Where is the Field of Robotics Going?

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I. Introduction

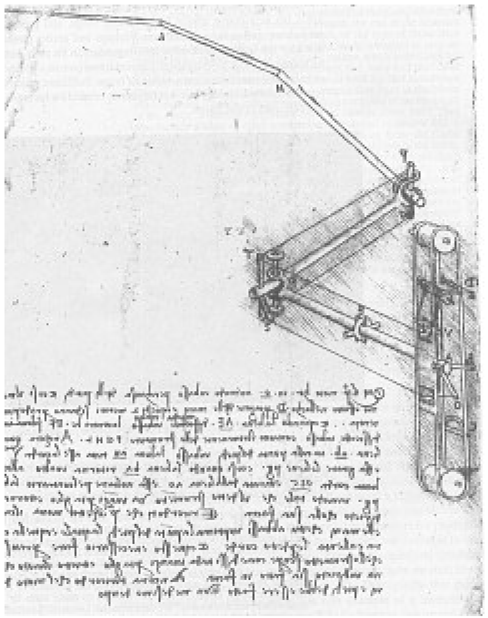
Robotics is now becoming a mature technology with increasing commercial viability. The market has tripled in the last three years in the United States. The opportunity to expand this market ten-fold will depend on a dramatic increase of performance (of several orders of magnitude) while reducing cost. This can only be achieved by using the lessons learned from the personal computer industry and finding the equivalent in robotics. This means standardization at the correct level of granularity (of machine modules) and the creation of a universal operating software system to drive any machine system that can be assembled on demand from these standard modules to meet a customer's requirements. For industrial applications, this will lead to dexterous manufacturing cells of 40 degrees-of-freedom (or more) that are rapidly reconfigurable to do automated warehousing, truck palletizing, food packaging, shoe manufacture, fettling of plastic parts, etc. The age of robotics is just before us. Unfortunately, more than 95% of our robots are imported at this time. The University of Texas is providing key leadership in the required development to create the foundations for a U.S. industry for robotics. This article outlines the basis for this enthusiasm for the technology and briefly outlines activity within UT Austin's Robotics Research Group.

II. Past Embodiments of Robotics?

The oldest form of the technology was represented by automata and its first sophisticated description was given by Leonardo da Vinci (see Fig.1) [1], approximately 500 years ago. This 4 input-4 output device was intended to duplicate the complex motion of a bird's wing, perhaps 200 years before the much simpler single output machines were first being conceptualized. Another exceptional example was provided by J. Vaucanson in 1738 (see Fig.1b), when he produced an automata to play a brief sonata with a flute (with correct fingering and air velocity control) [3,4]. This level of technology was then transferred to complex patterns in textiles resulting in the Jacquard loom with digital inputs in the form of a continuous belt of punched cards in 1801 [5]. It was subsequently embodied in the player pianos developed during the 19th century. One should consider the punched cards as the stored "map" of the program to govern the operation of the system. The player piano had one input - and 88 distinct and independent outputs - very similar to a modern automatic screw machine used in manufacturing. Today, the "electronic" map is more likely to be the functional description of the operation of the fuel system in a modern automobile. This map is obtained by carefully operated tests and experiments of the prototype system. Even though the fuel system may be extraordinarily complex, the highly refined map ensures that maximum performance is achieved under a very wide range of sensed conditions. This is the modern equivalent of an intelligent machine except that a majority of the decision making was done in advance and stored for retrieval during operation. Another more recent form of this type of automata is represented by the Sarcos World Anthropomorphic figure developed by Steve

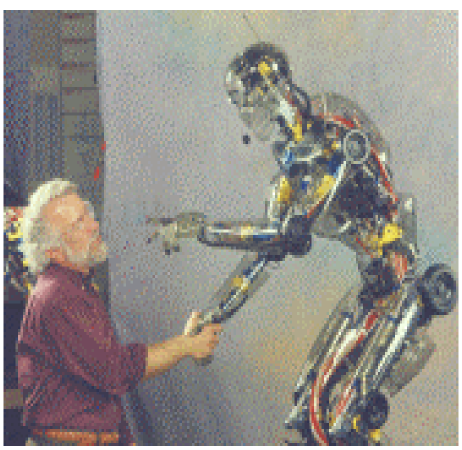
*This is an expanded version of a paper in the Discovery magazine published by The University of Texas at Austin, Fall, 1997.

Jacobson of the University of Utah (see Fig.1c) [6]. This system has a very large number of Degrees-of-Freedom (DOF) driven by a fixed digital memory (usually on a repeating tape). Although visually fascinating, it does not offer significant levels of precision, speed, force (or intelligence) that would be required in future production systems for manufacturing.



