SARSCEST
(Human Factors)

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INTRODUCTION

As we all know, people interact with the processes and products of contemporary technology. Individuals are affected by these in various ways and individuals shape them. Some eager souls investigate such interactions or try to influence them, under the label "human factors."

The term is easier to define--as I have just done--than the considerable territory it labels is to describe. What is in it? To expand the understanding of those to whom it is relatively unfamiliar, its domain includes both an applied science and applications of knowledge. It means both research and development, with implications of research both for basic science and for development. It encompasses not only design and testing but also training and personnel requirements, even though some unwisely try to split these apart both by name and institutionally. The territory includes more than performance at work, though concentration on that aspect, epitomized in the derivation of the term ergonomics, has overshadowed human factors interests in interactions between technology and the home, health, safety, consumers, children and later life, the handicapped, sports and recreation, education, and travel.

Technology affects our emotions, but other than stress these, unfortunately, have aroused little interest, as though it were immaterial whether technology adds or subtracts enjoyment or depression or anxiety in our daily lives. Technology affects the interactions between individuals--our social and organizational lives, and these influence how we use or create technology. NASA has been alert to these aspects, which have been relatively neglected in human factors otherwise despite efforts to widen an involvement in studies of habitability and organization design. Who knows? Eventually human factors scientists and engineers may also investigate relationships between technology and motivational variables in the behavior of those who use its products and processes--especially incentives and disincentives, rewards and deterrents, and conditions that strengthen or weaken these.

But rather than talk about such matters, important as they are, in this paper I shall discuss two aspects of technology I consider most significant for work performance, systems and automation, and four approaches to these that hold much current interest for both the Air Force and NASA and present new challenges for human factors science and applications.

SYSTEMS

This topic accounts for the initial S in the paper's title, which is an acronym. (Acronyms are a product of technology, in part, reflecting the need to conserve program space in software and the law of least effort in humans. Another instance is SOAR.) Human factors scientists and engineers deal with systems as well as components. A system model consists of input, processing, output, and feedback (SIPOF); the corresponding human model is HIPOF.

One contribution human factors can make is a systems perspective. This does more than include the roles of humans as well as machines in some proposed or developing system. It considers more than a single workplace for one or two individuals. It embraces more than optimizing the design; the human can also be improved. It extends beyond some traditional boundaries in investigating human-machine performance, such as servo-controlled negative feedback loops. It asks how the goals, set points, or criteria are established in task or mission planning. It views an automated or semi-automated system in more than a control context. Indeed, the human role in control may be virtually eliminated or is diminished. But the human roles in programming and maintenance are likely to become more significant. In fact, some maintenance operations, as in space travel, may be the primary human interventions--though I believe astronauts have not usually characterized themselves as "maintenance personnel." As a new AAMRL project demonstrates (Mohr, 1986; Julian and Anderson, 198), flight-line maintenance of aircraft is a candidate for robotic automation. The design of applications software--and training to use it--has become a major target of human factors research and applications. Maintenance and programming, along with planning and control operations, constitute interrelated system loops, so to speak, to be improved with help from human factors.

AUTOMATION

Thus heading supplies the second letter in the paper's acronymic title. Innovations in automation impose difficult demands on human factors. From the perspective of either a system or a workplace, what should be the division of labor? What should be automated and what left to some human performance? This is the proverbial allocation-of-tasks-and-functions problem, perhaps better stated as a combination-of-tasks (or subtasks) problem to emphasize what is properly its synergistic or symbiotic nature. It is novel to neither the Air Force nor NASA, as, for example, I found in a NAS-AF summer study for the former in 1981 (Air Force Studies Board, 1982) and a 1984 workshop on teleoperation for the latter. Nor is it novel in other contexts. One outstanding instance is machine translation, heralded in the early 1960s by the youthful artificial intelligentsia as a great advance in automation. When I spent a summer in Vietnam in 1970 for our Department of Defense to try to improve the training of the ROV armed forces, I was assured by our military personnel there that machine translation was about to solve the problem of converting masses of technical documents from English to Vietnamese. Five years later as a consultant to the United Nations I encountered wishful thinking that simultaneous interpretation in the General Assembly and Security Council could be automated in short order. Recently I found that the Pan-American Health Organization was among those finally using machine translation--but with post-editing by a human translator operating a word processor. Why had it taken so long to adopt the symbiotic solution rather than cling to the dichotomous position that humans and automation shouldn't mix?

Such experiences have left a residue of skepticism, modified, to be sure, by the automation that is assisting me in typing this paper. (On occasion I still use my old mechanical typewriter, however, especially during power failures when it's the only contrivance in my company's offices with which to compose some urgent communication.) The dilemma for human factors professionals springs not from any resistance to automation. In a world much of which could hardly exist if the automobile had not replaced the horse, it is essential. Nor is it likely that automation will put us human factors folks out of work; the more complex technology becomes due to automation, the more we seem to be needed. Rather, we don't know what to believe. If prognostications about new automation reflect wishful thinking and hyperbole, the historical record shows that advances in automation will nevertheless occur while the general competence of people remains in a steady state (except for variations due to training). But what, exactly, will be the advances, and how soon? Fortunately, computer scientists and electronic and mechanical engineers are less skeptical; they rush in where angels fear to tread. Unfortunately, they usually disregard the angels--who, of course, are the human factors scientists and engineers.

The division of labor is often determined before a human factors analyst has a chance to propose one. If the opportunity does occur, various guidelines can be invoked, including the relative competencies of automation and personnel, their relative costs, and the

prospects of improved (human-engineered) design, training, and personnel selection as alternatives. A symbiotic strategy may be proposed at least for the interim before new automation is perfected, perhaps with the rationale that the system developer will regress to that strategy in any case as the hyperbole melts in the heat of reality.

