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Active Research Topics in Human Machine Interfaces

Michael J. McDonald

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Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Active Research Topics in Human Machine Interfaces

Michael J. McDonald
Intelligent Systems and Robotics Center
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1004

ABSTRACT

This paper identifies active research topics concerning human machine interfaces for intelligent machine systems. The paper was compiled by performing a series of literature searches and organizing the information according to the author's interest in better directing his own Human Machine Interface (HMI) research. Introductory literature from outside the HMI communities is also referenced to provide context.

1 Motivation

Currently, much of the robot community is at a loss as to why users are unwilling or unable to take advantage of robot technologies. Often, robots that perform perfectly well by trained practitioners, fail when put into the hands of the intended users. The author's primary interest at Sandia National Laboratories is to build Human Machine Interfaces (HMIs) that work right for the people that the robots are built for.

Similar interests are shared outside Sandia. From the perspective of Yaskawa Electrical Corp of Japan, [Kumamoto 1995] concludes that for the automotive industry, "the challenges are to enhance robot functions in accommodation of new design and manufacturing techniques, to achieve a cooperative harmony between man and robot, and to increase the effectiveness of the interface between the two."

In addition, the author recognizes that the user interface is a driving technology for the successful application of a variety of robotic technologies. Understanding the capabilities of robots and how they do their job is a fundamental part of the robot user interface and of human machine interfaces in general. By asking the question "how would people like robots to help them do their job," one can gain a great deal of insight into *what* the robots should really do and *how* they should do their job. Thus, the author's secondary interest is in understanding how interface issues need to direct robot systems research.

To address these broad issues, this paper surveys a wide breadth of HMI-related research. This is in direct comparison to searching for a particular approach or technological solution. Here, the focus is on finding patterns among the research themes rather than finding the extent to which solutions have been found.

The remainder of the paper is broken into four sections; The *Related Literature Reviews* section reports on attempts specifically made to perform reviews that are similar to this. The *HMI Approaches and Technologies* section categorizes research that is focused toward developing or refining HMI approaches. The *Hard and Important Problems Being Addressed* section categorizes research that appears to be focused first to a particular hard problem and secondarily toward the approach chosen. The *Conclusions* section makes an attempt to identify the ongoing themes that were discovered. Appendices discussing the search strategy used to locate the references and the list of references follow.

2 Related Literature Reviews

The literature cites few reviews focused toward human machine interaction as applied to robotics. [Nordqvist & Eriksson 1998] reviews literature in usability evaluation as a basis to present how digital plant technology may be utilized in the evaluation phase when designing distributed adaptive user interfaces for manufacturing systems. [NERAC 1995] contains 59 citations concerning the design, development, and implementation of robot programming languages, and their applications in industrial and research activities. [Sawaragi 1998] reviews research including human-centered automation and interface agents. In addition, several of the papers noted below contain large reference sections that form more pointed reviews.

3 HMI Approaches and Technologies

3.1 Design Theories, Processes and Methods

Design theories and processes are key to the industrial design approach to interface design. For example, IDEO, a leading industrial design company, was founded on the principals of its design process. Likewise, a key aspect in judging design in competitions like the I.D. Annual Design Review (America's largest and most prestigious juried design recognition program) is the review of the process used to create the design. Illinois Institute of Technology's Institute of Design (ID), Carnegie Mellon's School of Design and other institutes offer degree programs focused toward extending the body of knowledge about design theory and process.

Engineering-related HMI research concerning design takes a significantly different approach than does industrial design. Unlike industrial design, engineering-related HMI design methods focus on the technical details of building particular user interfaces. [Santoni, Francois, Furtado, Romitti, Ntuen, & Park 1995] shows both models and processes used to automatically generate supervision system interfaces from models of the problem-resolving tasks of processes. [Ferrucci, Tortora, Tucci, & Vitiello 1996] describes a semantics-based grammatical inference methodology for the generation of visual languages and a tool for specifying, designing, and interpreting customized visual languages for different applications. [Hoogewijs 1997] describes how a language or syntax cast in a particular traditional form can be used to produce automatically motion control software, object recognizers and human-computer interfaces. [Fowler 1999] presents guidelines for building HMI interfaces for electronic equipment. [Voronin & Kozlov 1998] proposes an experimental-theoretical method for prediction and optimization of operator's activity in multi-objective man-machine systems with applied simulation.

Several design standards exist for human machine interfaces for government-sponsored systems. Department of Defense MIL-STD-1472E establishes general human engineering criteria for design and development of military systems, equipment and facilities. NASA-STD-3000 establishes similar criteria for space-based systems. MIL-STD-1787B (USAF) describes symbols, symbol formats, and information content for electro-optical displays that provide aircrew members with information for takeoff, navigation, terrain following and avoidance, weapon delivery, and landing. ESD-TR-86-278 offers guidelines for the design of user interface software in six functional areas: data entry, data display, sequence control, user guidance, data transmission, and data protection.

1.2 Language

1.2.1 Textual Languages

Most existing industrial robots are programmed through a language. A significant amount of HMI-related research concerns extending existing or developing new languages for various robot applications. [Tatsuno, Kokubo, Matsuyama, Kawabata, & Kobayashi 1996] represents motions by sets of keywords and tasks as sequences of the words. Another avenue of language-related

HMI research is the toolkit approach. [Jennings, Whelan, & Evans 1997] provide high-level programming constructs for task distribution across robots. [MacKenzie & Arkin 1998] evaluates the MissionLab toolset as a concrete example when exploring the issues of evaluating such toolsets as to their usability.

