FINAL REPORT FOR

"HUMAN-SYSTEM TECHNOLOGY"

(N00014-04-1-0384)

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
10-11-2005

2. REPORT TYPE
Final Technical Report

3. DATES COVERED *(From - To)*
05-APR-2004 to 30-SEP-2005

4. TITLE AND SUBTITLE
Final Report for Human-System Technology

5a. CONTRACT NUMBER
NA

5b. GRANT NUMBER
N00014-04-1-0384

5c. PROGRAM ELEMENT NUMBER
NA

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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Arlngton VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR 342CN

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unrestricted

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Final Technical Report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Larry Warrenfeltz
Unclassified	Unclassified	Unclassified		14	19b. TELEPHONE NUMBER *(Include area code)* 850-202-4473

INTRODUCTION

The Institute for Human and Machine Cognition (IHMC) is pleased to submit a report of progress on the continuation project Human Systems Technology for the 2004 fiscal year. This fiscal year work actually began on April 1, 2004 and was completed on September 30, 2005. Also called Human-Centered Computing, this multidisciplinary field exploits advances in cognitive research together with those in computer science and related areas to optimize the cognitive, perceptual, and/or physical performance of experts and expert teams and the information systems that support them. The work reported on extends that conducted in the second increment of ONR funding for Human Systems Technology. The FY 2004 work focused in particular on (1) advanced visual information displays exploiting the effectiveness with which the human brain processes spatial orientation information; (2) advanced tactile displays that provide enhanced situational awareness in such complex operational domains as aviation and special forces operations; and (3) continued development of improved algorithms for Knowledge Discovery and Data Mining (KDD) from large data sets and associated investigations of displays and training principles to improve human abilities to rapidly diagnose failures in complex systems. The work in each of these areas reflects the growing appreciation for the enormous potential that information technology has to leverage and amplify human capabilities. Realization of this potential requires a deep understanding of human cognition, perception, and/or locomotion; the relevant areas of computer science; and the nature of the human activity to be enabled. This inherently multidisciplinary approach to realizing the full potential of emerging information technology capabilities is at the heart of the Institute for Human and Machine Cognition (IHMC) and the research conducted during FY 2004.

In what follows the progress made in each of these areas is described, along with a brief statement of plans for FY 05. This includes a list of publications resulting from the work. During the performance period a total of 16 publications have been prepared and published, are in press, are currently under review.

OZ: A HUMAN-CENTERED COMPUTING COCKPIT DISPLAY

Background

Contemporary instrument design for aircraft is inherently inefficient in that it forces the pilot to view each instrument sequentially in order to gather information. This process, called the 'instrument scan,' is a huge visual and mental workload for the pilot engaged in instrument flight, and this presentation format does not facilitate integration of the information by the pilot to identify flight conditions that may be dangerous. Drs. David Still (Institute for Human and Machine Cognition) and Leonard Temme (Naval Aerospace Medical Research Laboratory) have designed an alternative method of presenting cockpit information, OZ, which capitalizes on what the human eye was designed to see best, quickest, and easiest. It is an integrated display of all relevant information in a manner that is both intuitive and takes full advantage of the bandwidth of both peripheral and fovial vision. OZ allows pilots to view an integrated picture of how different flight parameters affect aircraft performance instead of having to mentally input individual pieces of information into a memorized flight model and then generate performance predictions. Furthermore, OZ symbology can tolerate substantial visual insult in the form of blur and laser trauma. IHMC and NAMRL evaluations of OZ have found that non-pilots learned flight tasks faster and performed better with OZ than with conventional instruments. Additionally, for both rated pilots and non-pilots, as flight tasks become more challenging, performance deteriorated significantly with conventional displays but remained unaffected with OZ.

OZ consists of abstract metaphorical objects that convey multiple data streams of aircraft state parameters by the scale of the objects' component parts and that indicate the underlying controlling algorithms by the objects' configurations.

