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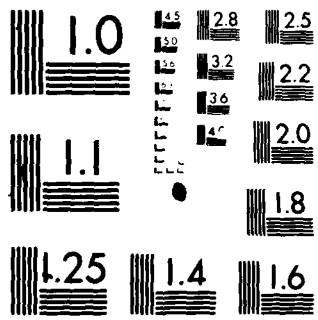

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Human Factors and Robotics: Current Status and Future Prospects

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The purpose of this article is to introduce the human factors community to the field of robotics including current and future applications and needed areas of research.

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PREFATORY NOTE

Under a contract from the U.S. Army Human Engineering Laboratory, HumRRO scientists H. McIlvaine Parsons and Greg P. Kearsley reviewed near-term and potential involvements of human factors engineering in the planning, design, and use of robots in industrial and military applications. That research effort produced a report entitled *Human Factors Engineering Considerations for the Planning, Design, and Use of Robots*, July 1981.

This HumRRO Professional Paper, which summarizes the project findings and conclusions, was prepared to make the information more widely available than would be possible through the report alone. Support for its preparation was provided by Dr. John D. Weisz, Director of the U.S. Army Human Engineering Laboratory, and Dr. Benjamin E. Cummings, the Laboratory's technical monitor for this HumRRO project.

HUMAN FACTORS AND ROBOTICS: CURRENT STATUS AND FUTURE PROSPECTS

H. McIlvaine Parsons
and
Greg P. Kearsley

INTRODUCTION

The purpose of this article is to introduce the human factors community to the field of robotics including current and future applications and needed areas of research. It also aims to explain to the robotics community why human factors engineering is important to this field. We hope to encourage human factors professionals to participate in a significant new domain of technology that needs their involvement.

We will discuss relationships between robots and people. Generally, such discussions dwell on the organizational and societal impacts of robots. These are truly important themes, appropriately addressed within the total human factors domain. They are not our concern here. Rather, the relationships we review are limited to workplaces and performance there. Such workplaces include industrial, commercial, and military settings. How can person-machine interfaces and interactions in these be arranged so the joint activities of robots and people are as effective as possible? This objective is recognizable as the essence of human factors engineering, though for some it may be obscured by more volatile issues more likely to intrigue the lay public.

Up to the present time, the human factors community has been little involved in robotics, although some exceptions will be described later in this article. There have been a number of reasons for this lack of attention. Most robot applications at present and in the near future are in the domain of manufacturing, an area in which few human factors scientists have worked extensively. Further, much of the basic research in robotics has come from the field of artificial intelligence, another domain in which few human factors researchers have been significantly involved. Perhaps the most important reason is that until recently there were only a handful of actual robot installations to present problems or issues to study.

Popular histories of robots can be found in Malone (1978) and Reichardt (1978). It is currently estimated there are about 10,000 industrial robots in use in the world, the majority in the U.S. and Japan, though European nations have been advancing rapidly. Due to sagging productivity in many nations during the past few years, interest has increased greatly in industrial automation, with a resulting boom in robot applications. Advances in the electronics industry, especially LSI circuits, are leading to robots that are compact, powerful, and affordable.

From our viewpoint, the principal human factors engineering issue in robotics is the division of labor between automation (robots) and human beings (participation in the same overall enterprise). There exists little possibility that people will be entirely excluded. This issue reflects what has always been a prime human factors engineering consideration in system design—what equipment should do and what operators and maintainers should do. To which should functions, tasks, and task elements be allocated? How should machine and human be combined?

If we must examine primarily how the performances of robots and people are or should be interrelated, we must try to understand the *capabilities and limitations of each.* The first part of the article will describe robots—their niche in automation, their functional capabilities, their applications, criteria for their use, and prospects for the future. The second part will examine human factors engineering issues, related investigations already undertaken, and potentials for human factors engineering applications and research in robotics.

ROBOTS

Niche In Automation

Preceding the development of robots in industry was that of numerical control (NC), and subsequently DNC (direct numerical control) and CNC (computer numerical control), for automatic control of machine tools. The machine tool is controlled for a specific operation, perhaps by a punched paper tape programmed by first guiding the machine tool manually through its required sequence. For other manufacturing purposes, there exist somewhat analogous dedicated machines, "hard automation," or "special purpose" automation. As Engelberger (1980) has pointed out, "there are machines that make bottles and other machines that fill and cap these bottles. There are machines that automatically manufacture our light bulbs." There exist many kinds of mechanical transfer devices, including conveyors such as belts, rollers, and overhead devices, and mechanical loaders and unloaders, stacking machinery, and special-purpose parts handlers.

Automation of equipment/product design and manufacturing management (CAD-CAM) can be regarded as a *context* into which robots can readily fit. Computer-assisted design can be coordinated with the software that necessarily accompanies true robots. Computer-assisted management can support robotics through "*rationalization" of the factory to* standardize inputs to robots and can benefit from robots that record and report what they do, such as number of items processed and number and types of rejects in inspection, for management information and decision-making.

Teleoperators (also called telecherics or remote manipulators) possess the mechanical manipulation or locomotion function of a robot and also visual sensing but these are remotely controlled and responded to by a human operator. Teleoperators are not typically classified as robots. Distinctions between classes of automation are based on the degree of autonomy each has and the generality of its capabilities; autonomy and generality depend in turn on the versatility and flexibility of the control function—the programming of a computer that constitutes the robot's "brain." Many factors affect the desired degree of autonomy and generality.

The presence or absence of servo-control constitutes another aspect of machine autonomy. Servo-control in a robot requires some sensing device that will cause a change in its performance through feedback. Some mechanisms are called robots though they lack servo-control; they are programmed but they operate in an open-loop mode. Many are relatively simple "pick and place" machines which have mechanical arms and hands for transferring workpieces, and may be reprogrammable. Japan's definition of these as robots has helped account for its large robot population.