Language research is also being directed toward the interactive phase of robot control. [Pauly, Kraiss, & Sheridan 1995] describes a new concept for symbolic interaction with semi-autonomous mobile systems using a symbolic world model and a human-like communications interface. [Pauly & Kraiss 1998] extends on this concept and describes a system architecture based on the blackboard concept, and the structure of the individual modules (agents) for a mobile robot. As an example the authors describe a world-modeling agent, a path-planning agent and a navigation agent.

1.2.2 Visual Programming Languages

Visual programming concerns the development of computer languages that are represented in the form of visual symbols and actions. [Weck & Dammertz 1995] uses a flowchart language. [Taner & Brignell 1995] describes a system that lets a programmer work from a schematic diagram of an intelligent subsystem to trace and execute signal flow through the various nodes of the system. [Zuhike & Mobius 1996] describes a visual programming approach and program that allows inexperienced users to design, build, and document any program in any code using graphical symbols without knowledge of a textual programming language. [Cox, Smedley, Garden, & McManus 1997] describes their experiences in applying visual programming to simple robot control. [Rogers, Murphy, Ericson, Johnson, & Hayes-Roth 1997] presents an architecture for facilitating visual problem solving between robots and humans. [Heger, Cypher, & Smith 1998] describes Cocoa, a visual programming language for children, and its performance in the “Visual Programming Challenge ’97” in navigating a Lego robot.

1.2.3 Teaching by Demonstration

The concept of programming or teaching by demonstration is not new. At a basic level, teach pendant programming is a programming by demonstration approach. [Qi Wang & De Schutter 1998] describes a system wherein a robot performs an operation while force, velocity, and position, as well as human manipulation through a joystick, are measured and recorded into a textual program. [Bordegoni, Cugini, Rizzi, Casals, & de Almeida 1997] uses a digital simulation and haptic interaction for the purpose of analyzing human skill and mapping it into a skilled robotics system. [Myers 1999] develops a teach-by-showing approach that monitors both sensor inputs to the robot controller and the control outputs from the controller during a training session to automatically generate sensor-based autonomous programs from taught motions. [Onda, Hirokawa, Tomita, Suehiro, & Takase 1997] describes a teaching system that is based on a model of assembly as a series of operations for achieving target contact states among objects. [Friedrich, Holle, & Dillmann 1998], [Friedrich, Muench, Dillmann, Bocionek, & Sassin 1996], and [Friedrich, Hofmann, & Dillmann 1997] develop a programming by demonstration approach that allows the user to supervise the entire program generation process and to annotate and edit system hypotheses. Other approaches are described in [Takahashi 1997], [Yeasin & Chaudhuri 1997], [Delson & West 1994], [Shimokura & Liu 1994], [Ogata & Takahashi 1994], [Jagersand & Nelson 1995], and [Rafflin & Fournier 1996].

Demonstration can also be used to train robots to perform at a higher level of abstraction. [Kitazawa, Sakai, & Kochhar 1995] appears to describe a method which monitors how humans solve problems in vehicle driving to feed an expert system for automating vehicles. The text seems to indicate that the user interacts with toys to affect a running simulation. (The writing is unclear.) In a related paper, [Sakai, Kitazawa, & Nakamura 1995] monitors how people do the job of fish drying to obtain a basic set of drying equations for automatic control. "What factors can be applicable for evaluating dried fish is gradually understood by a novice, through observing a human expert's way and sharing the same situations with him, again and again." [Kurata & Uchiyama 1999] describes a path planning method based on the use of human factors obtained by many questionnaires.

1.3 Graphics-Dominated Interfaces

A significant body of work has developed technologies that rely on computer-generated displays. While some of this work focuses on the display or rendering aspect, another significant portion focuses on using sophisticated displays to present simulation and high-level control information to the user.

1.3.1 Virtual Reality and 3D Viewing in Telerobotics

Remote viewing is important in remotely operated mobile and underwater vehicles. As a result, a significant portion of the literature in VR-based telepresence comes from this community. [Brutzman 1995] describes the development on a virtual reality interface for remotely driving an underwater vehicle and its use in the worldwide sharing of scientific information with collaborators. [Aucoin, Sandbekkhaug, Jenkin, & Hamza 1996] uses a VR interface for mobile robot control. [I-Shen Lin, Wallner, Dillmann, Rembold, Dillmann, Hertzberger, & Kanade 1995] and [I-Shen Lin, Wallner, & Dillmann 1996] claim to demonstrate that a graphical interface and 3D animation are important aspects in teleoperation of mobile robots. [Kheddar, Atlani, Iles, & Blazevic 1996] considers legged robot teleoperation using VR-based supervisory tools. [Skrzypczyliski 1997] extends this concept to presenting multisensor data to the human operator and presents methods for cooperation between the operator and navigation system of the mobile robot. [Wang Jiangang, Dong Zaili, & Xu Xinping 1997] describes an object modeling and virtual environment rendering system for teleoperated mobile robots. [Steele, Thomas, Blackmon, Rosenblum, Astheimer, & Teichmann 1999] describes the virtual reality interface for Pioneer, a robot designed to generate a 3D, multi-data map of Chernobyl. [Qingping Lin & Chengi Kuo 1997] concludes that virtual telepresence improves efficiency and forms the basis for supervisory and automated control of underwater robots. [Schmitt & Kraiss 1998] describes operator control and localization of mobile robots using a VR environment. [Fischer & Schmidt 1998] discusses requirements for exchange between a human operator and a semi-autonomous service robot operating in a remote indoor environment. The proposed solution uses a 3D viewing model augmented by the image of an onboard CCD camera. [Lin & Kuo 1998] describes a virtual environment-based system for the navigation of underwater robots.