In this paper the four kinds of technology discussed have differing distributions of labor. They will be presented in a crude rank order from least to most human involvement. They are robotics, supervisory control, expert systems, and telepresence (which includes telerobotics and teleoperators). Together their initials generate the remaining letters of SARSCEST. At the end of the paper the four will be related to each other.

ROBOTICS

Non-technical observers consider industrial robots as autonomous because the observers rarely if ever see them being maintained or programmed. Nor do they usually see an operator start or stop them, calibrate them, intervene when some tool or workpiece needs adjustment, or change their programs; in any case, compared with closed-loop human control of machines such operations are relatively simple and infrequent. But robotic maintenance, either preventive or remedial, is a fact of life on the factory floor, as might be expected for mechanical, electrical, electronic, and hydraulic machines that incur wear from use and interference from ambient conditions. Such maintenance has human factors interest to the same extent that machines with similar components arouse such interest, except that industrial robots present special hazards due to unexpected movements.

It is the creation and use of application programs that call particularly for human factors investigation and application, as I discovered in a survey I conducted among ten major robot manufacturers for the Army's Human Engineering Laboratory (Parsons and Mavor, 1986). The following is taken from a recent summary (Parsons, 1988a; see also Parsons, 1988b,c) dealing with industrial robots and their programming.

The principal equipment units are a teach pendant (portable control panel) and a computer terminal; for programming continuous paths, as in spray painting, controls are attached to the robot arm or to a surrogate arm. A major design problem has been the division of programming between the pendant and the terminal; the former is carried inside the robot work envelope (bounded by a barrier or fence, with a gate), whereas the latter is usually next to the robot controller housing a microprocessor outside the enclosure. To program with sufficient precision the locations to which the robot's end effector will move automatically in a production run, in some tasks the programmer must go very close to the alignment of the end effector with a workpiece, operating the pendant's controls to move the robot. This requirement for visual discrimination accounts largely for the portable control panel. But many additional steps have to be programmed, such as robot arm speeds, pauses, inputs from and outputs to other equipment, decisions, and

repetitions. The hardware/software designer must choose between adding control and display components to the pendant, thereby increasing its size and weight, and performing additional programming at the terminal--rushing in and out of the work envelope to do so.

Teach Pendant Design

Presumably improving the pendant's design should be a human factors objective. Its controls must be operated quickly and without error, to save production time and forestall errors that might result in accidents or interruptions. Since exclusive space is not available for all the required functions, more than one of these may be assigned to a single control element, with selection by another element. What functions are assigned, and how? How are control elements grouped and coded? Which are better, push buttons or joysticks? What should appear on the LCD display? Might the pendant use a menu system with soft buttons? How should errors be indicated? What warnings are needed? Though the dozens of functions on the pendant make it seem like a simple enough device relative to the much larger number on control and display panels in a nuclear power control room, nevertheless the pendant design is a challenge.

That challenge has been met, according to the survey mentioned, by a great variety of designs. No two pendants are alike. There has been virtually no systematic resort to human factors applications. The same can be said of the associated applications software, as in the names and categorizations of commands, the structures of menus, and error prevention and recovery. Neither the hardware nor software appears to be as user-friendly as it might be. Indeed, as a result of the survey the Robotic Industries Association is attempting to generate an ANSI standard for the human engineering design of teach pendants, though to date this has consisted mostly of copying sections from MIL-STD-1472C.

But are teach pendants really that important for programming industrial robots? What alternatives are there to this use of the robot as its own measurement device, so to speak? If robotic applications programming could be entirely textual, computing positional and rotational information based on data from other sources, there would be no need for pendants. Such sources include machine vision and other sensors, stored geometric and other data (world models) about robots and workplaces (for example, from CAD), and graphical simulation. Indeed, it has been suggested that these will reach a level of precision or flexibility to cope with the variability that occurs even in an engineered environment such as a robot installation. For some installations, involving assembly tasks by small robots, teach pendants seem unnecessary. The basic questions are how reliable other data sources can be made and how much variability and unpredictability will be encountered. These are even more serious in other environments, such as in space and especially in military settings where there may be variability and unpredictability due to an adversary. Such variability and unpredictability range along a continuum. "Structured" and "unstructured" environments are a false dichotomy.

Meanwhile, as other data sources improve for programming industrial robots, one human factors task may be that of helping to fuse data from various sources, including teach pendants--which may function primarily to post-edit the position and orientation commands otherwise derived.

When it is more widely realized that "autonomous" robots must be programmed and maintained--at some cost and by human skills-- there may be less optimism about the tasks they may undertake outside of manufacturing, especially in homes, in service occupations, and in space, and especially for occasional rather than repetitive tasks for which remote or removed human operators or supervisors are available. Again, much will depend on the versatility of the robot and the predictability of the setting.

SUPERVISORY CONTROL

In the present context, the term "supervisory control" labels one solution to the issue of allocating or combining tasks among humans and machines. As we all are aware, supervisory control exists also among humans. If I may be permitted a personal reflection, a single individual can have experienced it as a child supervised by parents (and vice versa), driving a car with back-seat advice (also vice versa), as a student controlled by teachers (again vice versa), as a newspaper reporter subject to the whims of editors, as a ship's commander exerting military control, as an investigator supervising the behavior of white rats, and as a R&D manager trying to control the performance of investigators. The varieties of situations and types of supervision in supervisory control among humans are paralleled in those among humans and machines.

