needed to identify and execute the recovery procedures for two habitat systems instead of one. Additionally, the absence of experimenter available for the Year 2 Study, and differences in training may have increased the difficulty of the problem-solving tasks in HERA.

HERA Automation-Manual Investigation. The kinds of errors that users perform with electronic procedures are described. Our error analyses suggest that the mode differences (manual versus automated), between two low error rates, would be expected again in similar conditions. Thus executing with maximal automation may reduce errors relative to manual execution. Executing procedures with maximal automation also may reduce execution timing relative to executing the same procedures manual only. Small reductions in execution timing with automation were observed. Faster execution time with automation versus manual only modes should be investigated further [Schreckenghost, et al, 2015].

3. Impact of key findings: The results from the HERA and prior studies conducted for this project have informed the identification of candidate design guidance and factors for effective task allocation strategies within our procedure-automation approach. This design guidance directly addresses the Human Research Program (HRP) Risk of Inadequate Design of Human and Automation/Robotic Integration, Gap SHFE-HARI-01. The design guidance and factors are reported in the Main Findings section.

4. Research plan next year: None; this project ended in September 2015.

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1. Project aims

We investigate the hypothesis that selecting units of work to automate based on human procedures will improve human-automation designs. The structured actions sets within procedures, such as steps, can be used as the basis for meaningful, sharable organization of what is automated and how information should be passed between humans and automation. We hypothesize that human-automation interaction organized this way will provide several benefits, relative both to manual operations and to less user-centric automation, including effective execution and more adaptable use with flexible levels of automation. To test this hypothesis we will 1) develop strategies for using procedures to identify units of work for adjustable automation, 2) build a test environment with software for manual or partially automated execution of procedures, and 3) use this environment to evaluate the effectiveness of alternative strategies for automating procedures.

2. Key findings

We analyzed data collected in Year 1 comparing manual execution of the new procedure system (PRIDE Interface) to a system analogous to procedures for ISS (Legacy Interface). We assessed whether manual performance with PRIDE would be as good or better than with the legacy system. This lays the foundation for integrating automated execution into the flow of procedures designed for humans. We found speed and accuracy of manual procedure execution was better using PRIDE interface over Legacy interface. When using PRIDE interface, less than 3% of procedures had errors. For Legacy Interface, 33% of procedures had errors. Using PRIDE interface took less time than Legacy interface for all trials. We also analyzed Year 1 data where participants used PRIDE procedure automation. These results informed a redesign of the PRIDE software for procedure automation that is being evaluated in Year 2 experiments. Using the original PRIDE interface it was hard to predict what can be automated, what should be automated, and the

consequences of attempting to automate elements that cannot or should not be automated. Methods to identify what cannot or should not be automated were an important direction for development. Support for constructing and checking an advance automation plan also was identified as valuable. Automation plans may be more complex than was easily supported by the original approach of automating between the focus bar and a breakpoint. Users may find it useful to specify spans of procedure lines to automate. Since steps are a central unit of work in procedures, supporting step-level automation control may be valuable. Procedure technology was demonstrated to 4 astronauts on the User Panel. Crew Factors scores were all high. Systems score were high or medium.

3. Impact of key findings

Our identification of strategies for allocating tasks to automation and techniques for assessing strategy effectiveness directly addresses the HRP Risk of Inadequate Design of Human and Automation/Robotic Integration, Gap SHFE-HARI-01 (We need to evaluate, develop, and validate methods and guidelines for identifying human-automation/robot task information needs, function allocation, and team composition for future long duration, long distance space missions). We observed 3 models of automation use when performing procedures, which varied according to the style and effort spent planning what actions to automate.

1. Minimal planners spent no time planning automation and relied on the software to stop automatic execution when it reached a non-automatable instruction. This model incurs no cost to plan automation, but is the least operationally flexible of these strategies.

2. Incremental planners automated 1 span of actions at a time, interleaving automation planning with procedure execution. This model is suited to simple automation plans with few handovers, or situations where the decision of which tasks to automate can be altered by the effects of intervening procedure actions.

3. Predictive planners built a plan for automating the entire procedure prior to taking any action in the procedure. This model is suited to situations where deciding what to automate is based on information known prior to execution. This predictability means that it may be useful to save automation plans for reuse when executing the procedure later. Observation suggested that human performance is impacted by the frequency and number of handovers between automation and manual execution, and the time between these handovers. We are investigating techniques to characterize use of handovers in a task allocation strategy to provide insight into its effectiveness. Partial automation of procedures can make it possible for the user to perform secondary tasks during periods of automation. We are investigating techniques to assess how well an allocation strategy supports multitasking, including measuring supervision costs to assess how independent automation is from its supervisor. For an allocation strategy to support effective multitasking, these costs should be low relative to time made available for a secondary task.