Remote viewing is also needed in hazardous-duty teleoperation environments. [McKay & Anderson 1996] describes Idaho National Engineering Lab's VR-based telepresence system, VirtualwindoW, for nuclear operations and recommends that a prolonged use study be conducted to bench mark the length of time users can be safely exposed to this technology. [Elliott &

Eagleson 1997] and [Stuart, Chapman, & Eagleson 1997] use 3D viewing systems for viewing and control of teleoperated systems. [Tourtellott 1997] describes the Interactive Computer-Enhanced Remote Viewing System (ICERVS) developed by Mechanical Technology Incorporated (MTI) for DOE's robotics program.

1.3.2 Simulation-based or Graphical Programming Interfaces

In the early 1990s, Sandia National Laboratories [Christensen, Drotning, & Thunborg 1990] and the Jet Propulsion Laboratories [Backes 1991] and [Backes & Tso 1993] developed simulation-based interfaces for telerobotics. These systems are characterized by the use of 3D simulations in the operator's graphical user interface. By the middle 1990s, these groups had significantly refined the technology. [McDonald & Palmquist 1993a], [McDonald & Palmquist 1993b], [McDonald, Palmquist, & Desjarlais 1993], [Pinkerton, McDonald, Palmquist, & Patten 1993], and [Small & McDonald 1997] describe Sandia's successive advances in graphical programming. [Kim, Weidner, & Sacks 1994] describes a basic Mars mission control system that was later refined for the Mars Pathfinder.

Outside Sandia and JPL, [Lloyd, Beis, Pai, & Lowe 1997] describes a model-based telrobotic system designed to investigate assembly and other contact and manipulation tasks. For mobile robots, [Kronreif & Probst 1998] describes a mobile robot control system whereby through its GUI, the user can send commands to the robot in a task-oriented meta-language, monitor command execution by seeing the robot actually moving on the screen, and visualize instantaneous and cumulated sensor data.

1.3.3 Virtual Tools and Point and Direct Programming

[Cannon 1992] develops the concept of Point and Direct (PAD) robot programming. The basic concept uses a tool metaphor for contol objects to define robot tasks and interact with the robot system. This concept was extended by Cannon and colleagues in [Thomas, Cannon, & Goldberg 1995], [Wang & Cannon 1993] and [Wang & Cannon 1996]. PAD systems now typically include 3D graphics with projective texture overlays and data glove interfaces for manipulating the virtual tools. [Xiaobu Yuan, Hanqiu Sun, Thorburn, & Quaicoe 1997] and [Myung Hwan Yun, Cannon, Freivalds, & Thomas 1997] separately develop related concepts in virtual tools.

1.3.4 Collaboration and Remote Robot Control Via the Internet

A particular application to simulation-based interfaces are those that control robots via the Internet. [Davies, McDonald, & Harrigan 1994] introduces the concept of Virtual Collaborative Environments (VCEs). [McDonald, Small, Graves, & Cannon 1997] refines this concept and demonstrates that collaborative control can provide machine utilization and efficiency gains. This VCE environment was built by combining Sandia's graphical programming technology with Cannon's PAD technologies. [McDonald & Ice 1997] develops a visualization tool for use with VCEs.

[Lumia 1997] introduces a low-cost VCE system for university research. [Bajcsy, Enciso, Kamberova, Nocera, & Sara 1998] addresses an application of computer vision as a testbed for telecollaboration and the demonstration of live recovery and simultaneous display and manipulation of 3D models in a dynamically changing environment.

Collaboration technologies are yielding successes in speeding research. [Guzzoni, Cheyev, Julia, & Konolige 1997] describes Internet-based collaborative work between SRI (CA) and the Swiss Federal Institute of Technology in Lausanne. The teams developed and controlled three physical robots and a set of software agents via the Internet to rapidly design and implement a winning team of collaborating robots in the six weeks before the Fifth Annual AAAI Mobile Robot Competition and Exhibition.

1.3.5 Webbots

A special class of remote user interfaces are those that use standard web-browsing technologies. [Taylor, Dalton, & Trevelyan 1999] describes a robotic system that has been continuously available via the web since 1994, making it among the first and most long-running webbots. [Monteiro, Rocha, Menezes, Silva, & Dias 1997] and [Salazar-Silva, Martinez-Garcia, & Garrido 1999] describe Java-based systems for controlling a robot through a web browser. [Gracanin, Matijasevic, & Valavanis 1997] describes an approach for a VR-based testbed for an underwater robot that uses VRML and Java. [Luo & Tse Min Chen 1997] describes a web-controlled mobile robot system. [Agah, Walker, & Ziemer 1998] describes a telepresence system where a mobile manipulator robot is utilized to explore a museum at a remote site. [Sequeira, Bovisio, & Goncalves 1999] describes a demonstration consisting of piloting a remote mobile platform using Internet protocols and standards.