Basically, it seems that the term "supervisory control" in human-machine systems has been introduced to denote one or more humans presumably at a computer linked to one or more computers directly controlling some process or device(s) in real time and acquiring information that is sent to the supervisory controller. Thus, the human role, except for interventions when there's a special problem or crisis, does not include much real-time control--and the term "supervisory control" is something of a misnomer. According to a report of the Committee on Human Factors of the National Academy of Sciences and National Research Council (Sheridan and Hennessy, 1984), "supervisory control behavior is interpreted to apply broadly to vehicle control (aircraft and spacecraft, ships undersea vehicles), continuous process control (oil, chemicals, power generation), and robots and discrete task machines (manufacturing, space, undersea mining)" (p.8), and also (p. 5) command, control and communication systems. I believe the term originated from human factors work on undersea and space teleoperations and on nuclear power plant control rooms. This kind of division of labor has been aimed at helping to helped solve communication and workload problems. For example, supervisory control might cope with the problem of communication lags between NASA ground control and distant teleoperated space vehicles and manipulators. It might ease the complex and time-limited monitoring and remediation operations in nuclear power control rooms.

According to Sheridan and Hennessy (1984, p. 12), "In all forms of supervisory control there is a typical five-step cycle in the human supervisor's behavior: (1) planning, including the setting of subgoals relative to the given task goals, (2) instructing the computer, (3) monitoring its execution of instructions and making minor adjustments, (4) intervening to circumvent the automatic controller as necessary, and (5) learning from the experience in order to plan better." In the proceedings of a symposium on human factors in automated and robotic space systems, Sheridan (1987, p. 286) observed that "The problem of what to control manually and what to have the computer execute by following supervisory instructions is something that cannot be solved in general but probably must be decided in each new context."

Akin, Howard, and Oliveira (1983) distinguished two types of supervisory control: traded and shared. In the former, the human defines a subtask for a computer, which then takes over, the human interrupting at will. In the latter, the human describes goals and manipulates high level information from a world model or textual input, and the on-site computer modifies the human's commands if there are misjudgments or delays, using a more precise world model.

Some lessons from all-human parallels seem pertinent. The human subordinate is often given considerable responsibility and authority so he or she can learn by doing, including mistakes, except perhaps in a real crisis. If the subordinate in human-machine supervisory control is a computer, it too must be adaptable. That means that the subordinate computer must acquire new behavior through feedback from its own performance and built-in learning algorithms or heuristics or by being tutored by the supervisory controller, perhaps through simulation. Another lesson is that supervision may extend through a hierarchy or be exerted by or on multiple individuals. Hierarchical aspects have been noted by the sources already cited, as well as control over multiple subprocesses--limits on human span of control being one reason for computer automation. The third lesson is that the supervisory relationship might in some situations be reversed, with a human at the "subordinate" position exercising considerable choice and a computer at the "supervisory" position developing plans and issuing them without human participation. The tail wags the dog, for example, when to avoid a major, unexpected obstacle the remote driver of a personless vehicle changes a supervisory computer's entire routing-- perhaps an instance of shared control.

"Supervisory control" seems to need more analysis from actual systems and empirical support as to its applicability beyond laboratory studies that launched the concept. Although its descriptions have not given much heed to maintenance and programming, perhaps because of its explicit emphasis on "control," some supervisory control interventions, as in nuclear power incidents, would actually appear to concern maintenance, that is, troubleshooting and remediation. Suggestions that some programming is supervisory control will be noted subsequently.

EXPERT SYSTEMS

An expert system is an artificial intelligence undertaking incorporating an interactive computer program containing expertise for a non-expert end user. Why should such a system involve human factors? First, though it manipulates words (or graphics) instead of sensor inputs and motor outputs, it possesses the same SIPOF structure as other types of systems to which human factors science and practice are applicable (though the F--feedback--is not explicitly considered by AI developers in this venture any more than in others). Second, it has three or more human interfaces, more than enough to justify human factors interventions. Third, it represents, in a way, the apotheosis of symbiosis in computer automation.

Although human factors support apparently was not sought by ES developers initially (and ESs were more processing-oriented than user-oriented, perhaps to their disadvantage), the human factors community has leaped into the act. The Proceedings of the annual meetings of the Human Factors Society had two ES presentations in 1984, three in 1985, eight in 1986, and six in 1987. Of the 19, four discussed human factors in ES in general, 11 were concerned with expert systems in particular contexts--four of these being aircraft and seven troubleshooting and other search tasks, and four described the use of ES as human factors methodology. Among these last, Antonelli (1987) compared an ES with a hard copy user's manual as a job performance aid; Parng and Ellingstad (1987) developed an ES to help design menu systems; Hartley and Rice (1987) developed an ES to help design the screen color of video displays; and Karwowski, Mulholland, and Ward (1986) developed an ES to analyze manual lifting tasks. The aircraft-related ESs were authored by Endsley (1987), Kuperman and Wilson (1986), Aretz et al. (1986), and Ott (1985); two originated in the Armstrong Aerospace Medical Research Laboratory and a third in the Air Force Academy. Of the troubleshooting/search ES talks, two arose from work for NASA at Carlow Associates (Phillips et al., 1986; Eike et al., 1986); two from work for the Electric Power Research Institute (EPRI) at Honeywell (Koch, 1985, 1987); one from Westinghouse (Roth et al., 1985); one from Idaho National Engineering Laboratory (Nelson, 1986); and one from Martin Marietta--Denver (Petersen et al., 1984). The general discussions were by Hamill (1984), Ostberg (1986), Fotta (1986) and Gehlen and Schwartz (1987), this last a study of display formatting. Other examinations of expert systems from a human factors viewpoint have appeared in journals.