Functional Capabilities

Robot capabilities can be described in terms of four major functional categories: manipulation, locomotion, sensing, and executive (control/communication). Figure 1 (on the following page) illustrates these. The boxed entries represent capabilities

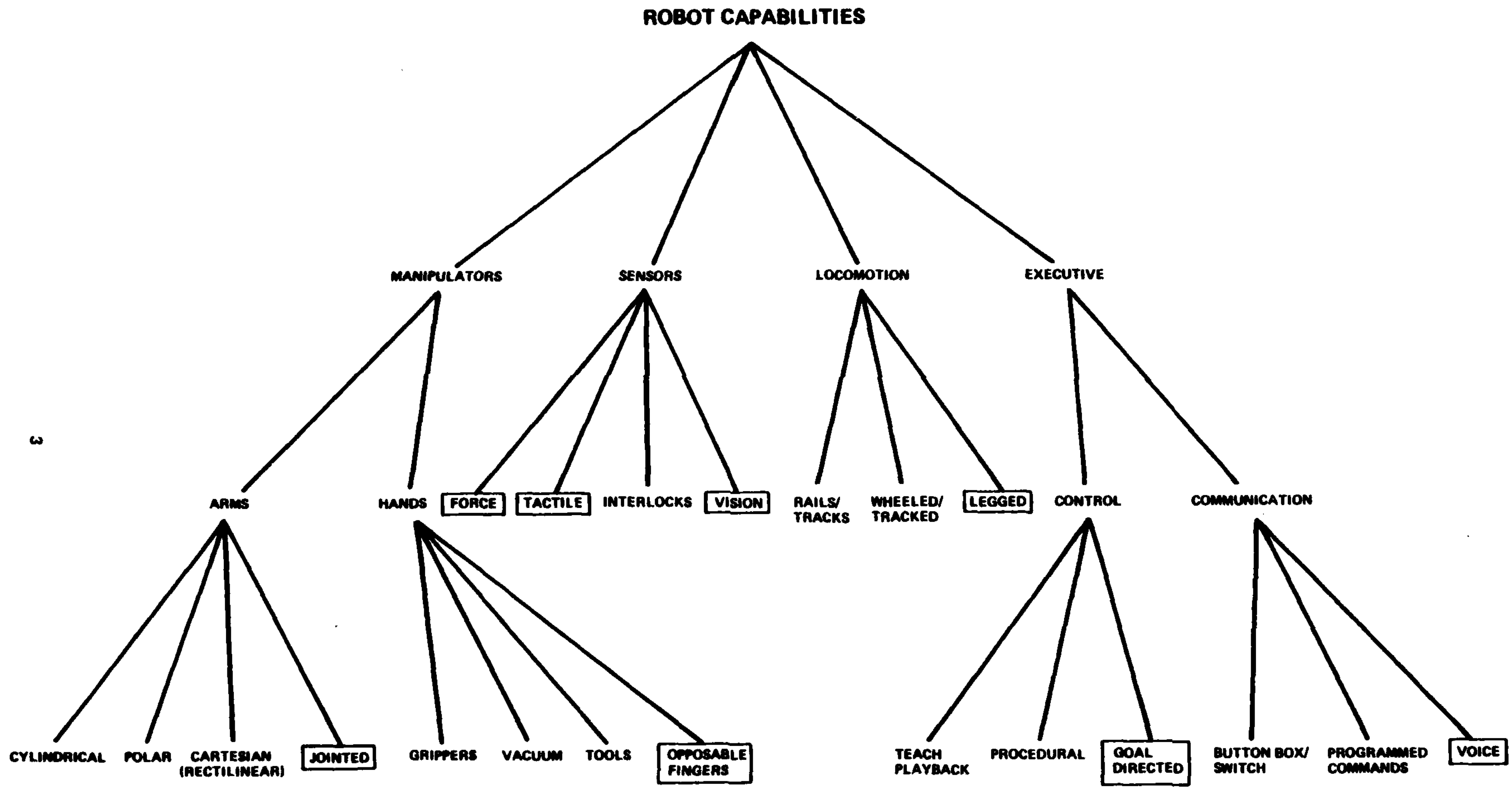

FIGURE 1: MAJOR ROBOT CAPABILITIES

which are the subject of current research rather than completely operational in industrial applications.

The sensing capabilities of current robots are relatively undeveloped. At present, most sensing functions are carried out by a diverse range of interlocks (e.g., microswitches, gates, photoelectric or infrared detectors, etc.) which initiate a robot action or prevent any dangerious action from occurring. For example, a conveyor belt which supplies or removes parts for a robot may not start up until the robot is currently positioned, or the jaws of a metal press will not close until the robot has removed its hand.

Three sensing capabilities are currently in different stages of development: force, tactile and vision. Work is underway at General Motors and the Jet Propulsion Laboratory on force sensors that can detect torque, touch and slippage. These force-sensing capabilities are essential for a robot arm to determine that it has made contact with a part or a machine, to determine that two parts are correctly aligned, and to determine that it has a good grip on something being grasped. Tactile sensors are needed to provide similar kinds of information, although contact sensors (such as a "skin" being developed at Massachusetts Institute of Technology) can also provide information about the shape and orientation of an object being touched or grasped.

Vision capability is considered essential in order for robots to accomplish inspection, positioning, and monitoring tasks. A number of vision systems are actually in use in industrial settings. For example, the AutoPlace Opto-Sense System has been used by Chesebrough-Pond's to inspect medical thermometers and by Bulova Watch's Systems and Instruments Division to set timers on military explosives. General Motors has developed a vision system called Consight, and Machine Intelligence Corporation has a similar vision system, both designed to pick up specified parts from a conveyor. However, none of these currently available vision systems is sophisticated enough to do complex recognition tasks in real time.

The area of manipulators and end effectors probably represents the most developed capabilities of current robots. There are a number of different types of arm movement available from different robot manufacturers. The differences in movement are primarily due to the kind of geometry involved: cylindrical, cartesian (rectilinear) or polar coordinates. While each of these movement geometries can usually produce the same end result, some geometries are better suited to particular applications. The type of arm structure which is currently the subject of research is a jointed arm which would be much lighter and more agile than present arms, but just as powerful.

A diverse range of "hands" has been developed to meet the needs of different applications (see Engelberger, 1980). A common category of hands consists of different types of grippers designed for transferring particular types of parts or for certain kinds of grasping situations. In another common category of hands, vacuum cups primarily pick up flat or delicate parts. One of the most common categories of hands consists of special-purpose tools such as heating or welding torches, spray guns, grinders, impact wrenches, etc. Hands currently undergoing development have opposable fingers which would provide the kind of flexibility and universality of the human hand. Alternatively, dedicated or "modular" robots are combinations of small devices on metal mounts on a workstation for particular pick-and-place operations.

Control capabilities involve the overall integration and coordination of a robot's actions, as well as learning how to perform those actions. Two major types of control are possible with current robots: point-to-point and continuous. With point-to-point control, the robot can be programmed to stop at many specified points, but the movement is not controlled between these points. On the other hand, a continuous path robot can follow an irregular path exactly. Point-to-point robots are typically more accurate in their positioning.

There are three major ways to program robots at present. In the teach and playback approach, an operator specifies the desired positions by means of a teach box or by actually putting the arm through the desired action (called a walk-through). In both these cases, the robot simply records the points or path and repeats it on cue. Alternatively, it is possible to specify the desired actions of the robot procedurally in the form of a computer program. A number of programming languages such as VAL (Shimano, 1979), AL (Finkel, Taylor, Bolles, Paul & Feldman, 1975), TEACH (Ruoff, 1979), Autopass (Lieberman & Wesley, 1977), and LAMA (Lozano-Perez, 1976) have been developed and are in use in industrial applications or research projects. Higher-level software, which allows goal-directed programming where the operator has only to specify the end result desired rather than the entire sequence of operations, has been under development in the artificial intelligence field for some time (e.g., Fikes, Hart & Nilsson, 1972). However, development of such higher-level languages requires a considerable understanding of decision-making, planning, and modeling processes, still emerging at this time.