Khepera is a small, widely-used research robot (sized for tabletop research). [Michel & Heudin 1998] describes OpenGL and VRML-based simulators and control systems for driving Khepera mobile robots on the Internet for research applications including robot vision, artificial life games, and robot learning. [de Meneses, Michel, & Heudin 1998] presents an implementation of a panoramic, linear, artificial retina EDI within the frame of this simulator.

1.3.6 Multimedia

As an example of human-robot cooperative system, [Ishii, Saita, & Kopacek 1995], [Ishii, Saita, Stelson, & Oba 1996], and [Ishii & Saita 1997] propose an intuitive approach to robot teaching method with multimedia tools. [Xu, Van Brussel, & Moreas 1997] takes advantage of multimedia technology to combine graphics, speech, and visualization into a coherent multimodal interface for handicapped people. [Angelidis, Anogianakis, Maglavera, Pappas, Maglaveras, & Scherrer 1997] describes a multimedia man-machine interface that allows severely disabled or bed-ridden users to operate service robots.

With 69 citations, [Dennis, Valacich, & Sprague 1999] "describes a new theory called a theory of media synchronicity which proposes that a set of five media capabilities are important to group work, and that all tasks are composed of two fundamental communication processes (conveyance and convergence)." Matching the media capabilities to the needs of the fundamental communication processes, not aggregate collections of these processes (i.e., tasks) as proposed by media richness theory, influences communication effectiveness. "The theory also proposes that the relationships between communication processes and media capabilities will vary between established and newly formed groups, and will change over time."

1.3.7 Visual Servo or Video Selection Interfaces

[Cleary & Crisman 1997] describes what they call a diectic (*Gr. for serving to show or point out*) visual servoing interface for mobile robot control. [Baldwin, Basu, & Hong Zhang 1998] uses predictive Kalman filters to optimize video image display in low bandwidth telepresence applications. [Huster, Fleischer, & Rock 1998] describes an image-based user interface to specify desired vehicle locations for a hover-capable underwater vehicle. [Sekimoto, Tsubouchi, & Yuta 1995], [Sekimoto, Tsubouchi, & Yuta 1996], and [Sekimoto, Tsubouchi, & Yuta 1997] describe an interface for mobile robots that allows users to guide a vehicle by touching a monitor showing video images from the vehicle cameras.

1.4 Transduction

Transduction research concerns the development and evaluation of new devices and controls that provide new mechanisms to allow humans to interact with machines. Transduction research often draws on a variety of sources outside the traditional human machine interface community. The Department of Defense's significant investments in war machine control, simulation, and training equipment provides one source of transduction technologies. *Jane's Simulation and Training Systems* provides a comprehensive listing of military training and simulation equipment worldwide, with manufacturers' details and expert reviews of the technologies. Recent flight simulator technologies are described in [NTIS-95].

1.4.1 Technology Evaluations

Several transduction technologies were evaluated at the Wright-Patterson AFB research labs. [Anderson 1998] examines applications of speech-based control in aerospace environments. [McMillan 1998a] reviews the technology for using electrical signals from the muscles and brain as a means for interacting with computers and other physical devices. [McMillan 1998b] reviews the technology for using hand, body and facial gestures as a means for interacting with computers.

1.4.2 Head Mounted Displays (HMDs)

[Browne & Moffitt 1996] describes comparative studies and experiments for using HMDs as compared to traditional Operator Control Units (OCUs) for controlling unmanned ground vehicles (UGVs). [Kheddar & Coiffet 1995] addresses the problem of navigation within virtual environments and proposes a navigation control algorithm based on operator head behavior. [Nelson, Hettinger, Cunningham, Roe, Haas, & Dennis 1997] describes an experiment conducted in which participants used a CyberLink interface, which monitors EEG and EMG signals, to navigate or *fly* along a virtual flight path.

1.4.3 VR with Force Reflection and Haptic Interfaces

Force reflection and touch are also important aspects to add in telerobot/VR applications. [Anderson 1992], [Anderson 1994], and [Anderson & Davies 1994] embed responsive models into a robots' real time control environment to provide the operator with force feedback responses to virtual as well as physically-sensed objects. [Taylor 1995], [Taylor, Hosseini-Sianaki, Varley, & Bullough 1995], [Taylor, McKay, Hosseini-Sianaki, Varley, & Bullough 1995], [Taylor, Hosseini-Sianaki, & Varley 1996] [Taylor, Moser, & Creed 1997], and [Taylor, Dalton, & Trevelyan 1999] develop a tactile array system to provide a means of providing tactile and kinesthetic interaction to virtual environments. [Crawshaw et al. 1996] presents results in the psychological issues in tactile virtual environments.