AI descriptions of expert systems conventionally specify three parts: knowledge engineering to create a knowledge base, an inference engine to manipulate this, and a user interface. A SIPOF model, followed here, differs somewhat. A system component (S) is where decisions are made as to what domain should be put in an ES or left to other, perhaps non-computer, methods. Another decision is whether the ES should be "autonomous" or advisory; some ESs are the former. The second, input (I) component is knowledge acquisition (facts, relations, well or ill defined, in numeric or symbolic form). It has two parts. One is the expert

source--a human expert providing self-reports through interviews or questionnaires, manuals or other literature, think-through protocols, simulations/scenarios, even experiments--though these are mentioned as rarely in this AI context as in others. The second part is the agent acquiring the knowledge, the knowledge engineer in the conventional ES description. In the third, two-part processing (P) component, the acquired knowledge is first converted (by a knowledge engineer) into a form that can be computer-processed. It is decomposed or structured into rules, frames, scripts, schemas, arrays, property lists, hierarchies, semantic networks, analogical representations, or propositional or predicate calculus-- relational formalisms on which the program in the inference engine can operate; these may be essentially procedural in form ("how" sequences) or situational/declarative, perhaps concerning non-verbal skills. The conversion process must attempt to standardize terms and make them consistent. It may include criteria for the selection of the premises in (production) rules. Confidence/certainty values can be assigned to items as well as importance values. In the second part of processing, the resulting "knowledge base" is further structured and sequenced in the computer program so the program in interaction with a user can produce various relationships, e.g., causal or hierarchical, with combinations of premises and forward or backward sequencing among rules related by sharing premises or conclusions. The fourth (Output--O) component is the interface with the user. It consists of presentations or queries (by computer or user) on a visual display (or perhaps by voice synthesis and recognition), proceeding through the program sequences, culminating with a conclusion or recommendations (advice). This O component also usually includes explanations of the program's reasoning process and conclusions, i.e., rationales. It may note conflicts and trade-offs. Some ESs include lists of references for further information or as evidence. The last (feedback--F) component in an ES, though seldom if ever identified as such, is implied in user queries, user additions to or elaborations of the knowledge base, and subsequent growth of the ES through iterations. In addition, a human factors approach calls for examining interactions between these components and for conducting a systematic ES evaluation.

The three human interfaces are (1) between the source (if a human expert) and the knowledge engineer; (2) between the knowledge engineer and the inference engine; and (3) between the output of the inference engine and the user. Some interfacing occurs also between the inference engine and the user or source expert.

Some Human Factors Considerations

System. As already noted, a determination must be made whether the ES's conclusions will simply inform the user or be advisory-- an allocation matter. Criteria include criticality, frequency, technological capabilities, and pilot acceptance/trust (Endsley, 1987). Should the simpler or more routine tasks receive priority for ES handling, though some may be trivial? The same author said that expert systems are "severely limited in dealing with unforeseen circumstances," another consideration typical of computer-based systems.

Input. How large a domain should be included? It has been generally accepted that expert systems can deal with only limited domains. How complete is the input even within a limited domain? According to Ostberg (1986), an ES is likely to omit tacit or "common sense" knowledge. What types of domains or repertoires are appropriate? What sorts of "thought" can be verbalized reliably or at all by an expert-- though much of the thought may have been originally verbal? Expert systems are inevitably subject to biases, misinformation, inadvertent or deliberate misinterpretations or exaggerations, omissions, rationalizations, dependent as they are on human long-term memories, mismatches in sophistication between expert and knowledge elicitor, and the latter's incentives and disincentives. Conceivably during the current national election campaign each major political party might produce an expert system demonstrating not only that it should win but would win--especially in light of the diversity of views of economists or columnists who might be the "experts." Also possible but perhaps less likely is the exploitation of expert systems by UFOlogists, astrologers, and others victimizing the credulous with occult claims. ES dependence on self-report induces caution in any human factors scientist or engineer, to whom the hazards of this kind of evidence or knowledge are well known. One way around this dilemma is to query more than one expert (Endsley, 1987). But an extensive survey of USAF jet interceptor pilots showed considerable disagreement among them about the procedures they used and how a return-to-base system should be designed (Parsons and Karroll, 1954). Should expert views be determined by majority vote? Much work apparently remains to be done to assure suitable and reliable input to ESs.

Processing. In the initial processing by a "knowledge engineer" there lie further hazards. That individual may have many options concerning the techniques to invoke, formalisms to use, terms to select, and confidence or importance values to attach. According to Ostberg (1986), knowledge engineers constitute a "priesthood" or can be viewed as "artists" with unsupported pretensions. Though they are analogous to work-study engineers or human factors engineers conducting task analyses, it is not clear what formal training they receive or should receive. How well can they orient to the needs of users as well as experts, especially if their cognitive styles differ? Categorization differs widely among individuals, as do direction of inference (data-driven or hypothesis-driven) and goals or incentives/disincentives.

In the processing in the ES computer program there may lie a mismatch between what the user is accustomed to do in his or her head and what the program does. If the user insists on knowing what the program has been doing, as astronauts and pilots, for example, may well do, the user may have difficulty in understanding or may not accept the conclusion or recommendation. Logic manipulations may perplex. Just because they are symbolic does not make them so different from perceptual-motor performance which, for example, requires designs that conform to group stereotypes. Mental (verbal, in-the-head) models vary among individuals as do perceptual-motor models. Users can misinfer, much as an operator may move a

control element in the wrong direction because the designer has designed it without due regard to the operator's habitual performance. As already indicated, mental models may vary in the direction of inference, data-driven forward chaining or hypothesis-driven backward chaining--which are alternatives for inference engines.