Communication capabilities encompass the nature of all interactions between an operator and a robot. The simplest form of interaction is when a button box or switches are used to control or instruct the robot, and lights or alarms indicate states. A more sophisticated level of communication exists when human-robot dialog proceeds via a command language which is displayed at a terminal. This obviously allows a much greater range of possible interactions than with the fixed set of alternatives possible with switches and lights/alarms.

On the other hand, voice input and output offer the greatest flexibility in human-robot interaction, since these allow the operator and machine to communicate from different locations and in circumstances where the operator needs hands and eyes for the task. Considerable research has been conducted in speech recognition and synthesis (e.g., Reddy, 1975) and many limited-capability systems are already in use in industrial applications (e.g., Martin, 1977). Voice input/output may become the major mode of robot-human communication in the future.

The last category of capabilities shown in Figure 1 is locomotion. The simplest form is to have robots mounted on rails or overhead tracks so that they can move along with a part on a conveyor line or move to another work station. This kind of locomotion is already used in a number of industrial applications. Research has been conducted on various kinds of wheeled and tracked robots, particularly in the context of the space program (e.g., Gatland, 1972), and this work continues. In addition, there have been a number of research efforts on legged robots which are capable of moving in terrain that is very rugged and around obstacles.

In addition to the major capabilities discussed above, a number of other considerations should be mentioned. One important practical aspect of a robot is the type of power source: pneumatic, hydraulic, or electrical. The kind of power source affects the total load the robot can handle, the energy requirements, and the type of safety considerations. Another consideration is the overall size of the robot; most robots are large, requiring 50 square feet or more for a workspace. On the other hand, newer robots such as Unimation's PUMA more closely match human size requirements.

Applications

Settings. Ten major categories of robot work settings are identified in Table 1. Each of these presents different operating conditions for a robot. Factory settings typically involve noise, heat, vibration, and hazardous substances. Applications in

Table 1

Taxonomy of Robot Settings

1. **FACTORIES**
   - Manufacturing (welding, machining, painting, moulding, etc.)
   - Light Industry (assembly, inspection, repair, loading, packaging, etc.)
2. **OFFICES & INSTITUTIONS (Hospitals, Schools, Prisons, etc.)**
   - Distribution (mail, supplies, food)
   - Cleaning (floors, windows, trash)
3. **SPACE**
   - Space Construction, Maintenance
   - Satellite Retrieval, Inspection, Servicing
   - Planetary Exploration
4. **UNDERSEA**
   - Surveying
   - Search and Rescue
   - Cable Laying, Construction
   - Extraction
5. **MINING/OIL & GAS**
   - Extraction/Drilling
   - Rescue (firefighting, boring)
   - Processing
6. **NUCLEAR PLANTS**
   - Maintenance
   - Emergency Operations
7. **HOME**
   - Housekeeping
   - Food Preparation
   - Security
8. **AGRICULTURE**
   - Harvesting and Planting
   - Crop Dusting
9. **CONSTRUCTION**
   - Excavations
   - Structure Erection/Demolition
10. **MILITARY**
    - Combat (weapons systems)
    - Supply

offices and institutions normally occur in a populated setting and with largely untrained operators. (For example, mail and delivery robots used in offices and hospitals are generally loaded and unloaded by clerical staff). Space, undersea, mining and nuclear plants all involve extreme conditions of one sort or another (e.g., pressure, temperature, poor visibility, corrosives, radiation).

In the home setting, the workplace is quite complex and the robot must be especially benign to interact with children, pets, visitors, etc. In both the agriculture and construction settings, robots must deal with a variety of terrains, climatic variations, and complex navigation/locomotion patterns. In the military setting, robots must meet special requirements such as hardening, standardization, and field deployability.

Note that while most of the present applications of robots are in factory settings (specifically, manufacturing), research has been conducted on the application of robots in all of the settings described in Table 1. A conference on Military and Space Applications of Robotics was held at the National Academy of Sciences in Washington, D.C., in November, 1980. Though human factors engineering was hardly mentioned, both the Army and Air Force have been developing some associations between this discipline and robotics, and the Navy has sponsored research in teleoperators. The Army's Human Engineering Laboratory is investigating the use of robots in munitions loading and battlefield transfer to artillery and in depot repair of heavy vehicles.

Different settings can require different capabilities. Robots in work settings such as undersea, nuclear plants, or agriculture may need locomotion capabilities which may not be required in factories or homes. Vision may be needed in some applications, but tactile sensing may be more critical in others. Not every robot will need all of the capabilities outlined in Figure 1, although the more capabilities, the more versatile the robot.

Work environments may be further differentiated into those presently in existence into which robots may be introduced, and those that will be designed or redesigned for them. Within the former, robots may displace manual operations or semi-automatic operations, such as numerical control and hard automation. Within the latter, robots may be "distributed" (special-purpose equipment under central control) or "stand alone" (single machines or groups of machines operating autonomously). Newly designed workplaces can be engineered to optimize the capabilities of the robot. On the other hand, existing workplaces have usually been designed to accommodate human capabilities and the robot will have to adapt. Consider the design of robot hands. In a workplace specifically designed for a robot, products or parts may have special handles to ensure a good grip by a certain type of robot hand. It may be difficult for a human to handle this specially designed part. However, in introducing a robot into an existing workplace, its hands must be able to grip products or parts designed for human handling. It may be difficult to design a robot hand to do this.

Operations. Some of the operations for which industrial robots are being or might be used are indicated in Table 1, under various settings. Table 2 shows current and future operations for industrial robots, as specified by Engelberger (1980), President of Unimation, Inc., or projected for the Air Force's ICAM project (described later) and so designated (Toepperwein, Blackmon, et al., 1980). An impressive student-staffed investigation of robots at Carnegie-Mellon University (Miller, 1981) has classified robots in three categories: those which simply move workpieces ("pure displacement"), those which process workpieces as well as move them ("displacement and processing"), and those which inspect workpieces as well as move them ("displacement and inspection").