1.4.4 Gesture Recognition

Gesture recognition is a very active area of transduction research. [Hasegawa, Nohara, Matsui, & Sato 1995] describes a novel teleoperation system that issues commands by recognizing hand movements. [Parsons et al. 1996] describes the development and use of a low-cost gesture measurement and recognition system employing electrolytic tilt sensors for a rehabilitation robotic system. [Cohen, Conway, & Koditschek 1996] presents a system for generation and recognition of oscillatory gestures as inspired by human-to-human control areas (i.e., similar to how crane operators communicate). [Hamada & Luo 1996] introduces a new method for gesture recognization that uses syntactical hand-sign parcing to provide a simple and compact recognition algorithm. [Sawada, Onoe, & Hashimoto 1997] investigates the use of gestures to better enable people to insert emotional feelings into sound. [Boehme et al. 1997] presents a neural architecture for gesture-based interaction between a mobile robot and human users. [Triesch, Von Der Malsburg, Wachsmuth, & Frohlich 1997] describes a vision-based gesture interface used to command real robot grasping objects on a table in front of it. [Waldherr, Thrun, Romero, de Padua Braga, & Ludermir 1998] describes a gesture-based interface for human-robot interaction which enables people to instruct robots through easy-to-perform arm gestures.

1.5 System Architectures

1.5.1 Adaptive or Learning User Interfaces

Adaptive or Learning User Interfaces use online user observations to automatically predict and assist future user inputs. [Bellika, Hartvigsen, & Widding 1998a], [Bellika, Hartvigsen, & Widding 1998b], [Chaochang Chiu, Chi-I Hsu, Norcio, Poo, & Seumahu 1995], [Ferrucci, Tortora, Tucci, & Vitiello 1996], [Karagiannidis et al. 1996], [Nonaka & Da-te 1998], [Ntuen, Koubek, Askin, Bidanda, & Jagdale 1996], [Santoni et al. 1995], and [Wolber, Sachse, Salvendy, Smith, & Koubek 1997] describe general adaptive user interface technologies. [Nonaka & Da-te 1998] uses a fuzzy behavior model to improve user performance in mouse pointing tasks. [Pegman 1999] proposes that the use of adaptive autonomous control with teleoperation allows operators to take a more supervisory role.

[Meech & Norros 1995] presents an architecture for providing an intelligent or adaptive user interface for real-time complex systems. [Fabiano, Lanza, & Zardetto 1995] describes an advanced and adaptive man-machine interface (MMI) for a thermal power plant. [Vale et al. 1996] describes an adaptive expert system for alarm processing and operator assistance in service restoration developed for the Portuguese transmission network. [Karagiannidis et al. 1996] describes the use of a queuing model in an adaptive user interface to facilitate assessment of the current state and prediction of the future behaviour of user computer interaction. [Ota, Van der Loos, & Leifer 1998] describes an adaptive motion generation interface system that uses VRML and Java. [Piaggio 1998] presents a programming environment that has been successfully used to develop adaptive intelligent interfaces to autonomous robots operating in civil environments.

[Chen & Hwang 1994] and [Luh & Shuyi Hu 1999] describe approaches for Learning User Interfaces that are restricted to motions and spatial relationships. [Langley, Brewka, Habel, & Nebel 1997] examines personalized user interfaces and explores the potential of machine learning in meeting that need.

1.5.2 Hierarchical Methods (Including Task Allocation) Research

Task allocation can be performed by dividing control between virtual objects or between various robots. In task allocation research, [Bing Xu, Halme, Helbo, & Kopacek 1995] describes a four-level human-to-robot task allocation scheme. [Halme, Jakubik, Schonberg, Vainio, & Kopacek 1995] reports using societal models to share control between robots and thereby provides a flexible operator interface that allows users to manage several robots. [Stahre, Onori, Johansson, Ericsson, & Kopacek 1995] describes a hybrid flexible automation assembly system that balances human and machine assembly capabilities to provide higher efficiency. [Klarer 1997] describes small scale intelligence (SSI) for multi-robot control and briefly proposes an approach to the hybridization of SSI control systems with a telerobotic man-machine interface.

Control systems can be implemented in hierarchical layers, with each layer forming an interface that transitions control between the human and the machine. Generally, the operator layer is made toward the top of the hierarchy while the lower layers interact with the robot. In the hierarchical methods research, [Giralt, Bidan, & Boverie 1995] describes three key generic concepts: autonomy, reactivity and human-machine intelligence that support what it describes as *seminal contending paradigms* for autonomous robots systems. [Prokhorov, Blumenthal, Gornostaev, & Unger 1995] describes research devoted to the problems of visual interfaces and graph representations of hierarchical multilanguage technologies in HCI. [Schraft & Volz 1996] discusses the process integrations which implement the mediation hierarchy in the multiple agent supervisory control (MASC) system interface. [Cheng & Zelinsky 1997] proposes a paradigm for teleoperating mobile robots that includes *self-preservation*; *instructive feedback*; *qualitative instructions*; *qualitative explanations*; and a *user interface*. [Jiyoon Chung, Byeong-Soon Ryu, & Yang 1998] proposes a control strategy made by combining the merits of behavior-based and planner-based approaches. The architecture consists of three major parts: behaviors, planner, and coordinator. [Guzzoni, Konolige, Myers, Cheyer, & Julia 1998] describes a three-level architecture that layers control through the local level (the navigation system), the global state, and a multimodal HMI.