•To reduce time restrictions imposed by sequential viewing, the metaphorical objects are constructed such that their informational content can be acquired without the use of central vision.
•To increase information density and decrease visual clutter, OZ relies upon such visual perception concepts as structure-from-motion, pop out, texture, continuity, and figure-ground discrimination to construct its metaphorical objects.
•To reduce mental computation requirements of the pilot, reference values, data streams, and performance capabilities are adjusted for current aircraft configuration and environmental conditions.
•To improve situational awareness, OZ maps external space with the same wide-angle frame of reference used to show aircraft orientation, location, and performance.
•To improve the pilot's ability to simultaneously perform secondary tasks, OZ allows the pilot to fly with peripheral vision while using central vision to read checklists or inspect secondary displays.
•To aid target acquisition and reacquisition sensor images (infrared, image intensification, and radar), both the object of regard and the sensor's field of view can be spatially located within the OZ frame of reference.

The overall result is that OZ shifts the workload requirements for flight from one of visual scanning of separate instruments and displays, requiring intensive integration/computation, to nearly instantaneous or 'direct' perception of an integrated picture. In essence, a glance at OZ lasting 200 ms conveys most of the information contained in the entire panel of conventional instruments that may take several seconds to scan. Although OZ presents the pilot with processed flight data, the processing does not obscure information nor does it make decisions for the operator.

According to the National Academy of Science, the Navy will need to develop the appropriate man-machine interface for the UCAV-N because the civilian sector is unlikely to provide them (NAS Review of ONR's Uninhabited Combat Air Vehicles Program, 2000). The continued incremental development of conventional instrumentation is unlikely to provide the required interface. The solution we propose, OZ, uses the design freedom allowed by new computer technology to take advantage of recent discoveries in vision and cognitive sciences to make a display that is tailored to the biology of the observer. The end result is a powerful cockpit environment that meets the needs of the UCAV–N community.

Progress to Date

During the course of this years funding, IHMC produced a design for the OZ UCAV Special Warfare display and implemented several of its key components.

1. Translation and motion cues were implemented that enable the starfield to move as a mirror image of the aircrafts movement. This gives an intuitive notion of slight changes in elevation or orientation, and also dramatically increases operator sensitivity to fore-aft and lateral drift.
2. Additional waypoints and ground reference markers were added. The altitude, size, and latitude/longitude location of waypoints in the sky can be read from a data file and displayed in OZ (when inside the maximum distance bound). These waypoints have been tested as part of the integration with the Predator STE simulation software. Using waypoints to mark critical decision/evaluation points in training tasks (such as landing) significantly reduce the mental effort required to complete the training tasks, and greatly ramps performance to test criteria. New ground markers were added to denote points of interest. They are created by the operator while in flight and can be shown or not based on a distance filter. The ground markers referencing GPS coordinates of the runway centerline were refined and tested in the context of severe crosswind landings. The extended runway centerline has demonstrated effectiveness in crosswind landings and for general runway alignment issues.
3. Wind indications were implemented that intuitively demonstrate the effects of the wind on the ground-track of the aircraft. By integrating a wind direction reference into the nose-ring of the OZ flight model, the operator is continually reminded of the wind direction. The effects of the wind are also indicated by the offset of the nose-ring from centerline. This integration allows both no crosswind and crosswind landings to be treated the same: as long as the airport runway is depicted inside of the nose-ring, the aircraft is headed directly for the runway. This eliminates special calculations/training for determining crosswind drifts, as this is computed and directly displayed in OZ.
4. An option to de-clutter the interface was implemented, where the background starfield can disappear if the operator is maintaining the selected altitude and heading. When the operator deviates by more that 100 ft in altitude or 10 degrees in heading, the starfield reappears. It is important to distinguish this from a simple alert sound, or a flashing message on the screen: This method of decluttering depends on operator adherence to a specified plan (i.e., heading, altitude). It makes the interface "active" in the sense that it now unobtrusively gets the operators attention by displaying the exact information that is needed to correct the deviation, rather than by producing a sound or message that then requires interpretation to be understood.