Some operations such as transfer, as well as spraying, welding, drilling, or machining, can be accomplished by relatively simple arm manipulations (either with or without sensors). A task such as assembly requires some more complex arm movements by one or more arms with one or more sensors for coordination. Inspection tasks can require

Table 2

Applications of Industrial Robots

CURRENT:	
• Die Casting	• Brick Manufacture
• Spot Welding	• Glass Handling
• Arc Welding	• Press Work
• Flame Cutting	• Heat Treating, Annealing
• Investment Casting	• Transferring (Pick and Place)
• Forging	• Swaging
• Spray Painting	• Assembly (Simple)
• Plastic Moulding	• Electroplating
• Machine Tool Loading, Changing	• Foundry Work (Limited) (ICAM)
• Deburring	• Sheet Metal Drilling, Routing (ICAM)
• Pattetizing (Loading, Unloading)	
FUTURE:	
• Machining (ICAM)	• Packaging
• Sheet Metal Fabricating (ICAM)	• Package Distributing
• Composite Materials Manufacturing (ICAM)	• Warehousing
• Cleaning Parts	• Troubleshooting/Repair
• Assembly (Complex)	• Supervision
• Inspection	

visual, tactile or other information input. Analysis and diagnostic activities can involve troubleshooting capabilities (e.g., for repair or fault isolation) and planning (e.g., for locomotion or work scheduling). Supervision tasks can consist of self-monitoring of activity or the control of other machines.

Spot welding in the manufacture of automobiles represents probably the major application of robots in the U.S. and the world. Engelberger (1980) estimates that there are currently about 1200 robots in use for this application alone. On an automobile production line, the robot must be able to remember several different body styles (e.g., 2-door versus 4-door) with different welding patterns for each. It has been suggested by Miller (1981), however, that four major problems remain unsolved in welding with robots: (1) automatic magazining, (2) clamping of parts to be welded, (3) control over welding parameters (and quality), and (4) precise positioning of seams. However, these "will gradually be surmounted. . . . with the development of better sensory feedback, oriented, and magazining devices."

Die casting was the original application area of industrial robots. The robot typically unloads the die casting machine, quenches the part, and then places it on a conveyor. In addition, the robot may also trim the part, load inserts into the die, or perform die lubrication.

Spray painting is an interesting application area because it constitutes a very undesirable environment for a human operator. Many solvents used in painting are toxic and highly flammable and some are suspected carcinogens. In addition, noise levels in a paint "shop" are very high from the high pressure air discharge of the sprayers. Thus, the use of robots in this application is quite humane. Furthermore, robots are capable of very uniform and consistent spraying.

Another interesting application, but for a different reason, is the use of robots for glass sheet handling. While robots are usually at a disadvantage when compared with humans for dexterity, this is not the case in handling glass sheets. Robot manipulators equipped with vacuum cups are able to pick up and move sheets of glass very efficiently. In addition to sheets of glass, robots are used to handle glass tubes (e.g., for flourescent lights) and television picture tubes.

As with different settings, different robot operations may call for different functional capabilities. As already indicated, some of these capabilities have been developed, some are essentially still in development. In a continuum from simple to complex robot installations, variable assembly and inspection operations are located at the complex end. Complexity can be defined in terms of the variety of inputs with which the robot must deal through sensors and variety of outputs which it must handle through effectors (actuators), as well as the demands these put on the "executive" (control) software. Some kinds of inspection are involved in many robot operations, in addition to final quality control. A variety of robot operations can be found in assembly of numerous parts. (Welding is a type of assembly, but generally the term is used for more complex operations.) As will be emphasized shortly, robotic assembly becomes especially complicated when a plant is engaged in batch production. Such assembly must be programmable to adjust to differences and variations in products. Since parts are unlikely to be precisely uniform, robot assembly must also be adaptable to slight alterations in tolerances. These needs present major challenges to sensors (especially visual and tactile), actuators, and executive software.

Scope of Industrial Robotics. It may be helpful to indicate the recent and potential growth of robots in American Industry. In the ten years between 1970 and 1980, the number of industrial robots in use has grown from 200 to approximately 3500. However, at the present time, almost one-third of all U.S. robots belong to six firms (Miller, 1981), and it is estimated that half of them are being used in the automobile industry (Engelberger, 1980).

The metal-working industry seems to be the most likely locale for robots. The current 3500 American robots stand in contrast to about fifteen million American production workers, and about 2,973,600 machines in use in the metal-working industry (including about 238,500 in the auto industry). Even if the growth rate for robots indeed becomes 20-50% per annum, as various sources have predicted, relatively few workers will be affected in the near term, and the proportion of robots among industrial machines will remain relatively small. In the more distant future, robots may displace some proportion of the 1,178,520 metal workers in assembly jobs (91% of those in all manufacturing), the 280,050 employed as checkers, examiners, inspectors, and testers in metalworking (37%), and the 55,430 (8.8%) in packaging. Much depends on how versatile robots become, especially in acquiring rudimentary sensors. Miller (1981) concluded:

> Nearly seven million manufacturing production workers (nearly 7% of the total workforce) do the types of jobs which currently are, or soon will be, in the domain of industrial robots. But robots cannot do all of these tasks in the foreseeable future, especially if they are retrofitted into existing facilities. More realistically, robots which are commercially available today could possibly perform nearly 16 percent of operative tasks within those manufacturing operations where robots are well suited (with estimates ranging between 8 and 32 percent); sensor based robots could possibly perform 40 percent of these operative tasks (with estimates ranging

between 20 and 80 percent). In the short term, maybe as many as two percent of the entire workforce could possibly be replaced by robots. Within the next two decades, maybe this number will increase to 4 percent.

Criteria for Using Robots

At least six criteria should be considered in deciding whether to use robots instead of humans, short of societal or organizational impacts or ethical considerations. Some or all of these can be applied also to decisions about using robots instead of hard automation, by substituting that term for humans.

(1) A robot does what humans don't or cannot do.
(2) A robot does what humans are not available for doing.
(3) A robot does what humans do but shouldn't do (e.g., due to dangerous or alienating work).
(4) A robot does what humans do but does it better (e.g., quality).
(5) A robot does what humans do but does it at less cost.
(6) A robot cannot do what humans do.

Financial. A manufacturer is primarily interested in the return on investment (such as 20-30% minimum), and the payback period (no more than 2-3 years in the U.S., probably longer in Japan). Costs include that of the robot itself and installation costs (perhaps as much as the robot itself), of testing (over some extended period), engineering, accessories tooling, redesign of the workplace, protective coverings, software programming, and operator and maintainer training. Ongoing costs include maintenance and periodic overhaul, operating power, and administrative functions. Viability considerations include the rate of production (essentially, cycle time and mean time between failure plus mean time to repair). Against costs must be compared the number and wages of persons replaced and robot/person ratio (with consideration of the number of shifts the persons worked and the robot will work). Engelberger (1980) has provided a discussion of current costs of industrial robots. Reliable estimates of software costs are difficult to obtain; as with computers, they can exceed hardware costs and incur substantial overruns.

Production. A distinction must be made between mass production of one or a few items, with little or no change in any operation or product over a considerable time period, and batch production, with mixes of products—variations in product family or style within the same time period or over a relatively short time period; volume of output is an important variable in either case. Assembly in batch production must be reprogrammed frequently. Actuators in assembly and machinery for producing parts may have to be changed as well, so frequency of setups is also a factor. A large proportion of American industry is engaged in batch production. Types of operations are also of significance; they may involve simple, repetitive actions, or more complex ones. The required extent of computer memory and programming can vary widely according to these production factors.