1.5.3 Controlling Emergent Behavior

Emergent behavior is an active research topic for robotic control. A fundamental problem is defining behaviors that result in appropriate emergent behaviors. [Labbani, Muller, & Bourjault 1997] describes a methodology that could be used to specify an emergent collective behavior of a tumor extraction by a group of robots.

1.6 Human and Animal-Like Interaction

1.6.1 Humanoid Robot Research

Humanoid robot research was recently invigorated through Brooks [Brooks & Stein 1993] in the form of an upper-torso humanoid robot called COG at MIT’s Artificial Intelligence Lab. A recent development from this work concerns the human-like interaction made possible through humanoid robots. [Brooks et al. 1999] explores issues of developmental structure, physical embodiment, integration of multiple sensory and motor systems, and social interaction through the study of Cog.

[Hoshino, Inaba, & Inoue 1998] describes the Humanoid robot at Waseda Univ., Tokyo, Japan. [Hoshino, Inaba, & Inoue 1998] describes the use of this robot along with a whole-body tactile sensor suit for processing its human-robot contact interaction. [Hashimoto, Jain, & Jain 1998] describes work toward building emotional response by adding a multimedia sensing system to track a speaking person using both image and sound processing and a model-based vision system to recognize the self position in the known environment. [Kikuchi et al. 1998] relates the control of the humanoid robot's gaze to the smoothness of turn taking in communication.

1.6.2 Emotion-based Interfaces

A relatively new research area is the use of emotion models within HMIs. [Zrehen 1998] and [Kitamura 1998] report using emotions to design animal-like behavior in interactive (dog-like) and autonomous robots. [Gazdik 1998] deals with an approach to formalizing intangible qualities, here limited to the assessment of personal quality. [Ogata & Sugano 1999] discusses the communication between autonomous robots and humans through the development of a robot which has an emotion model. [Billard 1999] integrates the capacity for communicating, for learning and for imitating into the design of social skills for robots to facilitate the robot's interaction with humans.

For emotion-based agents, [Ventura, Custodio, & Pinto-Ferreira 1998] hypothesizes that intelligence, based on a structured pictorial knowledge representation, can bridge the gap between purely reactive agents and complex, logic-based, reasoning systems to allow system operation in real, aggressive, and unpredictable environments. [Gadanho & Hallam 1998] discusses conceptual frameworks to design and construct emotion-based agents to bridge the gap between purely reactive agents and complex, logic-based, reasoning systems. [Dautenhahn & Nehaniv 1999] addresses embodied social interaction in life-like agents for robot-human interaction, especially as it applies to autistic children.

1.7 Ubiquitous Robotics and Computing

[Kohno, Anzai, Salvendy, Smith, & Koubek 1997] introduces Intelligent-Sensor Actuator Networks (ISANs) consisting of mobile personal robots and intelligently-controlled devices (i.e., door openers). [Yamasaki & Anzai 1995] and [Yamasaki, Anzai, Anzai, Ogawa, & Mori 1995] describe ISAN active interface work concerning a speech dialog system and a video conference system for personal robots. A key aspect of these active interfaces is their ability to passively monitor the person to gather information and then react spontaneously as the situation warrants.

[Iwakura, Shiraishi, Nakauchi, & Anzai 1997b], [Iwakura, Shiraishi, Nakauchi, & Anzai 1997a], and [Iwakura, Shiraishi, Nakauchi, & Anzai 1998] propose a real-world-oriented distributed human interface system named AIDA (Architecture for Interfacing Distributed Agents). AIDA supports human activities in the real world (i.e., in offices or in houses) without restricting the user's physical activities. AIDA is based on a multi-agent model in which the interfacing elements (i.e. mobile robots, workstations) cooperate to provide context-aware support to the user. An agent is constructed by a set of behavior modules for providing reactive responses to the user. Also, with AIDA, the system can adapt to the uncertainty of the user's position and attention, which may change as time passes. [Mori & Sato 1999] describes a room type robot system for social service, proposes a robotic room as a feasible human-robot symbiosis system, and presents several realized components of a robotic sick room as a concrete example.

1.8 Human Factors

Human factors engineering and research is concerned with issues including the relationship between ergonomics and biomechanics and worker productivity. Practical applications that use human factors research are occasionally reported. For example, [Draper, Noakes, Schempf, & Blair 1997] and [Schempf, Warwick, Piepgras, Fung, & Blackwell 1997] describe how well-known human-factors approaches were used to design a multi-purpose control center for the U.S. Department of Energy remote handling applications.

4 Hard and Important Problems Being Addressed

Several papers report driving interface work through the selection of difficult or challenging problems. Others report having built solutions to various hard problems that are of particular interest to Sandia. While work above often involves addressing these hard problems, the work described below appears to be primarily focused toward the problem and secondarily toward any particular solution.

4.1 Safety

Several researchers use safety as a key parameter for evaluating and refining HMIs. [Reason 1990] provides a general review of research concerning human mistakes. For mistakes that have safety implications, Reason points out, in particular, that inappropriate attention to interfaces for off-normal event handling has led to turning serious incidents, like those at Chernobyl and Three Mile Island into catastrophes.