4. Research plan next year

Our project is being considered for 2 HERA FY15 missions. These experiments will evaluate partial automation strategies developed in Year 2 during longer duration experiments under more flight-like conditions with participants more similar to astronauts. Each participant will perform procedures both manually and partially automated during 7 one-hour sessions per mission. Performance measures include completion time, errors, and workload. Performance under both conditions will be compared, within subject. We will update the procedure software for these experiments, based on Year 2 findings. We will document our findings about using units of work in procedures as the basis of automation, including strategies for allocating tasks to automation and techniques for evaluating strategy effectiveness.

Rationale for HRP Directed Research:	

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As crewed missions move deeper into space and communication latency increases, astronauts will be unable to depend on real-time support from flight controllers, such as performing or advising on procedures as done for the International Space Station (ISS). Astronauts will have a longer time lag between task training and execution while also needing to perform more, and more diverse, tasks. These can increase astronaut workload, decrease efficiency, and increase the risk of sub-optimal task execution. A critical resource for meeting these challenges is greater reliance on spacecraft automation. Today astronauts and flight controllers carry out tasks by following written procedures. As a result approaches that integrate automation with procedures are a good fit to NASA's concept of operations. If human-automation integration (HAI) for such procedure automation is not appropriately designed, however, increased automation may contribute to rather than alleviate these challenges. The strategies for allocating tasks to automation resulting from this project is of direct benefit to current and future NASA human space exploration missions. Since the Deep Water Horizon accident, the oil and gas industry has become increasingly interested in technologies to improve the safety and traceability of drilling operations. Similar to NASA, these industries use Standard Operating Procedures (SOPs) as the basis of their operations. TRACLabs is currently developing and testing procedure automation technology for well-site automation to be used by an oil and gas service company. This software incorporates the automation functions and interface design modified and evaluated under the NSBRI project. This software will be deployed for testing at a drilling site. The successful completion of this test should result in the gradual phasing of the procedure automation technology into operational use by the service company. The Department of Defense (DoD) also uses procedures for operations. TRACLabs has two Department of Defense (DoD) contracts that use the PRIDE procedure technology for human-in-the-loop automation. The AMP project (Phase II Navy SBIR) is using procedure automation to control multiple coordinated unmanned vehicles for the Navy. The COACT project (Phase I Air Force SBIR) completed in June 2015 used procedure automation technology for remote control and coordination of smart weapons systems for the Air Force. The automation functions and, in some cases, the interface design developed under the NSBRI project have been adopted for use in future PRIDE applications, such as these. It is anticipated that task allocation strategies demonstrated effective for NASA and the oil and gas industry would have potential use for any industry operating in complex dynamic environments with a high cost of failure. Such industries include chemical and nuclear process control, and power management and distribution.

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Research Impact/Earth Benefits:	

As crewed missions move deeper into space and communication latency increases, astronauts will be unable to depend on real-time support from flight controllers, such as performing or advising on procedures as done for the International Space Station (ISS). Astronauts will have a longer time lag between task training and execution while also needing to

perform more, and more diverse, tasks. These can increase astronaut workload, decrease efficiency, and increase the risk of suboptimal task execution. A critical resource for meeting these challenges is greater reliance on spacecraft automation. Today astronauts and flight controllers carry out tasks by following written procedures. As a result approaches that integrate automation with procedures are a good fit to NASA's concept of operations. If human-automation integration (HAI) for such procedure automation is not appropriately designed, however, increased automation may contribute to rather than alleviate these challenges. The strategies for allocating tasks to automation resulting from this project is of direct benefit to current and future NASA human space exploration missions. The PRIDE procedure software being evaluated and revised under this project has been used to flight follow two International Space Station (ISS) Extra Vehicular Activities (EVA), and is currently being modified to support manual execution of multiple coordinated procedures during EVA. PRIDE has been used to author test procedures for Morpheus, and is being considered for authoring and execution mission procedures by Sierra Nevada. Since the Deep Water Horizon accident, the oil and gas industry has become increasingly interested in technologies to improve the safety and traceability of drilling operations. Like NASA, these industries use Standard Operating Procedures (SOPs) as the basis of their operations. TRACLabs is currently developing procedure automation technology for well-site automation to be used by an oil and gas service company. This software will incorporate the automation planning functions and interface design developed and evaluated under the NSBRI project. This software will be deployed for testing at a drilling site in Oklahoma in 2015. The successful completion of this test should result in the gradual phasing of the procedure automation technology into operational use by the service company. The Department of Defense (DoD) also uses procedures for operations. TRACLabs has three DoD contracts that plan to use PRIDE procedure technology for human-in-the-loop automation. The AMP project will use procedure automation to control multiple coordinated unmanned vehicles for the Navy. The COACT project will use procedure automation technology for remote control and coordination of smart weapons systems for the Air Force. And the CHESS project will use procedure technology for missile defense. The automation functions and, in some cases, the interface design developed under the NSBRI project has been adopted for use in future PRIDE applications, such as these. We anticipate that task allocation strategies demonstrated effective for NASA and the oil and gas industry would have potential use for any industry operating in complex dynamic environments with a high cost of failure. Such industries include chemical and nuclear process control, and power management and distribution.