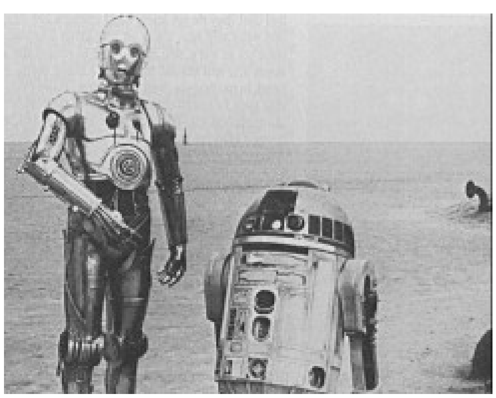
a) Leonardo da Vinci's mechanical wing (~1486)[2

b) J. Vaucanson flute player (1783) [3].

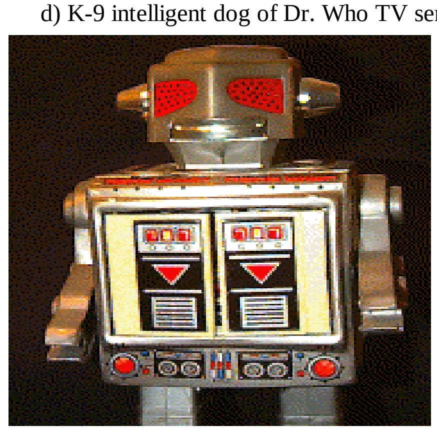


c) Sarcos' articulated entertainment robot [6].

d) K-9 intelligent dog of Dr. Who TV series



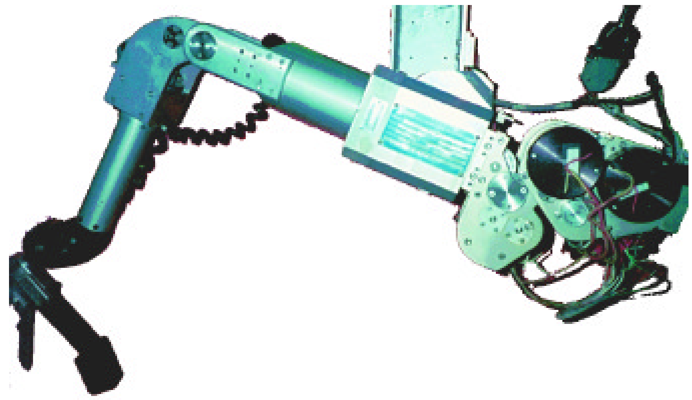
e) Popular Star Wars robotic pair [8].



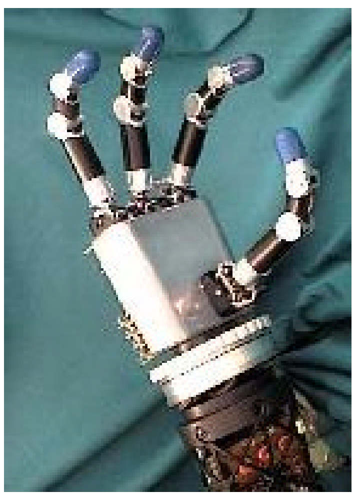
f) Typical toy robot [9].

Figure 1. Automata and science fiction devices.

a) Hardyman (by G.E., 1968) multiplies human lifting capacity 10 times [10].



b) Argonne derived manual controller by K. Flatau (1981).



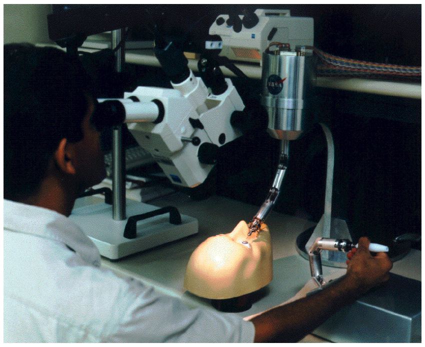
c) DLR Articulated Hand (1997) [11].

d) Ohio State's 6 legged Adaptive Suspension Vehicle (1984) [13].

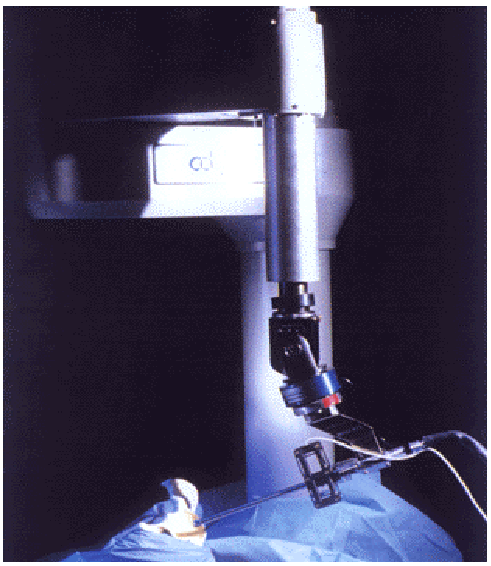
Figure 2: Human like prototypes.