Parts. Parts to be transferred or assembled can vary extensively in weight, size, location, orientation, positioning, tolerances, and quality. Orientation is also "a touchstone of machine tool loading and unloading by robots" (Engelberger, 1980). Some parts variation calls for robot versatility, other variation for robot vision. The "bin picking" problem is notorious. Parts reach the robot in bins, or are otherwise scrambled, because it seems uneconomical to put them into some meticulous order and orientation in advance. The bins or tubs also function as buffer storage. The robots must recognize, identify and grasp these parts—too tall an order for practical applications to date, though the problem is being researched. It exists also in warehousing. Factory "rationalization" of production and "group technology" would be *one* solution; "parts en route to finished goods are (then) never dropped into tubs for interdepartmental transfer or buffer storage. Their orientation can be maintained . . ." (Engelberger, 1980). Parts may also be defective, for example, screws; it would cost too much to be assured of no defects. Boothroyd (1977) commented as follows:

> One of the main problems in applying automation to the assembly process is the loss in production resulting from stoppages of automatic workheads when defective component parts are fed to the machine. With manual workstations on an assembly line, the operators are able to discard defective parts quickly and little loss of production occurs. However, a defective part fed to an automatic workhead can, on an indexing machine, cause a stoppage of the whole machine and production will cease until the fault is cleared. The resulting downtime can be very high with assembly machines having several automatic workheads. This can result in a serious loss in production and a consequent increase in the cost of assembly.

Quality. In contrast to the defective parts problem, many workpieces processed by industrial robots may be of better quality than those manually processed because the robots operate more consistently than humans or with greater precision. Though it may become necessary to standardize parts and products so they can be processed and produced robotically, quality control as an outcome of robotics will depend primarily on the extent to which various sensing techniques—not just vision—can be developed and used for inspection of finished products.

Reliability. Considerations of MTBF and MTTR for robots have already been mentioned. Their reliability and durability are important factors. All mechanical devices are subject to wear and need periodic maintenance. Software is likely to contain bugs. Although it has been alleged that robots never take sick leave and are not subject to turnover like humans, that really is not so if these terms are generously interpreted.

Space. As Engelberger (1980) commented, "Most robots require substantially more floor space than do their human counterparts." Factories have been designed for human operations; ideally, to forestall "intrusions," future factories should be designed to accommodate robots, or robots will be made smaller, as apparently is being done, though weight-handling capacity is a limiting factor. Some robots have to "stroll" or be synchronized with moving workpieces. In any case, robot siting is another criterion for their use.

Safety. Asimov (1950) published "Three Laws of Robotics": (1) A robot must not harm a human being, nor through inaction allow one to come to harm. (2) A robot must always obey human beings, unless that is in conflict with the first law. (3) A robot must protect itself from harm, unless that is in conflict with the first or second laws. Robot manufacturers and users are extremely concerned, for humane and other reasons, lest a robot inadvertently collide with a worker (who would not be expecting an arm movement) or other equipment (damaging the robot as well); a fatality could seriously set back progress in robot adoption, it is believed. Various techniques have been introduced to assure safety. Toepperwein, et al. (1980) have discussed safety considerations extensively under the headings of protection against software failures, protection against hardware failures, fail-safe design, intrusion monitoring, deadman switches and panic buttons, workplace design considerations, restricting arm motion, and operator training (pp. 114-119).

Environment. Engelberger (1980) reviewed ambient factors influencing decisions to use robots or presenting environmental requirements: ambient temperature, shock and vibration, electrical noise and interference, liquid sprays, gases, and harmful particles; fumes and vapors, particulate matter, and risk of fire and explosion. Robots can stand a lot more ambient stress than humans in many respects but they are by no means impervious to harm. On the other hand, by being more impervious than humans, their environments may not have to conform to the requirements for humans (in industrial plants or on the battlefield), such as OSHA regulations. Yet, if robots and humans work together, the humans must be protected.

Management. Managerial considerations about installing robots include the time requirements for installation and extent of personnel resources, as well as prior experience with robots. Many industrial managers are conservative about innovations and may tend to resist them.

Prospects

Many of the needs for improvements in robots have already been mentioned. The robotics community is optimistic about prospects for these, though distressed that government support has been limited despite assistance from the National Science Foundation, NASA, and increasingly the military departments. The community seems somewhat divided as to whether industry should wait until improvements arrive or make maximum use of what is presently available. Perhaps those with the latter view realize how difficult it is to forecast technological change, in view of excess hope about technical breakthroughs and uncertainties about financial affordability. Machine vision is one of the more significant areas. C.A. Rosen (1979), President of Machine Intelligence Corporation and formerly of SRI International, has concluded that "present robots and machine vision techniques are already sufficiently advanced to permit their initial introduction into factories on a pilot basis."

Toepperwein, et al. (1980) have presented a somewhat less encouraging picture:

> Industrial robots are presently treated as semi-hard automation, i.e., performing repetitive jobs in long production runs and working with parts that are rigidly constrained and accurately positioned. This is directly related to the difficulty in programming new tasks and the inability to interact with sensory feedback data that would inform the system of misalignment of parts and error situations in the work environment.

It may be that exploitation of human factors engineering will contribute to robotics progress. So will basic research being conducted at a number of universities and research centers. These efforts encompass problems in sensors, manipulators, locomotion, and control systems (including software). A considerable portion of this research is being conducted in the context of artificial intelligence. In fact, some of the more successful work in this field has been done in a robotics framework (e.g., Winograd, 1972; Winston, 1977).

HUMAN FACTORS ENGINEERING

Issues

As stated in the Introduction, we view the primary human factors engineering issue in robotics as the division of labor between robots and people in an overall enterprise.

We must first try to analyze what roles people will play before examining such human factors engineering issues as design, procedurization, and protection.

Division of Labor. Past attempts to allocate functions and tasks between man and machine have followed the "MABA-MABA" model first adduced by Paul Fitts, a very generalized type of guidance indicating what "Men Are Better At and Machines Are Better At." For robotics, it might be rechristened HABA-RABA—"Humans Are Better At and Robots Are Better At." We see insufficient assistance to designers in such a broad approach, though it can have some heuristic value. More advantageous is a detailed analysis of relative abilities, such as the one presented by Komali, Moodie, and Salvendy (1981) and Nof, Knight, and Salvendy (1980). These industrial/human factors engineers have developed a "job and skills analysis approach" in which the relative abilities of humans and current industrial robots are compared in considerable detail, within the categories of "(a) action and manipulation, (b) brain and control, (c) energy and utility, (d) interface, and (e) miscellaneous factors."