A multi-user capability was implemented that allows for communication of speed, altitude, and heading information to be transmitted between separate OZ installations. This permits other aircraft in a group to be visually located within OZ and tracked.

Proposed Work

This activity has now reached a high degree of maturity, so FY 2005 activities will be limited to facilitating transition to application.

PSYCHOPHYSICAL STUDIES OF TACTILE INTERFACES FOR SENSORY SUBSTITUTION OR AUGMENTATION IN COMPLEX TASKS

Background

The US Navy has an existing requirement for tactile interfaces to improve situation awareness. Tactile interfaces have been developed for sensory substitution applications such as aids for the vision or hearing impaired. Tactile interfaces have also been developed for sensory augmentation in complex dynamic environments such as aviation applications. In the former application great effort is taken to represent the sensory information in as high resolution as possible (e.g., to let the operator "see" detail with the sense of touch.) The latter application seeks to reduce the resolution to the most base useful representation of particular sensor information in order to reduce the cognitive workload of understanding the information displayed tactually. In their current incarnations, both methods operate without competition for sensory or cognitive assets, as little other tactile information is useful in their respective operational environments.

In 1995, the Naval Aerospace Medical Research Laboratory (NAMRL) and the University of West Florida (UWF) Institute for Human and Machine Cognition (IHMC) began collaborating on flight-testing NAMRL's Tactile Situation Awareness System (TSAS). The relationship has continued to develop and conduct demonstrations with a suit that provides pilots with spatial orientation information via tactile stimulation in order to reduce the number of SD accidents occurring with pilots. The suit displayed ground reference information from the attitude indicator to orient blind folded pilots. The suit was successfully flight tested on a blind folded pilot of a fixed-wing (T-34) aircraft and on several blind folded pilots of a rotary-wing (UH-60) aircraft. The UH-60 pilots successfully flew basic instrument tasks including unusual attitude recovery and in the T-34, the pilot successfully flew acrobatic flight maneuvers in addition to instrument flight tasks.

In September 1997, NAMRL and IHMC developed an improved air-driven tactile display to provide Differential Global Positioning Satellite (DGPS) based drift information to UH-60 pilots for the Office of Joint Strike Fighter (JSF). Seven pilots used the tactile display vest and hovered the UH-60 with limited outside visual cues (their vision was obscured to 20/200 by optical filters). This demonstration was performed to show that pilots could obtain drift and rate of drift information through the tactile modality sufficiently to hover. A number of flight maneuvers were performed, including stationary hover in and out of ground effect (IGE, OGE), translational maneuvers and simulated shipboard take-offs and landings.

Further rotary wing and unmanned aerial vehicle (UAV) flight-testing and laboratory simulations have further demonstrated the effectiveness of tactile interfaces for situation awareness. TSAS like any other avionics system is susceptible to feature creep as more end users evaluate and understand the benefits. In order to provide more information tactually, the data must either be intelligently scheduled for display or presented at higher resolution. The former control methodology is currently under investigation by this research team. The latter will be investigated under this project.

High-resolution tactile displays can only be effective if the areas they contact are highly innervated. Mapping of sensitivities has shown that the highest resolution of innervation occurs in the hands, face and tongue. In the aviation environment the tongue makes for an ideal location for a high-resolution tactile interface. Unlike the hands it is not in active use, except during verbal communications, and it has no keratinized skin layer, allowing for more efficient transduction of the tactile signal. We will use our tongue based tactile interface to provide higher resolution information in concert with the lower resolution information of TSAS. This will represent a confluence of two tracks of thought on tactile displays, one of providing sensory augmentation displaying intuitive, dimensional/ directional information (as with TSAS) and the other of sensory substitution where information normally perceived via the eyes or ears is perceived through a tactile interface. The goal of this integration will be to create a tactile interface that operates, in 3D, in a manner similar to the eye, with low resolution "peripheral" sensation provided on the torso by TSAS and high resolution "foveal" sensation provided on the tongue. The resultant multi-faceted tactile display will be tested in concert with visual and audio displays using a fixed base simulator at IHMC.