Output. According to Ostberg (1986), the user interface accounts for almost one-half of ES programming but has often been poorly done. Perhaps the first matter to consider is a user's goals, which Pew (1988) has emphasized. Since the user wants to put the output to some end, what kinds of purposes exist? Expert systems are aimed at decision-aiding and problem-solving of various kinds, predictions as well as comprehension. They are intended to do what the non-expert cannot do, or do well, and should be tailored to the user's goals, not what a program can accomplish. They should also be tailored to users' levels of expertise, which will vary among them. Aretz et al. (1986) advocated designing-in three levels, Parng et al. (1987) six. So the knowledge engineer or the computer program must be flexible and function as a kind of translator between the expert and the user. When an ES is used for human factors purposes, these as we have seen can include trouble-shooting, replacement of TPAs, design of hardware or software, personnel selection, and training (as in coaching new technicians). These objectives may call for different interface aspects. A major output consideration is the kind of language that is desirable. Although this has been described as "natural," that term calls for better definition; everyday spoken language not only differs from the written but is likely to vary widely in syntax or a lack thereof. Some restrictions seem inevitable to avoid confusion, since users will have their own vocabularies and usages. That fundamental human proclivity, generalization, is a major problem (as well as an advantage) in symbolic communication, though it has not always been recognized as such under this label. (Concepts, heuristics, and synonyms are examples of generalization, and fuzzy set theory has tried to cope with it in a limited fashion.) Along this line, Pew (1988) has noted the variations in users' abstraction levels. Because some ES output may be difficult to convey in symbolic form, it may be advisable to use graphic representations.

A major aspect of ES output is the capability it includes for explaining to the user how or why it reached some conclusion or recommendation. As Pew (1988) and others have noted, apparently it is not sufficient simply to list the rules the inference engine used or to convert these into text. Citing other sources, Eike et al. (1986) listed five criteria for an explanation facility in an ES. For example, an ES "should be able to alert the user when a problem is beyond its current capabilities and instruct the user as to what additional factors and/or rules would be required to complete the transaction." Further, "the explanation facility should be capable of recalling each invoked rule and associating it with a specific event to explain the rationale for the machine's assessment of the event."

Feedback. Despite the rarity of specific mention in the AI literature, some feedback does occur in the use of expert systems. For example, a user's queries about methods the ES employed, requests for justification, and meaning of questions the program asked (Phillips et al., 1986) can be regarded as kinds of feedback to the ES. Still another variety would be program or knowledge base updating or alteration requested by the user. Perhaps the most significant feedback is rejection of the expert system by intended users. Such may occur because they find it too difficult, they get lost, or they lose confidence in it. Or the system, especially if the user must query it for information or explanation, increases rather than diminishes the workload--an especially sensitive matter for military pilots. In short, due to the consequences of using an ES, an individual avoids doing so, in what would technically be called avoidance conditioning.

Evaluation

The need for evaluating expert systems before their use seems self-evident but has not always been satisfied; in fact, evaluation appears to have occurred mostly in the course of their use, on occasion with poor results. But Kuperman and Wilson (1986) have described a research facility to include ES assessment at AAMRL. Aretz et al. (1986), Nelson (1986) and Koch (1987) have reported experimental evaluations. Ott (1985) listed ES programs within the Department of Defense and NASA. Though he did not include individual assessments--which may not have been available, he did contrast current and desired/required capabilities of "intelligent aiding in the cockpit" and concluded that "significant additional progress must be made before an AI system can be used in a combat airborne application."

TELEPRESENCE

By and large, manipulators and vehicles are remotely operated (or maintained) by humans (1) when it would be too hazardous or, possibly, too arduous, for a human to be in the same place or (2) the nature of the task (e.g., non-repetitive or too unpredictable) argues against using an autonomous robot in view of the robot's total cost (including programming) and lower level of adaptability. But like human activities in general, remote manipulation and locomotion depend on sensory feedback to the human operator. How much and of what kind are important and interesting human factors issues.

The increasing use of teleoperators has given prominence to information feedback's significance in human performance (Smith and Smith, 1985). In general, people are not nearly as aware of the feedback they receive, as feedback, as they are of sensory inputs that do not seem contingent on what they do. There seem to be some kinds of information feedback of which we are especially unaware, perhaps because we cannot see the receptors. These are feedbacks from movements and positions of parts of our body to kinesthetic or proprioceptive receptors conveying information about movement and positions in space. Unlike vision and audition, kinesthetic/proprioceptive feedback is difficult to isolate and manipulate experimentally, so it has been studied less than these other

senses in investigations of human performance. Delayed feedback in audition in the past has dramatized feedback's role in audition, and delayed feedback in teleoperation has more recently emphasized its significance in kinesthesis/proprioception.

To some this is a welcome development. Feedback in general has received short shrift in cognitive psychology, notably the kinesthetic/proprioceptive variety, which occurs outside the cranium and seems foreign to self-report. But teleoperations' dependence on feedback through a number of sensory modalities forces a more comprehensive understanding of our behavior.

If I were compelled to select an alternative term for teleoperations or telerobotics, I might choose telefeedback. But I have been preempted by the choice of "telepresence," and I'm sufficiently grateful for any label that emphasizes in any way the need for examining sensory feedback that I won't quibble.

"Telepresence" calls attention also to the significance of generalization, another piece of behavioral bedrock (Shepard, 1987). Essentially, telepresence means the generalization of sensory inputs from those that would occur if an operator were at the remote manipulator or vehicle to those where the operator is actually present. The aim is to enhance such generalization-- which also has been called transfer, stimulus equivalence, and metaphor. Generalization, whether of input or output (acts), has likewise received relatively short shrift in cognitive psychology, perhaps because of its behaviorist forebears. However, it is the behavioral basis of such concepts as fidelity, validity, realism, and verisimilitude in simulation for training or experimentation and also in the super-simulation known as "virtual" imagery or proprioception and "artificial reality."

Telepresence, then, is linked to such concepts through generalization, as it is to empathy and deja vu. By increasing the fidelity and number of sensory channels, combining vision and proprioception and audition, it has effects on its audience--the teleoperation operators--not unlike what happened when color and sound were introduced into black and white and silent movies, television proved more appealing than radio, and, perhaps, video-conferencing has supplanted telephonic conference calls. Artists, novelists, poets, dramatists all have tried at times to make readers, viewers, or listeners feel they were in the situation depicted in words, music, or pictures, that is, to react in some fashion as though they were there.