According to Nof, et al. (1980), usually three cases can be identified in deciding between human and robot: (1) Whether a "task is too complex to be performed economically by an available robot"; (2) whether "a robot must perform the job because of safety reasons, space limitation, or special accuracy requirements"; and (3) whether "a robot can replace a human operator on an existing job, and the shift to robot operation could result in improvements such as higher consistency, better quality, etc." as well as cope with labor shortages. Such criteria have been noted earlier in this article. The authors wrote that their table of detailed robot abilities can help make the decision in the third case. They developed their "job and skills analysis for robots" as a modification of their detailed table and applied it to the assembly of a water pump.

Valuable though these two analyses are, we have taken another approach by identifying nine types of tasks that are likely to be required for any industrial operation that might involve robots. We suggest that generally humans and robots may perform jointly within each of these—though in some cases, one or the other may act alone—and that humans and robots should perform symbiotically over the entire set of tasks. Just how the labor is divided will depend on relative abilities and on the kind of setting and operation, a matter for careful investigation and analysis in each case. Our set of tasks is more encompassing than those described by the authors cited. Although our approach is oriented toward effective performance as the prime objective, other criteria (such as cost) should also be considered, since they can be very important.

For easy human information processing, ours is called the "simbiosis" model. (Forgive the misspelling.) The nine tasks are: Surveillance, Intervention, Maintenance, Backup, Input, Output, Supervision, Inspection, and Synergy.

Surveillance means monitoring. This kind of task is required for all types of automation. Some human monitoring will always be required, we presume, for roboticized operations, though robots may also engage in self-monitoring and produce warning signals as well as status indicators. The division of labor can take various forms.

Intervention by humans can consist of setup, startup, and shutdown, programming and reprogramming, "teaching" the robot (by lead-through), on-line editing for small changes during the operating cycle, and taking corrective actions in case of malfunctions, misalignments, defective feeding, and positioning errors. Robots may themselves make interventions.

Maintenance may be periodic or emergency. It can involve either hardware or software (as in debugging). It may be applied to the robot itself or to ancillary equipment. It can encompass troubleshooting, repair, calibration, and substituting a standby robot. Robots can engage in self-diagnoses.

Backup can consist of substituting manual operation for robotic, though, as just indicated, robot redundancy may often be preferable. Backup occurs with breakdown; without backup, industrial production can be seriously degraded, with financial losses. Backup will be needed also in non-industrial settings, as is true for all these generic tasks.

Input refers to the front end of a robotized operation and is especially important for assembly of numerous parts. Parts have to be fed manually into magazines, certainly until robots can pick them out of bins; from magazines they can be delivered to robots in a relatively orderly fashion through various conveyor and structural methods. A robot can then pick up a part and transfer it, perhaps after identifying it, as input to assembly operations.

Output involves dealing with a workpiece or product after it has been processed by a robot. It maybe transferred by a human (machine-aided), by another robot, or by a conveyor to another process or to packaging. It may be a reject. A simple kind of manual output task is sweeping up the cuttings on the floor; no robots have been devised for this.

Supervision entails overall management of the humans and robots at work, the planning of operations, and dealing with emergencies. It should not be confused with "supervisory control," which is included in synergy, below. Supervision is likely to be mostly human. However, robots can collect processing data (output, errors, etc.), as information for management.

Inspection can occur during processing and as quality control of products. Though robots may eventually be able to perform much of the inspection task, instances of uncertainty could be referred to human inspectors. Humans and robots may complement each other in other ways in inspection.

Synergy is the combination of human and automatic (robotic) actions in various aspects and portions of an operation, so the operation is more effective than it would be if only a human or a robot executed it. "Supervisory control" illustrates synergy in teleoperations. In an assembly operation, some tasks may be performed by robots and some by humans. The Komali, et al. (1981) water pump example illustrates synergy.

Symbiosis may be required particularly near the complex end of the robotics continuum, in inspection and assembly. It should be noted that we did not invent using the term "symbiosis" to characterize relationships between people and robots. Engelberger (1974) stated:

> Even the most sophisticated industrial robot in the field today would have to accept being called a mere oaf as a high accolade. Nonetheless, there is already a faltering, reaching out between these two very dissimilar organisms, robot and man. Consider the die casting plant wherein five industrial robots may be producing castings under the supervision, tutelage, and tender care of one human worker. The human worker schedules work load, programs the robots, ministers to the robot's service needs, and monitors the robot's output. In symbiotic response, the robot relieves the human organism from physical hazard at the bed of the die casting machine and from mental debility from the boring repetitiveness of the task.
>
> Hammer forging classically involves a team of operators who feed furnaces, transport hot billets, descale the hot billets, feed billets through sequential dies, feed hot parts to trim presses, deliver finished parts and dispose of scrap. The job always entails some of the severest drudgery and very often it requires surprising artistry. In a man-robot partnership, the drudgery is assigned to the untiring robot and the artistry continues to be man's contribution.

This symbiosis is prevalent in most robot installations, even in those cases when apparently a robot has completely displaced human labor. Wherever a robot seems to have taken over complete responsibility, there is ordinarily some people-kind of work that has been created elsewhere in the operation.

Further in his paper, Engelberger enlarged on the concept of symbiosis to predict that: "By 1984, sophisticated industrial robots working in junior partnership with knowledge workers and utilizing all of the technology that will have been digested during the decade, will have clearly demonstrated the obsolescence of human labor in factory drudgery. One expects that broad adoption would, for social, political and financial reasons, be on a much longer time base."

Other Issues in Human Factors Engineering. One of these is human engineering design of hardware and software. Hardware design involves control panels, including displays and controls, warning signals, workspace layout, seating, illumination, and ambient conditions. Software design includes the programming and on-line languages used for the control computer and the presentation of software-determined information on a CRT or other displays. Another issue in the development of procedures, such as what to do in robot breakdowns and in telephonic and other communications, and the incorporation of procedures in handbooks or computer data bases for CRT display. Protection is a third issue. As indicated earlier, it is a serious one. Although protection should be as automatic as possible, some techniques such as intrusion monitoring and warning devices are human factors engineering considerations, as are deadman switches and panic buttons.

Related Issues. People must be trained to carry out the various human responsibilities outlined in the foregoing discussion of division of labor (except for sweeping up the cuttings). Maintaining their proficiency in some of them, such as backup, can be a problem. Attention should be given to structuring jobs so they provide a reasonable amount of satisfaction through diversity, and intrinsic or extrinsic feedback. The impact of introducing robots on career development and organizational structure should also be considered, though here we are venturing somewhat afield from human factors engineering.

Human-Robot Differences. Still further afield, but of interest, are questions as to how the absence of emotional and motivational properties in robots may affect the people who interact with them, and reciprocally how the presence of these in humans may also affect those interactions.