Progress to Date

We have integrated our Adaptive Multiagent Integration (AMI) architecture, developed under funding from DARPA with our tactile interface devices (the TSAS torso tactile interface and BrainPort™) to facilitate integrated testing. We are awaiting delivery of a current generation version of the Wicab BrainPort™ to use in our FY05 integrated high and low resolution tactile display protocol. Custom torso tactile interface hardware fabricated in FY04 has been redesigned and revised to improve discrete control of the torso tactile interface and to enable use of intelligent automation features made available through integration with AMI. Two journal articles have been drafted describing the results of the FY04 experiments (presented at the Aerospace Medical Association 2004 Annual Scientific Meeting, abstract numbers 330-Tactile Display landing Safety, Situational Awareness, and Workload Reduction Improvements for the Space Shuttle, and 331-An Application of the Tactile Situation Awareness System to the Learning of a Complex Dynamic Task – ILS Approach and Landing). One article is being revised following initial peer review, the second is in final draft for initial submission (estimated date of submission is June 05, following completion of post hoc analysis and full analysis of pilot studies.

The pilot studies included a dynamic tracking task based on the Space Shuttle Head Up Display (HUD) approach and landing deviation display. In the first condition, the guidance and velocity vector icons were driven in a pseudorandom fashion using the sum of 5 sinusoidal waveforms (0.04, 0.08, 0.12, 0.16 and 0.22 Hz) in the X and Y axes. The subjects were instructed to use the rotational hand controller joystick to keep the two icons superimposed. A second condition used surround sound (visual screens were blank) to provided the directional error between the two data points (driven by the same sinusoids) and a third condition provided the subjects with the same deviation display using TSAS. Four more conditions that represented combinations of visual, audio and tactile stimuli were presented in a counterbalanced fashion. Fourier analysis was performed to determine the gain and phase for each display modality at the stimulus frequencies (see Figure 1).