Sense of Presence

But what is that reaction? It has been called "a sense of presence," an awareness, a perception, a "sense of being there." But physiologists would disclaim the existence of any sensory receptors that could be readily identified with these terms. Is "telepresence" poetry or is it science? Sheridan (1987) said that telepresence itself is not the goal of "telepresence"--it is really performance. But, he added, we should develop a cognitive theory of presence. He further (p. 279) discussed the "ideal" of sensing and communicating to a remote operator "in a sufficiently

natural way that she feels herself to be physically present at the remote site," and more restrictively, a teleoperator's dexterity matching a bare-handed operator's. Akin, Howard, and Oliveira (1983, p.35) equated telepresence with teleoperation that "makes the operator feel natural." Stark (1987, p. 298) said one should "provide the human operator with a telepresence feeling that he is actually in the remote site and controls the telemanipulator directly." The glossary in Autonomy and the Human Element in Space (1985), the final report of the 1983 NASA/ASEE Summer Faculty Workshop, gives the most comprehensive definition of telepresence: "Teleoperation with maximum sensory feedback to the operator, providing a feeling of 'being there' thus allowing greater precision and reliability in performance; remote presence."

The issue is whether better performance results from the feeling or performance and reported subjective reactions are merely correlated. Some justifications of telepresence seem to disregard performance, at least directly. The Soviets designed their cosmonauts' environments in part to resemble their home settings, so they would feel at home (Wise, 1988). As I suggested at the start of this paper, there's more to be investigated in human factors than simply work performance. In any case, the construct "telepresence" might benefit from experimental analysis and objective (or even subjective) measurement. For example, operators might be stationed at both the control and remote sites and their performances, feedbacks, and reported feelings recorded and compared.

If telepresence (as defined) is important, might it be augmented beyond three-dimensional CCTV, pressure or force sensing that mimics what is encountered by a teleoperator's hand in pushing or grasping or twisting, and beyond feedback from head and eye movements and gestures? What about feedback from facial and jaw tensions or movements and the musculature of the vocal apparatus? What about walking, stooping, climbing, and kneeling--or lying down, for that matter, asleep or awake? What about telepresence for locomotion? The term has been directed primarily at remote manipulation, but teleoperators can also be vehicular (perhaps carrying a manipulator, or only sensors, or nothing--e.g., for deception). Legged vehicles offer an obvious challenge to telepresence, especially since they have more legs than the human operator's. A wheeled or tracked vehicle is even more of a challenge, unless some cognitive link is inferred through the operator's familiarity with automobiles. If so, should the operator's controls resemble the steering wheel and pedals of his auto?

To what extent should there be concern about divergences between the teleoperator and individuals controlling it-- individuals who differ among themselves? Might divergences in forces exerted differ in scale--as they often do with teleoperators--thus improving performance but reducing the resemblance? How might reduced gravity or other divergent ambient effects be handled? What about rotational differences in joints, as well as differences in joint types, e.g., prismatic joints in telerobots that humans lack? To what extent should reactions be elicited from an operator such as he or she would experience if present at the teleoperator, such as anxieties, stress, fatigue,

excitement, even pleasure, so the operator will really feel as the operator would if he or she were there?

Performance

Though this discussion of telepresence has centered on subjective reactions in remote control, most human factors research and development in teleoperations has emphasized performance, whatever the label. Indeed, neither the Department of Energy nor the Department of the Army has been using the term "telepresence." The former has active human factors involvements in teleoperation research and development at Oak Ridge National Laboratory and at Sandia National Laboratory, the latter at its Human Engineering Laboratory at the Aberdeen Proving Ground (and elsewhere, including some work for it both at Oak Ridge and Sandia). The Navy's human factors work in teleoperations has been concentrated largely at the Naval Ocean Systems Center, Hawaii. NASA has for some time supported human factors in teleoperations (especially at the Jet Propulsion Laboratory and Ames Research Center), as have the Electric Power Research Institute, Woods Hole Oceanographic Institution, various universities, notably M.I.T., and several corporations, such as Martin Marietta, Lockheed, Grumman, ARD, and Essex.

To describe the work already done in these locations and continuing there would overextend the reach of this paper. It is fitting, however, to mention some recent projects. For example, Sandia has been developing the control station for the Army's TMAP (Teleoperated Mobile Antiarmor Platform) Project. Miller (1987) has reported a Sandia pilot study in which actual (interactive) and video-taped (simulated) remote driving were compared for search, detection, and clearance judgments of obstacles; the aim was to find out whether the video-taped technique could be used for more economical and better-controlled studies of variables in remote control of vehicles, such as TMAP, in difficult, off-road terrain. Sandia is interested in color vs. black-and-white video for viewing such terrain, field of view with panning vs. multiple cameras for local area navigation and turns, camera placement and steering coupling, and resolution effects. McGovern (1988) has described problems encountered in testing some of Sandia's fleet of seven remotely or directly controlled vehicles. These problems have included accidents due to tilt and roll, non-avoidance of "negative" obstacles (e.g., holes), over-control in steering, television minification vs. magnification, and recognition of spatial landmarks.