Investigations

To date, essentially no empirical studies have addressed human factors engineering in robotics. However, there have been a number of analyses and expressions of views worth considering, as well as research related to robots. The work of Salvendy and his associates has already been described.

Teleoperators. Human factors engineering has come closest to robots in investigations of and applications to teleoperators. Where teleoperators have differed has been in the control function; humans have maintained control instead of programmed software, and thereby the interface between human and machine has assumed paramount concern. Nevertheless, it seems likely much can be learned from human factors experience with teleoperators to apply to robotics.

The Air Force's Aerospace Medical Research Laboratory had an extensive research program in teleoperators (for nuclear power tasks) in the late 1950s and early 1960s, summarized by Pigg (1961). R.W. Highland, a participant in that program, was quoted by Knowles (1962) as stating "that the time is especially ripe for a closer rapprochement between human factors engineers and remote handling and nuclear power engineers." (Substitute robotics engineers for the latter to bring such sentiments up to date.) Highland and Knowles suggested that human engineering methodologies could be applied not only to remote handling but to nuclear power plants to minimize safety hazards, "but as yet no particular effort has been made to apply them" (nor was any applied until Three-Mile Island, or shortly before it). Knowles, who reviewed teleoperations under the heading "robotology," criticized an engineering concept then current of a teleoperator as a replacement of a human operator, asserting that "the purpose of remote handling equipment is to extend, not replace, human capabilities."

More recently there have been human factors engineering programs in teleoperators at the Jet Propulsion Laboratory and Massachusetts Institute of Technology. Bejczy (1980) described the work at JPL and commented:

> Researchers in this area face four basic challenges: (i) construction of sensor information displays in integrated, easily perceivable, and task related forms; (ii) construction of efficient and simple control/command languages tailored to the mechanical, sensing, and electronic properties of the manipulator and to anticipated task scenarios; (iii) construction of hybrid (analog/symbiotic) interfaces to intensify the operator's command capabilities; and (iv) extending man-machine communication to audio-vocal channels in order to deal efficiently with the demands of an increasingly complex control and information environment.

The MIT work, much of it funded by the Office of Naval Research, has been extensively described by Sheridan and Verplank (1978), Brooks and Sheridan (1979, 1980), and Sheridan (1980). Sheridan and Verplank commented that it was "interesting to consider a continuum along which the 'degree of automation' can vary from none (direct manual control by person) to complete (hypothetical intelligent robot with no intervention by person)." The kinds of tasks each mix of human and computer control would be capable of would be measured in terms of unpredictability or "entropy." In other analyses of relationships between human and computer, Sheridan and Verplank distinguished between sharing control by operator and computer (both active at the same time) and trading control (when one is active, the other is not); and Sheridan set forth ten levels of automation in decision-making. These continua have interest if only because we also have indicated a continuum of a sort between worker and robot, with various kinds of symbiosis along it. But the concept in Sheridan's work most pertinent, perhaps, to our analysis is that of "supervisory control," mentioned earlier. This is a "hierarchical control scheme whereby a teleoperator or other device having sensors, actuators, and a computer, and capable of autonomous decision-making and control over short periods and restricted conditions, is remotely monitored and intermittently operated directly or reprogrammed by a person" with his own local computer. Sheridan and Verplank noted:

> The physical separation of local and remote computer is not necessary in aircraft, industrial plants, or other systems where the operator is physically nearby, and where supervisory control is used for reasons other than physical remoteness and limited communication channel capacity between human operator and the object of control. In such situations supervisory control may be advantageous, nevertheless, to achieve faster or more accurate control, or to control simultaneously in more degrees-of-freedom than the operator can achieve by direct servo-control, or to relieve him of tedium.

Brooks and Sheridan (1979) labeled their system for supervisory control of manipulation "Superman" (pun intentional, we presume).

ICAM. Mentioned earlier, an Integrated Computer-Aided Manufacturing Program (ICAM) was initiated several years ago by the Air Force Systems Command as part of its MANTECH Program. It has been administered by the Materials Laboratory at Wright-Patterson Air Force Base and has had close associations with the National Bureau of Standards. A major undertaking is a prototype sheet metal fabrication plant (being planned by Boeing), to be followed by a project in sheet metal assembly and then one in composite materials manufacturing. According to Slay (1980), ICAM eventually will tackle other shop floor areas: welding, machining, forging. General Dynamics Corporation has produced the ICAM Robotics Application Guide (Toepperwein, et al. 1980) quoted a number of times in this article.

As part of the ICAM effort, a "Human Factors Affecting ICAM Implementation" program was initiated, phase I of which consisted of a state-of-the-art literature search. The product was an "issue tree," which identified independent and dependent human factors variables that would be involved in the study of any new man-machine system, with the addition of a fourth branch, "Human Factors in Management." In an April, 1981, revision, a sub-sub-branch was added under "Worker-Machine Interface," namely, "Worker-Computer Interface." Nothing in the issue tree dealt explicitly with robotics, though robots are a principal interest in ICAM. Phase II applied the issue tree to several projects in three case studies. One of these was the expansion of a robot station in the General Dynamics Technical Modernization Project.

APAS. The Westinghouse Research and Development Center and the National Science Foundation have jointly supported an investigation of Adaptable-Programmable Assembly Systems, in Pittsburgh, since the beginning of 1977 (Abraham, et al., 1977; Cowart, et al., 1980). Westinghouse engineers examined a number of company products to choose one to which to apply robotics for assembly. At different times, they used two sets of rating scales to make the choice. The first had seven 10-point scales: utilization of available technology, degree of transferability (to other businesses or products), social desirability, inspection and recognition, fixturing and tooling, economics, and product redesign. The second set of rating scales included an economics scale (annual labor costs, maintenance, equipment cost, engineering cost, installation cost), a time scale (cycle time, setup time, changeover time, downtime), a performance scale (product consistency, product quality, system efficiency, risk, ease of meeting OSHA regulations), a utilization scale (required operator skills, required maintenance skills, difficulty of equipment shutdown/restart, and union acceptance), and a "human resources" scale (operator acceptance, task desirability, hostile environment, fatigue, confined space).

The product selected was a small motor with end bell. Westinghouse will test the end bell assembly system in the spring of 1982, but the motor assembly system has been put aside after considerable development due to software problems. The end bell assembly system deals with a dozen parts (plus lubrication and greasing) at six stations, two of which are robots; the other four also involve programmable machinery. A PUMA robot at the first station picks up an end bell, orients and presents it to the TV vision system for inspection and identification as to style/family, puts a rejected end bell into a bin, and positions an accepted one on a conveyor to proceed to the next station. The other robot, in the last station, presents the assembled end bells for inspection and transfers them into a storage bin. Control is vested in a computer-based master supervisory subsystem and seven microcomputers for vision, local, and path control. The system is supposed to deal with five basic styles, 450 style configurations, and numerous tolerance requirements.