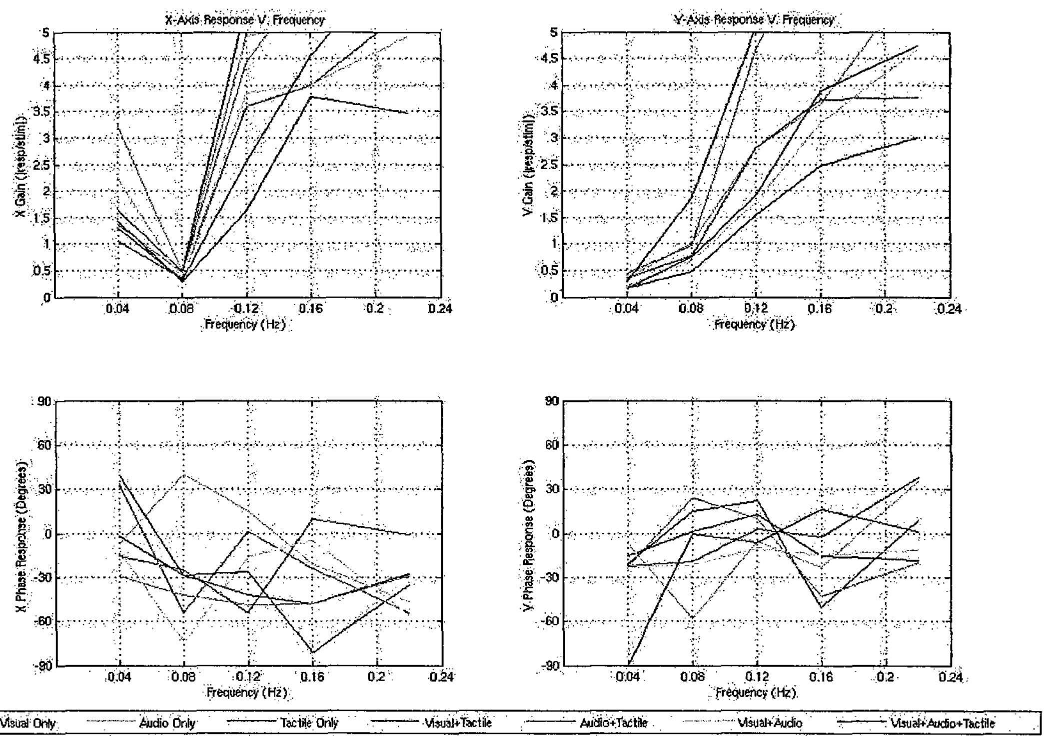

Figure 1: Bode plots for the seven pilot study conditions. Gain of 1 and phase lead/lag of 0 degrees are ideal.

The initial analysis demonstrates that the tracking task was sufficiently difficult, even at relatively low frequencies, to induce large pilot induced oscillations (large gains with phase shifts). Given that the task was based on a visual tracking paradigm, it is not surprising to see that the visual only presentation provided the best response in gain (both axes). The multi-modal display (visual+audio+tactile) is however the next best across the majority of the frequencies tested. It is obvious from the data that the high frequencies in this task were too fast for accurate tracking. Follow up studies will focus on the range from 0.04 to 0.1 Hz to better characterize where the transition to over compensatory response arises. Additionally, we will investigate the tracking response to single frequency sinusoids to verify that the pseudorandom nature of the tracking task did not adversely affect individual performance.

Tables 1-4 provide the means and standard deviations for the average (n=14) gain and phase responses depicted in Figure 1.

Presentation		***.04hz***	***.08hz***	***.12hz***	***.16hz***	***.22hz***
Visual	Mean	1.42	0.30	1.63	3.77	3.46
	STD DEV	0.85	0.14	1.89	2.80	2.32
Audio	Mean	3.23	0.48	4.93	5.11	7.18
	STD DEV	2.35	0.31	2.74	3.76	4.65
Tactile	Mean	1.65	0.47	5.56	6.57	7.65
	STD DEV	1.01	0.28	3.38	5.66	3.69
Visual-Tactile	Mean	1.04	0.36	3.58	4.00	5.42
	STD DEV	0.60	0.18	1.92	3.55	3.35
Audio-Tactile	Mean	1.37	0.46	4.44	5.98	8.12
	STD DEV	0.97	0.21	4.47	3.62	6.69
Visual-Audio	Mean	2.24	0.32	3.85	4.02	4.90
	STD DEV	2.24	0.17	2.77	2.74	2.55
Visual-Audio-Tactile	Mean	1.30	0.33	2.55	4.56	6.57
	STD DEV	0.74	0.22	1.76	1.82	5.35

Table 1. Gain means and standard deviations for X Position.

Presentation		***.04hz***	***.08hz***	***.12hz***	***.16hz***	***.22hz***
Visual	Mean	-1.9	-28.3	-42.1	-48.6	-27.8
	STD DEV	140.9	102.5	110.5	121.3	121.1
Audio	Mean	-7.2	40.4	14.9	-20.8	-46.7
	STD DEV	101.1	100.5	87.8	129.2	109.6
Tactile	Mean	-15.3	-24.5	-54.3	9.5	-1.0
	STD DEV	122.9	88.7	125.1	108.8	115.7
Visual-Tactile	Mean	33.4	-54.2	1.4	-24.1	-54.4
	STD DEV	117.3	59.4	130.5	105.0	90.6
Audio-Tactile	Mean	-29.6	-42.2	-49.3	-48.3	-29.1
	STD DEV	112.9	81.0	84.5	80.9	66.4
Visual-Audio	Mean	-11.5	-74.5	-16.5	-4.7	-55.9
	STD DEV	102.9	66.9	118.7	123.8	85.7
Visual-Audio-Tactile	Mean	39.2	-28.7	-26.3	-81.5	-35.7
	STD DEV	125.3	80.4	125.4	67.4	89.9

Table 2. Phase means and standard deviations for X Position.