[Beauchamp & Stobbe 1995] briefly describes and synthesizes the experimental results generated in the human factors studies, makes recommendations to improve the safety of the persons working in the vicinity of industrial robots, and proposes future research avenues in this area. [Stubler & O'Hara 1998] discusses the application of design approaches for reducing the likelihood of such errors. [LaSala 1999] describes a system, called the Reliable Human-Machine System Developer (REHMS-D) that can be used to reduce human performance-related risk. [Repperger, Haas, & Koivo 1999] applies methods from fault diagnosis studies and signal detection theory to formulate an optimal model involving decision making of the human operator.

4.2 Rehabilitative and Assistive Systems

Rehabilitative and assistive systems primarily concern intelligent machines to enhance the abilities of disabled or elderly people.

4.2.1 General Rehabilitative and Assistive Systems

[Kazi et al. 1996] and [Kazi & Foulds 1998] report on Multimodal User Supervised Interface and Intelligent Control (MUSIIC), which is targeted toward users with physical disabilities. [Lacey & Dawson-Howe 1998] describes the design and user interface for a guide dog-like robot. [Dallaway & Langton 1996] describes their recent research in HCI for the command of rehabilitation robot systems. Davis reports on a prototype “playing robot” which may enrich the sensory experiences of children with disabilities.

[Parsons et al. 1996] describes an adaptive interface developed for a robot arm mounted to a wheelchair. [Komeda et al. 1996] describes a small mobile robot, with arm, for bedridden patients. The system is controlled through a visual interface to move small objects about the room. [Hillman, Hagan, Hagan, & Orpwood 1998] describes two assistive systems, one with a robotic arm mounted on a trolley and the other with an arm mounted to a wheelchair.

4.2.2 Wheelchair Automation

A special case of rehabilitative system research is wheelchair automation. The key problems being addressed focus on wheelchair users with fine motor control limitations. The bulk of the research is focused toward building interfaces that provide higher levels of automation or smoother control. [Agostini, Bourhis, & Kopacek 1995], [Bourhis & Agostini 1998b], [Bourhis & Agostini 1996], and [Bourhis & Agostini 1998a] describe sustained research in a mobile robot control architecture, applied to wheelchairs, which facilitates task and information sharing and trading between man and machine. [Pires, Honorio, Lopes, Nunes, & Almeida 1997] describes the RobChair project that includes a behavior-based control architecture. [Borgolte, Hoyer, Buhler, Heck, & Hoelper 1998] describes a smart, sensor-assisted wheelchair system for the vocational rehabilitation of people with severe and multiple handicap. [Abascal, Cagigas, Garay, & Gardeazabal 1999] describes the user interface to a guidance system for wheelchairs directed to users with severe mobility restrictions. [Pino, Arnoud, Brangier, Jain, & Jain 1998] describes the results from integrating the smart wheelchair project with the interacting telethesis project. In addition, [Pires, Honorio, Lopes, Nunes, & Almeida 1997], [Higgins, Glass, Leiber, Foulds, & Sprigle 1997], [Katevas et al. 1997], [Hillman, Hagan, Hagan, & Orpwood 1998], [Fioretti, Leo, & Longhi 1998], and [Yanco, Mittal, Yanco, Aronis, & Simpson 1998] describe other wheelchair automation projects.

1.3 Robotic Vehicles and Service Robots

[Veruggio, Caccia, & Virgili 1995] discusses architectures for both remotely operated and autonomous underwater vehicles. [Nelson & Yangsheng Xu 1995] describes a modular robot with reconfigurable hardware and real-time controls for lunar exploration and maintenance. [Baudoin, Kocijan, & Karba 1995] summarizes design aspects for telerobotics in intervention and reconnaissance tasks through the opinion of international experts and analysis of existing international programs. [Pai, Barman, Ralph, Khatib, & Salisbury 1995] describes programming alternatives for a new class of high degree of freedom, spherically symmetric legged robots called platonic beasts. [Petriu et al. 1996] presents a multisensor system for navigation of an experimental mobile robot. [Wang, Rock, & Lee 1996] describes OTTER; an underwater robot designed to be used as a testbed for autonomous technologies.

[Schraft & Volz 1996] demonstrates roles of operator or user-interaction with service robots in three example prototype systems. [Hanebeck, Fischer, & Schmidt 1997] describes a mobile robotic assistant for indoor service applications (see related VR work by Fischer above). [Tigli, Workert, & Thomas 1997] describes achievements in the design of human/autonomous underwater vehicle interactions in the specification phase of the robot mission of an instrumented underwater vehicle. [Thrun et al. 1999] describes MINERVA, a second-generation museum tour guide robot. [Fiorini, Ali, & Seraji 1997] describes an approach followed in the design of a service robot for health care applications. [Fromm & Drews 1998] describes a smart-vehicle architecture. [Maslowski et al. 1998] describes a mobile robot for surveillance and security that will be controlled remotely by operators equipped with VR helmets. [Graves & Czarnecki 1999] describes a telerobotic system designed for the specific task of bomb disposal.

1.4 Robots for Heavy Industries

[Lin, Ang, Lim, Ng, & Kang 1997] reports on a robot system for ship panel line welding. [Basu, Jacobsen, Fichtner, & Mackay 1997] describes how the integration of a product model and offline programming can speed robotic shipbuilding operatons. [Karlsson 1998] describes man-machine communications requirements in multi-run welding of heavy components.