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Task 1. Define scenarios and metrics for HERA Study: Three habitat systems were simulated - Carbon Dioxide Removal System (CDRS), Active Thermal Control System (ATCS), and Electrical Power System (EPS). The EPS provides power to the CDRS and ATCS, which provides cooling water for the CDRS. Procedures were developed for these systems, and for a secondary manual task to assess images collected by a robot. Performance was measured for impact on the controlled system (e.g., entry into unsafe states) and correctness of user actions (e.g., adherence to specified method to achieve goal).

Task 2. Complete HERA software development: Software activities for HERA experiments included 1) developing daily tasks that could be performed without an experimenter present, 2) simplifying startup, shutdown, and transfer of data for the PRIDE procedure software, and 3) connecting PRIDE software to Webmirage to retrieve HERA data. Software development supporting data analysis included reading PRIDE database, computing performance measures, and saving these measures to Excel spreadsheet.

Task 3. Conduct HERA Experiment: Experiments were conducted in all missions of HERA Campaign 2. The HERA investigation embedded two study-designs (n=16). The Step-List Study tested the hypothesis that performance using Step formatted procedures would be better than using List formatted procedures. The Problem-Solving Study investigated the effects of repetition on problem solving, and the effects of a secondary manual task done in conjunction with the primary habitat task where a problem occurs. Additional exploratory tasks were performed. Participants received two hours of training prior to the mission and performed procedure during 7 one-hour sessions.

Task 4. Analyze and document experimental results: Analysis of data collected in Year 2 was completed. This study investigates strategies participants used to problem-solve when the preconditions of procedure actions do not match operational conditions. Study results are reported in a paper presented at Human Factors and Ergonimcs Society (HFES 2015) meeting in October 2015. Analysis of data collected in the HERA experiment was completed. Because HERA Campaign 2 ended in late August 2015, results of the Step-List and the Problem-Solving Studies have not yet been published; they are reported in the Main Findings section. An exploratory task compares manual performance of a single procedure to performance using maximal automation. Preliminary results are reported in a paper presented at the AI in Space Workshop in July 2015.

Tasks 5. Document design guidance for allocating tasks to procedure automation: Results from the HERA study, with results from prior project studies, informed the identification of candidate design guidance and factors for effective task allocation strategies for our procedure-automation approach. They are reported in the Main Findings section.

Task Progress:

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Task 1. Define scenarios, allocation strategies, and metrics for Year 2 Experiment. Year 2 scenarios reuse the Year 1 Carbon Dioxide Removal System (CDRS) procedures and simulation, and add new Active Thermal Control System (ATCS) procedures and simulation. The ATCS provides cooling water for the CDRS. This system coupling is used to create problem-solving situations where participants must detect and resolve problems using procedures. User task allocation strategy and performance are compared when using procedures organized by units of work (Step) to procedures without this organization (Flat). Metrics include errors, timing, and workload. Error will be assessed at 3 levels: undesired device commanding, execution of non-standard action sequence, and action execution in a mode different than requested.

Task 2. Complete Year 2 software development. PRIDE software for procedure automation was redesigned using observations of automation use in Year 1. The PRIDE interface was modified to inform the user which actions are automatable. User functions were added to mark units of work (lines or steps) for automatic execution. Automation functions were modified to use these markings during procedure execution.

Task 3. Conduct Year 2 Experiment. A key purpose of the Year 2 Experiment is to identify user strategies for automation use, and how they vary in different situations. This will inform the identification of core principles affecting the quality of automation allocation strategies. This experiment also provides a first usability assessment of new PRIDE

automation planning capability. Independent variables are Scenario (7 scenarios), Procedure Structure (Steps, Flat), and Order (Steps-First, Flat-First). The Scenario and Structure factors are within-subject and Order is between-subject. Data collection from a planned 12 subjects is in progress at the time of this report.

Task 4. Analyze and document experimental results. Analysis of manual performance data collected in Year 1 was completed. Speed and accuracy of manual procedure execution was better using the PRIDE interface than the ISS-like interface. Results are documented in a paper at HFES 2014. Analysis of Year 1 data also was completed on how participants used PRIDE procedure software to allocate tasks to automation. Results are documented in a paper at IEEE Aerospace 2014. Results also informed the redesign of procedure automation software being evaluated in Experiment 2.

Task 5. Begin development of Year 3 software. Our project is being considered for HERA FY15 missions. These experiments will evaluate partial automation strategies during long duration experiments under in flight-similar conditions with crew-like participants. To improve our ability to collect data during HERA missions, we are developing software for automatic collection and scoring of performance data. Procedure automation software will be revised for usability once analysis of Year 2 data is complete.

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