Presentation		***.04hz***	***.08hz***	***.12hz***	***.16hz***	***.22hz***

Visual	Mean	0.17	0.47	1.53	2.47	3.00
	STD DEV	0.19	0.32	1.20	2.39	2.48
Audio	Mean	0.35	1.01	2.80	3.63	6.01
	STD DEV	0.26	0.75	2.11	2.95	5.21
Tactile	Mean	0.29	1.85	5.08	11.27	18.66
	STD DEV	0.21	1.16	2.91	7.71	18.29
Visual-Tactile	Mean	0.36	0.78	2.81	3.71	3.77
	STD DEV	0.29	0.44	2.22	2.89	2.60
Audio-Tactile	Mean	0.43	0.97	4.69	6.92	9.55
	STD DEV	0.36	0.57	3.94	6.27	6.87
Visual-Audio	Mean	0.20	0.67	1.78	3.27	4.67
	STD DEV	0.13	0.42	1.06	2.22	4.86
Visual-Audio-Tactile	Mean	0.15	0.75	1.92	3.90	4.75
	STD DEV	0.13	0.60	1.13	3.25	4.10

Table 3. Gain means and standard deviations for Y Position.

Presentation		***.04hz***	***.08hz***	***.12hz***	***.16hz***	***.22hz***
Visual	Mean	-15.8	1.1	12.4	-16.0	-18.4
	STD DEV	74.9	89.2	109.4	116.2	115.1
Audio	Mean	-7.2	-58.1	-5.5	-23.1	35.8
	STD DEV	108.4	117.4	119.6	102.9	103.0
Tactile	Mean	-21.1	14.8	21.6	-50.4	8.6
	STD DEV	101.9	58.8	117.2	111.4	108.9
Visual-Tactile	Mean	-22.2	-19.1	2.4	-2.5	37.5
	STD DEV	103.2	121.5	100.2	120.7	89.9
Audio-Tactile	Mean	-22.2	24.2	9.3	-43.1	-20.0
	STD DEV	75.0	104.9	104.2	95.3	101.4
Visual-Audio	Mean	-23.0	-21.6	-10.6	-14.6	-12.1
	STD DEV	96.6	109.9	101.3	105.2	111.5
Visual-Audio-Tactile	Mean	-90.9	-0.5	-6.1	16.7	0.9
	STD DEV	54.7	93.1	93.2	99.6	114.8

Table 4. Phase means and standard deviations for Y Position.

The work supported by ONR has also resulted in the preparation or submission of the following manuscripts:

Raj, A. K., Higgins, J., Abraham, L. J., Carff, R. W., & Rupert, A. H. (in preparation). An application of the tactile situation awareness system (TSAS) to the learning of a complex dynamic task – ILS approach and landing,

Olson, J. M., Raj, A. K., Thomas, R. E. and Davis, J. A. (in preparation following initial peer review) Tactile Display Landing Safety, Situational Awareness, and

Workload Reduction Improvements for the Space Shuttle (submitted to Aerospace and Environmental Medicine)

Proposed Research

In the work supported with FY 2005 funds, we will continue to use our team's expertise the two fields of tactile interface implementation (sensory augmentation and sensory substitution) to evaluate the psychophysical effects of combining both types of tactile interfaces into a single unified cockpit interface. Combining the tactile interfaces has been enabled using the AMI architecture and will prove useful in situations where the high-resolution component would augment synthetic vision and the low-resolution component would augment spatial awareness. Specific intelligent control methods will also be developed to manage this proposed multi-faceted tactile interface to minimize cognitive workload. A study will be performed to evaluate the effectiveness of the multi-faceted tactile display as an adjunctive avionics display in specific standard flight maneuvers.