According to Spain (1987), NOSC has developed six remote-driving courses with traffic cones to investigate different aspects of low-speed maneuverability under four conditions: direct (on-board) driver viewing, partially masked direct viewing, on-board viewing through stereo TV with the same field of view, and remote stereo TV viewing. NOSC is examining remote control of the Marine Corps TOV (TeleOperated Vehicle) using an Army HMMWV (High Mobility Multipurpose Vehicle). It plans to study two new stereo TV display systems. In one, the right eye sees a full 60 by 45 degrees view while the left sees a higher-resolution central area of 20 by 15 degrees. The other has a retroreflective screen and beam splitter to provide a

wide field of view. In a review of past, current, and future NOSC work, Hightower, Smith, and Wiker (1986) described a "hybrid" stereo display system in which one eye can get a high resolution black-and-white image and the other eye one in color. According to these authors, "NOSC has joined in a cooperative research and development effort with NASA to develop principles for design and construction of tactile display systems." One project involves a computer-graphics (virtual) arm.

At NASA's Ames Research Center, "an interactive virtual environment display system controlled by operator position, voice and gesture" has been developed in the Aerospace Human Factors Research Division (Fisher et al., 1987). It incorporates a wide-angle helmet-mounted stereo display that tracks head movement, lightweight glove-like devices that transmit finger shapes and hand and arm positions and orientations (gestures), connected speech recognition and synthesis in 3D, and 3D-graphic virtual objects with an articulated hand. Fisher (1986) has described the glove-like device ("DataGlove") in detail. A number of other simulated hands have been developed recently (Leifer, 1987; Thiele, 1987; and others).

My own organization, Essex Corporation, has done extensive human factors investigations in teleoperations for NASA at Marshall Space Flight Center and more recently for the Army's Human Engineering Laboratory. Currently we are helping H.E.L. develop a robotics laboratory as part of its Soldier-Robot Interface Program. Our responsibility is the human interface portion with associated software and equipment in a versatile control center; other organizations are providing the vehicle, a manipulator and sensors on the vehicle, and the software with which ours will interface through a fiber optics link. This facility will enable H.E.L. to experiment with different configurations and components of display and control equipment in a range of variables, such as 3D television and various types of controls. The control center will have both an operator station and an experimenter's station for both test direction and data collection, the former accomodating two operators so various dual control procedures can be investigated. Perhaps the most challenging aspect of this project is that it includes the control of both a vehicle and a manipulator, as well as sensors for each. For the most part, other human factors projects have concentrated on either the manipulator or the vehicle, with sensors for one or the other.

At an International Symposium on Teleoperation and Control just concluded at the University of Bristol, England, papers were given by A.K. Bejczy and B. Hannaford (JPL) on "Man-Machine Interaction in Space Telerobotics," R.L. Pepper (NOSC) on "Telepresence and Performance Assessment," C. Blais and R. Lyons (General Dynamics) on "Telepresence: Enough Is Enough," J.V. Draper et al. (ORNL) on "High Definition Television: Evaluation for Remote Task Performance," B.K. Lindauer and C.S. Hartley (Martin Marietta) on "Evolving Strategies for Supervised Autonomous Control," and a number of Europeans as well as several Americans who were referenced earlier and H.B. Meieran, who discussed teleoperations at the Chernoble power site.

RELATIONSHIPS

To my knowledge, R, SC, ES, and T have not all been compared in any systematic analysis. What follows are some illustrations of how they relate to each other.

Robotics and Supervisory Control

When used with remote manipulators or person-less vehicles, supervisory control occupies a position on the automation continuum between autonomous robots and telepresence (teleoperators). The actual control of the manipulator or vehicle resides in a co-located computer, as would be the case with an industrial robot, but a human can intervene and take over control, as in the case of a teleoperator. However, the human must generally intervene by means of another computer at the supervisory location.

Supervisory control can occur in a factory where a supervisor with a computer, or a computer with a supervisor, manages some number of devices, including robots, through their computers, in an automation network. In this situation, supervisory control primarily plans and schedules operations. Presumably its interventions consists mostly of starting, stopping, and interconnecting the robots and other devices in the network.

Most autonomous, factory robots are still teach-programmed, that is, a technician or engineer programs the robot's motions and other actions with a teach pendant or teaching arm or arm attachment. Akin, Howard, and Oliveira (1983, p. 58) described this sort of teach programming as a kind of "traded" supervisory control of an underwater manipulator, though without referencing its use for industrial robots. Sheridan (1987, p. 285) seemed to suggest something similar for trajectory programming as supervisory control.

Graphics simulation may be used in both robotics and supervisory control, though for somewhat different purposes. In robotics it can be exploited for off-line programming. In supervisory control it can forecast motions of a vehicle or manipulator, an especially useful technique when time delays occur in feedback messages.

Robotics and Expert Systems

In teach-programming an industrial robot, the programmer may be the same individual who originally performed a similar task before the robot was installed. Such is particularly likely in the teach-programming of trajectory or continuous robot movements, as in spray painting, in contrast to single or discrete positionings and orientations. Considerable skill is required and the extended movements of the teaching arm or of a robot with a teaching attachment may have to be repeated a number of times before the proper path can be recorded. In a sense, the programmer is an "expert" from pre-robotic experience with the same kind of task.

Akin, Howard, and Oliveira (1983) have likened the rules found in an ES to the "equations of motion of the manipulator arm and its interaction with the environment," apparently referring to the forward and inverse kinematics in the program controlling the arm's movements.

Both autonomous robots and expert systems are limited in their abilities to cope with circumstances unforeseen by their programmers. They cannot easily adapt to the unexpected, though the robot may have an advantage due to its sensors. The robot depends otherwise on data in a "world model" of itself and its setting and on data from teach programming. The expert system depends on what has been placed in its "knowledge base," containing data from an expert as teacher combined with actions by a knowledge engineer. Each might be quite helpless if faced by a clever adversary.

The robot is more similar to a human, with simulations of at least one jointed arm, a torso, and various sensors, including vision. The expert system is entirely cerebral and verbal, with symbols for input and output. On the other hand, the ES includes several significant human interfaces, not including maintenance, and the robot essentially only the applications programming interface, again not including maintenance. More human-machine symbiosis occurs in the expert system.