[Margrave, McKee, Widden, & Kopacek 1995] describes the use of virtual reality in user interfaces for construction equipment. [Abderrahim, Balaguer, Gimenez, Pastor, & Padron 1999] describes an operator interface for controlling a catepillar-concept robot that is being designed to climb on and inspect structures. [Pritschow, Dalacker, Kurz, & Gaenssle 1996] reports on the development of a sophisticated bricklaying robot that works from models of material tolerances and application of bonding in a single unit.

1.5 Micromanipulation

[Feddema, Simon, Kriegman, Hager, & Morse 1997], [Feddema, Keller, & Howe 1998], [Feddema & Simon 1998a], [Feddema & Simon 1998b], and [Feddema, Xavier, & Brown 1999] describe a large body of work in micromanipulation. Work includes visual servoing, Fourier optics methods used to generate synthetic microscope images from CAD drawings, and automated planning for microassembly. [Seyfried, Fatikow, & Guglielmi 1997] describes a semi-automated teleoperation system for micromanipulation. [Codourey, Rodriguez, & Pappas 1997] describes a mixed micro/nano-world teleoperation system, which is composed of both direct and task oriented teleoperation modes. [Rodriguez, Codourey, & Pappas 1996] adds tools for viewing live microscope video images with top and side view, and a 3D virtual solid model of the robot with perspective as well as orthogonal views available at the same time. [Sulzmann, Breguet, Carlier, & Jacot 1996] and [Sulzmann & Jacot 1995] describe a real-time virtual reality HMI environment that uses a vision system to convert and monitor microscopic actions to a 3D scene from which a user drives a microrobot.

1.6 Assembly Planning

Because of its close relationship to programming robotic assembly systems, automated assembly planning is closely related to and may drive new HMI interface issues. [Kaufman, Wilson, Jones, Calton, & Ames 1996] describes Sandia's work, started in 1989, on Archimedes, an automated assembly planner, and describes its use in automatically programming robotic assembly sequences. [Kopacek, Probst, & Kronreif 1995] deals with a new modular control software package that includes an assembly sequence editor and a sequence controller that is connected to a man-machine interface. [Rogalinski 1996] presents an approach to automatic synthesis of programs for robots in a flexible manufacturing cell. [Xiaobu Yuan, Hanqiu Sun, Thorburn, & Quaicoe 1997], [Yunqing Gu, Xiaobu Yuan, & Hornsey 1998], and [Xiaobu Yuan & Yuqing Gu 1999] integrate robot programming with sequence planning. These authors are also working in the Virtual Tools arena. [Crawshaw et al. 1996] and [Steffan, Schull, & Kuhlen 1998] describe using VR environments, with tactile and kinasthetic perception for assembly planning.

Due to the variety and quality of products arriving at a robotic station, automated disassembly (generally for recycling purposes) technologies require a strong HMI component. [Knackfuss, Schmidt, Meier, Gill, & Syan 1996] describes an autonomous robot system for the disassembling of automotive parts.

5 Conclusions

This work describes a great variety of current HMI interface works. Work in developing various HMI interface approaches and technologies appears concentrated in developing and extending

- methods for designing interfaces,
- languages for programming and interacting with machines,
- graphical interfaces for controlling machines,
- devices for interacting with the systems, and
- system architectures that have positive impacts on human machine interactions.

In addition, new research areas are being explored to allow machines to behave and interact with humans in a more human-like way. Conversely, work in human factors has transitioned toward applied engineering.

Beyond new interface technologies, interesting user interface concepts are being developed as part of solving specific problems. In particular, a significant amount of work is being done to address

- improving system safety,
- building rehabilitative and assistive systems for people with disabilities,
- deploying robotic vehicles and service robots,
- bringing robotic technologies to heavy industries,
- robotic micromanipulation, and
- robotic assembly and disassembly.

Current HMI research efforts appear to be generally uncoordinated and oriented toward solving *point solutions*. While new user interface technologies are being developed, a more coordinated effort is needed to allow robots to achieve their potential. In addition, few papers emphasized the use of formal methods to discover user needs or measure user performance in the resulting systems. Added rigor is called for. Finally, the bulk of the HMI research surveyed is focused on control level aspects of machine interfacing. Little work addresses high-level planning, task definition and ethnographic issues typically addressed by the industrial design communities in building products and computer interfaces.

6 Appendix A) Search Strategy Utilized

In performing the literature search, a variety of search terms were exploited. Several of these search terms come from standard categorization terms while others were terms that often appear within the literature of interest. The following terms were of particular importance. (INSPEC category numbers are given in parenthesis.)

Adaptive User Interface(s)
Biological and medical control systems (C3385)
Computer assistance for persons with handicaps (C7850)
Control applications in assembling (C3355F)
Control engineering computing (C7420)
Graphical user interfaces (C6180G)
Graphics techniques (C6130B)
Handicapped aids
High level languages (C6140D)
Human factors
Intelligent control
Interactive systems
Interactive-input devices (C5540B)
Manipulators (C3390M)
Man-machine systems (C1270)
Mobile robots (C3390C)
Path Planning
Production engineering computing (C7480)
Robot programming
Robotics (C3390)
Spatial variables control (C3120C)
Systems analysis and programming (C6110)
Telerobotics (C3390T)
User interfaces (C6180)
Virtual Reality
Visual programming (C6110V)

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