ADVANCED ALGORITHMS FOR HUMAN SYSTEMS TECHNOLOGY: Knowledge Discovery and Data Mining and Human Causal Learning

Background

The rapid development of data mining and machine learn algorithms has contributed to progress in several areas of importance to the Navy:

1. Ability to recognize and classify from databases with large numbers of variables and comparatively small samples of messy data.
   Data of this kind often arise in intelligence analysis, medical analysis, automated text interpretation and elsewhere.

2. Ability to learn causal mechanisms from distributed datasets with distinct variable sets.
   Data are often collected from distinct kinds of units with distinct record keeping practices and must be synthesized into a coherent causal representation.

3. Design of Efficient Fault Detection and Fault Location Algorithms.
   Automated systems can aid in both detecting and localizing faults in complex systems and in designing workarounds.

4. Development of instruction techniques and automated tutorials for improving human judgment of cause-effect relationships and diagnosing causal structure.

5. Derivation of social networks and command and control structures from communication data and observed military activities.

6. Development of algorithms for inferring causal structure in dynamical, non-linear systems.

A good deal of further research, development and testing is needed in several of these domains.

Progress to Date

The structure of a complex system consisting of many interconnected components may be completely known, or largely unknown, or in the case of a complex system (an engine, a power plant, etc.) that is behaving anomalously, we may not know what we do or do not know about it. In analyzing an incompletely known system, or in locating the sources of faults in an improperly working system, we would in many cases like to make maximal use of data, and minimize the number of interventions or probes required to identify the structure uniquely.

For systems that are not perfectly deterministic, there are reasonably fast computable procedures that identify some of the dependency relations among components from data on component behavior. These methods do not require experimental interventions or probes than manipulate or control internal components of the system; they merely require records of data on component behavior for a range of inputs. These methods have several limitations: they do not work well when components are densely connected; they often cannot determine the direction of signal or influence between components; and they do not work well for deterministic systems.

Some of our work under the ONR contract under FY 04 funds has focused on how to merge these methods with experimental interventions so as to minimize the number of experimental interventions required to determine the structure of the system. Experimental probes of a system with unknown properties can be risky, and data collection is expensive, so minimization is important. Superficially, the number of experiments required to determine all causal connections among N components is an exponential function of N. For to determine that a variable X does not in any state of the system directly influence another variable Y, one would, it seems, need to consider every set of values of the remaining variables and show that with that assignment of values to the other N – 2 variables, X and Y do not covary when X is randomized.

To the contrary, we have shown that, quite generally, when there are N components, for all of which there are recorded values, N -1 experiments that randomize one variable (component) at a time are always sufficient and in the worst case that many experiments are necessary. It may in some cases be cheaper (require that fewer data cases be collected) to randomize several variables simultaneously. When one experiment can randomize any number of variables, the number of required experiments is reduced still further, quite dramatically to $\log_2(N) + 1$. The proofs provide methods for obtaining these optima.

Our work during the FY 04 funding cycle has also progressed in the following additional areas:

- Interactive training and instruction in causal inference (Scheines, Easterday and Danks), an area we hope to develop much further, eventually to yield training methods for diagnosing causes of system failures;
- The psychology of human causal judgment (Danks, Danks and Schwartz), work which helps to provide scientific foundations for the previous topic;
- Automated classification with large numbers of prediction variables and small numbers of cases, where software has been implemented and tested (Ramsey);
- Further refinement of data polishing problems for messy data (Teng, Teng, Benferat and Teng), which is now being unified with Ramsey's automated classification procedure;
- Algorithms for identifying causal structure in time series data (Chu and Glymour);
- Algorithms for identifying when unobserved causes are acting on a system and for identifying the causal relations among those unobserved factors, which is an important expansion of data analytic methods for signal source detection;
- Development, implementation, and testing of an algorithm for identifying command, control and reporting relations from time stamped communication intercepts, even in an unknown language or in a known language with natural language codes.