Although no human factors engineers were involved in designing the pilot system, Westinghouse and the National Science Foundation did fund a small human factors study in 1980, reported by Hanes (1980). Following a preliminary meeting in April, a

Committee to Define Worker-Related Research held a four-day meeting in Dayton, Ohio, in August. The committee consisted of four human factors engineers (including the head of the Westinghouse human factors contingent and the senior author of this article), a social scientist, a union representative, an APAS engineer, a Westinghouse small-motors plant manager, and a Westinghouse division personnel manager. The committee visited the Westinghouse plant in Union City, Indiana, where small motors are manufactured, and viewed its manual assembly line (which might be replaced by APAS if it is finally put together).

The committee dealt with five questions by applying the Nominal Group Technique, in which individuals propose problems, these are discussed and consolidated, the surviving problems are ranked by each member to produce the group's composite ranking, and the reduction and ranking processes are repeated. The questions were: What do you consider to be the major people-related problems involved in introducing APAS-like technology into American factories? What do you consider to be the major advantages that may result from the introduction of APAS-like technology into American industry? What work-associated research should be conducted during APAS tests? What human factors tasks should be completed prior to the APAS tests? What people-related research should be conducted beyond the scope of APAS tests? Though this project produced only opinion data, it was notable as a systematic attempt to inject human factors (and human factors engineering) considerations into robotics. (Details of this entire study can be found in the Hanes report.)

Research and Applications in Human Factors Engineering

As already noted, the prime subject matter for human factors engineering in robotics is the division of labor between humans and robots and their symbiosis. Analysis and empirical studies, both observational and experimental, should be directed at such symbiosis in all nine of the generic tasks described earlier. A detailed examination of Engelberger's (1980) review of industrial operations has indicated there exists a wealth of diverse forms that such symbiosis has already taken, and more challenges will develop as the field of robotics grows in sophistication and versatility. Human factors engineering research should be directed at all of the settings and all of the operations described earlier in this article, and at all of the combinations of settings and operations. The settings include military, as well as industrial, commercial, and other environments—where robots will work shoulder-to-shoulder with people wearing uniforms as well as blue and white collars and aprons. The operations are many.

Applications of human factors engineering knowledge already available (and widely applied in other contexts) and knowledge to be gained through research should also be undertaken, as they have been in military ground-based and airborne systems and in some industrial and commercial situations. Such applications will take the form of working in-house with engineers in robot-using organizations and robot manufacturers, as well as consultation.

Symbiosis research means examining the roles humans and robots play or should play in the entirety of an operation involving robots, the actual and potential combinations of human activities—functions, tasks, task elements—and of robot activities—functions, tasks, task elements. Respective abilities must be considered as criteria, as well as other considerations such as costs and benefits to people.

Human factors engineering investigators must become and remain familiar with the abilities of robots as these steadily increase and must try to make considered judgments about the shape of the future. This will not be easy. A start can be made by studying the reviews of the state of knowledge in robotics and projections of advances in knowledge as reviewed by Engelberger (1980), Birk and Kelley (1980), Saveriano (1980), and others. Changes will occur not only in robots but in other machinery, parts, products, and procedures to accommodate the limitations that robots have and may always have. These other developments are also subject to human factors engineering investigation.

In the "simbiosis" model, surveillance will consist of monitoring robots both directly and through computer-driven displays and software-originated data. Intervention will occur for the most part through the control system—computers of various complexities and with various functions. Robotics adds another dimension to the growing involvement of human factors engineering in computer software and peripheral equipment. These and the other generic tasks in the model provide a convenient framework within which to examine human-robot relationships and combinations. The last, synergy, implies the greatest challenge. How human-robot symbiosis is optimized in this and the other generic tasks can be adequately established only through research, as David Nitzan commented (personal communication). But insights and hypotheses can be derived from human factors engineering research in teleoperators.

Dependent on and related to the nine generic tasks will be research and applications in the other human factors engineering fields: the human engineering of software and hardware design, development and specification of procedures, and provision of protection/safety. On-line languages, data presentations, and control panels and their elements must be designed so they can be used effectively by the particular workers or military personnel interacting with robots. Procedures associated with new equipment or required to deal with emergencies and other contingencies must be developed carefully and comprehensively and be suitably set forth in manuals or on CRTs. Personnel protection should not be left solely to training or automatic devices or software.

But training in the new forms that the nine generic tasks take when robots are involved must be systematically developed not only in protection/safety but in all of the activities in which humans must engage. Job satisfaction should not be considered as entirely outside the province of human factors engineering; feedback to operators can play a major part in creating it. Even organizational impact may be studied and directed appropriately, in association with other disciplines.

In a very general sense, those in human factors engineering will want to analyze the differences between humans and robots. What are these? What should they be? What are their results?

System experimentation in robotics should interest those in human factors engineering. It might be profitable to investigate a symbiotic assembly process experimentally. Probably the best known investigations of industrial processing were the Hawthorne studies (Parsons, 1974, 1978); in the principal study, women operators assembled telephone relays. Something similar might be undertaken with a mix of robots and humans. It could investigate not only performance and output but also human-robot communication, job satisfaction, and organizational impact. Such research could become the Hawthorne studies of the 1980s.

CONCLUSION

Interest in automation is very topical at this time within human factors engineering. Robotics is not the only instance. Other areas include avionics, command and control systems, air traffic control, and nuclear power plants. Research on the human factors of software (e.g., Shneiderman, 1980) has become critical to many fields. The present article resembles an early effort in *Human Factors* (Parsons, 1970) to interest the human factors community in software and other aspects of computer data processing, and the data processing community in human factors.

More and more it becomes necessary to focus on automation as the method advanced as a solution to system problems and ask whether by itself it will suffice. At the same time, human factors engineering must be adapted to new forms of automation. Robotics offers it many opportunities and challenges, and from human factors engineering may come some significant contributions.

Only a trickle of research on the human factors engineering aspects of robotics has been conducted to date. If robotics is to live up to its considerable potential for improving productivity in industrial and military settings, a great deal more research will be needed. Based upon our analysis, we would suggest the following research areas as high priority: (1) Application-specific studies which identify the most effective type of manipulation, sensor, control, communications, and locomotion designs for human-robot interaction. (2) The development of generic models which help to identify and prioritize the suitability of tasks for robot applications based upon human engineering parameters. (3) Basic and applied studies which investigate the human-robot control and communication interfaces for both naive and expert operators. (4) Proof-of-concept projects which demonstrate how human-robot teams can do better than either alone.

We suggest that these four research areas represent immediate needs and will lead to the greatest payoffs. It seems clear that robots are destined to become a major thread in the fabric of the workplace and society. Human factors professionals have an opportunity now to play a major role in how well robots are accepted and utilized.

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