Robotics and Telepresence

These are at opposite ends of the automation continuum in this paper. But they have a greater affinity than is usually recognized. The operations for programming a robot with a teach pendant resemble those for controlling a teleoperator. According to Mitchell (1987, p. 108), one way to train a robot "might be to use a teleoperator to guide the robot through several uses of the tool," which would be the equivalent of teach programming (though the author does not reference this). Though most teach pendants have push buttons for rotating or extending the links in the manipulator's arm, and a teleoperator's links are more likely to be actuated by a joystick, at least one major robot manufacturer uses a joystick, and a teleoperator could be controlled by push buttons. Resolved motion (in which joints move together to create a direct path to a point) occurs in both teleoperator control and robot teach programming.

The design of the workplace and of objects to be manipulated or avoided needs to be enhanced for both autonomous robots and teleoperators, whether stationary or mobile. Such enhancement can benefit the robot's programmer and the teleoperator's operator by making their tasks less complex.

Both robots and telepresence systems require sensors, especially vision. Robots use machine vision. Teleoperators use human vision. But both rely on closed circuit television as the intermediary. (Neither is as good as direct human vision.) Little heed has been given, it appears, to combining televised machine vision with televised human vision for either robots or teleoperation, a potential innovation in symbiosis. Some of this already occurs, in a limited fashion, when programmers create templates for machine vision (using the templates already in their heads) in

exploitng the human's superior pattern recognition. It has been suggested (Parsons and Mavor, 1986) that the same television apparatus for machine vision might be used in teach-programming a robot to relieve the programmer of the need to get close to the end effector with the teach pendant.

Supervisory Control and Expert Systems

An expert system might be regarded as a form of supervisory control. Or an expert system might be designed for the human supervisor's computer to aid in problem solving and decisions.

Expert systems are envisioned that can operate in real time, as, for example, in aircraft piloting, but most are not time constrained. Supervisory control may function in real time, in partially real time (when there's a communications delay, for example), and for some tasks, e.g., planning, without time constraints.

Supervisory Control and Telepresence

To the extent that "presence" rather than performance is emphasized in telepresence, telepresence may not be needed for supervisory control, or at least needed much less than for direct control. Except during interventions, the supervisory controller is not receiving visual or kinesthetic/proprioceptive feedback from control actions. One issue is whether nonfeedback visual monitoring would benefit from a "sense of presence."

One reason for having supervisory control is to be able to manage multiple manipulators or, even more, multiple vehicles. Providing a "sense of presence" derived from each of a number of locations and vehicles might be too confusing both for intervention feedback and for monitoring. This could be an interesting empirical problem to investigate.

With regard to the performance aspects of telepresence, it can be repeated that supervisory control resides between telepresence and robots on this paper's automation continuum. One purpose of supervisory control is to diminish an operator's workload by assigning most of teleoperations' control functions to a computer co-located with the manipulator or vehicle.

Expert Systems and Telepresence

One way in which these differ is with respect to the "sense of presence" aspect of telepresence. Because the expert system has no sensors or limbs, it gets no feedback except from its user, verbally. Any non-feedback "presence" would have to be expressed symbolically or in graphics, and kinesthetic feedback would be difficult to put into words. Much of the "reality" of the scene might be missing.

In terms of performance, an expert system and telepresence have some resemblance in that the user of each must progress from point to point, symbolically in one, by vehicle or manually in the other. This analogy is apt, however, only for forward, data-driven chaining in the expert system (except, perhaps, for a vehicle's return journey from the objective).

Expert systems and telepresence's "sense of presence" aspect share the need for a greater amount of evaluation. The performance aspects of both hold great interest for human factors in view of the extensive symbiosis and complex human interfaces in each.

Further Comparisons

R, SC, ES and T might be further compared with respect to the list of items in Figure 1, specifying human factors involvements in these four automation-related processes; the extent of involvement for each listed item for each of the four processes can be filled in for the particular system examined. In addition, each of the processes can be examined with respect to the components of the SIPOV model. For "system" that means task allocation/combination; for "input," symbolic or imagerial (graphic) in form; for "processing," control, maintenance, or programming; for "output," symbolic, imagerial, or motor; and for "feedback," informational or motivational.

This last category, motivational feedback, refers to the incentives and disincentives that influence so much of our performance, though they have not been emphasized in human factors R&D or in this paper. Motivational and informational feedback may share the same feedback events but are functionally distinct. A major incentive (prospective consequence) or positive reinforcer (past consequence) is money. Cost/benefit ratios affect whether managers or investors will adopt any of the four processes discussed. Disincentives or deterrents include difficulty, excessive mental workload, errors, and other unfriendly consequences (stressors) that end users experience with a process, inducing them to avoid or cease using it. These motivational feedback variables are pertinent to robotics, supervisory control, expert systems, and telepresence--that is, to all of SARSCEST.

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Figure 1. Human factors involvements in robotics, supervisory control, expert systems, and telepresence.

HUMAN FACTORS INVOLVEMENTS

TASK ANALYSIS

TASK ALLOCATION

INTERFACE DESIGN, HARDWARE

INTERFACE DESIGN, SOFTWARE

TEST/EVALUATION

SAFETY

JOB PERFORMANCE AIDS

TRAINING

PERSONNEL REQUIREMENTS

TEAMS

COMMUNICATIONS

SURVEY/SELF-REPORT

EXPERIMENTATION

PLANNING/GOAL SETTING

DECISION-MAKING

REAL-TIME CONTROL

MAINTENANCE

APPLICATIONS PROGRAMMING

FEEDBACK

PRESENCE

GENERALIZATION

WORKLOAD

TASK COMPLEXITY

TASK PREDICTABILITY