Our work on various aspects of automated causal inference will be the subject of a weeklong workshop for the Department of Defense in August of 2005. The work supported by ONR has also resulted in the preparation, submission, and where noted, the following publications/manuscripts:

Danks, David. (In press). "Theory Unification and Graphical Models in Human Categorization." In A. Gopnik & L. Schulz, eds. Causal Learning: Psychology, Philosophy, and Computation. Oxford: Oxford University Press.

Danks, David, & Samantha Schwartz. (In press). "Causal Learning from Biased Sequences." In _Proceedings of the 27th Annual Meeting of the Cognitive Science Society_.

Scheines, Richard, Matt Easterday, and David Danks. (In press). "Teaching the Normative Theory of Causal Reasoning." In A. Gopnik & L. Schulz, eds. Causal Learning: Psychology, Philosophy, and Computation_. Oxford: Oxford University Press.

Benferhat, Salem and Choh Man Teng, editors. Special issue on uncertain reasoning, Parts I and II, International Journal of Intelligent Systems, 19(8-9), 2004.

Teng, Choh Man. Polishing blemishes: Issues in data correction. IEEE Intelligent Systems, 19(2), pages 34--39, 2004.

Kyburg, Henry E. Jr. and Choh Man Teng. Randomization and Uncertain Inference. In Proceedings of Information Processing and Management of Uncertainty in Knowledge-Based Systems, pages 1177--1184, 2004.

Teng, Choh Man. Coping with partially corrupted data. Proceedings of the International Conference on Machine Learning and Applications, pages 429--435, 2004.

Glymour, C., Social Effects. In A. Gopnik & L. Schulz, eds. Causal Learning: Psychology, Philosophy, and Computation. Oxford: Oxford University Press.

Glymour, C. Learning the Causal Structure of Deterministic Systems. In A. Gopnik & L. Schulz, eds. Causal Learning: Psychology, Philosophy, and Computation. Oxford: Oxford University Press.

Silva, R., R. Scheines, and C. Glymour, Automatic Discovery of Linear Latent Variable Models, Journal of Machine Learning Research (submitted for publication).

Gerdes, D. and C. Glymour, Automated Discovery of Command and Control Structures from Time Series of Communication Logs, available only on request.

Chu, T. and C. Glymour, Semi-Parametric Causal Inference for Time Series, Knowledge Discovery and Data Mining Conference, 2005.

Englehardt, F., C. Glymour and R. Scheines, On the Number of Experiments Necessary and Sufficient to Determine the Causal Structure of a System, Uncertainty in Artificial Intelligence (submitted).

J. Ramsey, Markov Blanket Fan Search, Technical Report, Laboratory for Symbolic Computation, Carnegie Mellon University, 2005.

Proposed Research

A major focus area for FY 05 will be on how extend our work on the use of data associated with complex systems, specifically to merge the methods we have developed with experimental interventions so as to minimize the number of experimental interventions required to determine the structure of the system. These results are of practical value, but they would be of more use if the methods could be extended in three ways: (1) to deterministic systems; (2) to systems that may have unrecorded features that influence multiple recorded features (e.g., external heat source influences on space or aircraft; unrecorded signals and sources coordinating enemy movements, etc.), and to feedback systems. Our continuing work addresses all three problems. In particular, we have in hand a modification of search algorithms for deterministic systems, and are now testing it, and we have reason to believe that when there may be latent unrecorded common causes of recorded variables, all causal connections among recorded variables can nonetheless be identified in $2\log_2(N) + 1$ multiple intervention experiments.

SUMMARY

Very substantial progress has been made in all three areas of research undertaken in the FY 04 period of performance for this effort in Human Systems Technology. A follow- on year has been funded to continue this promising work. During FY 05 work on haptic information displays will continue, as will that addressing new methods for Knowledge Discovery and Data Mining. Additionally, fundamental work will be initiated on (1) trustworthy software agents, realized through a more adequate theory and implementation for adjustable autonomy; and (2) exoskeletons for human performance enhancement.