The dog, K-9, of the science fiction series, "Dr. Who," is, in fact, increasingly viable today (see Fig.1d) [7]. It had an encyclopedic memory and could rapidly respond to a very wide range of verbal questions. Today, the need for the equivalent system for entertainment purposes as represented by the popular "robots" of Star Wars (see Fig.1e) or for companion support for our independent but aging population is obvious. Finally, a wide range of toy robots (see Fig.1f) have been produced to respond to the fascination young people have for this technology.

Early attempts to develop realistic functional systems are shown in Figure 2. The manual controller (see Fig.2b) is used as a master to provide kinesthetic input to the system and force feedback to the operator of a slave manipulator device (this is called teleoperation where the slave can be remote from the master). In this case, the master is quite human like in its geometry (as is the slave manipulator). Hardyman [10] was a prototype (see Fig.2a) developed by GE to provide.



a) Robot Assisted Micro-Surgery (RAMS) by JPL [14].



b) Bone milling robot by CMU Robotics Institute [15].

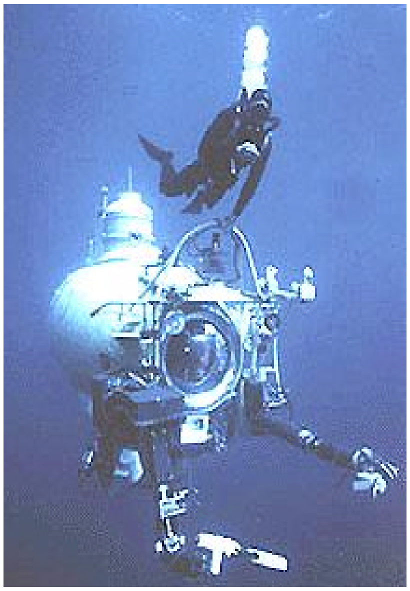
c) Mobile platform by Helpmate Robotics, Inc [16].

Figure 3: Health related technologies.

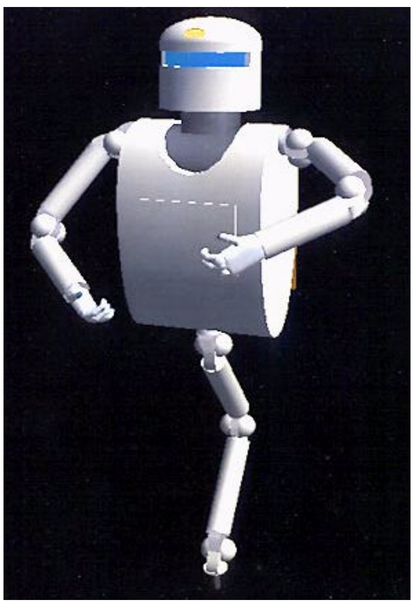
force amplification for the human making the combination capable of picking up ten times the load possible by the man alone. Today, this remains a very desirable goal (human augmentation) although the dominant requirement for specialized backdriveable actuators has not yet been met. The hand prototype (see Fig.2c) by G. Hirzinger involves 12 DOF, 28 sensors, a unique embedded actuator module, and an on-board electronic controller. This prototype, in total, is an exceptional development coming from the field of feinwerktechnik - fine mechanics - a field common to central Europe and recently emerging in the United States as MEMS - Micro-ElectroMechanical Systems [12].

A topic of broad interest over the past four decades is walking. Two legged walking prototype systems do exist but they remain far from satisfactory. The six legged system by Ohio State University [13] was a major effort during the 80's funded by DARPA (see Fig.2d). It did show that six legged walking (and some running gates) were feasible although expensive and complex.

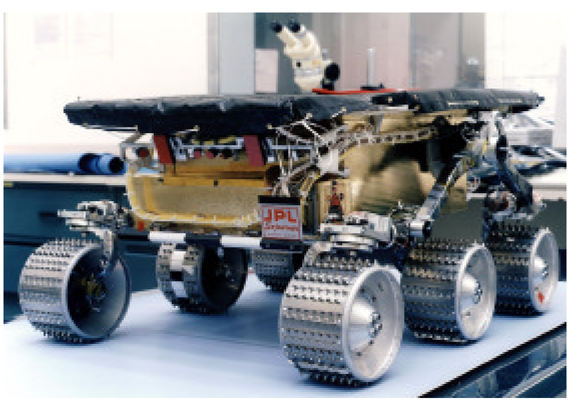
Another topic that has been proposed for robotics is associated with health care (see Fig.3). Eye surgery is one of those opportunities. Recently JPL, in concert with Dr. Steve Charles, a renowned eye surgeon, has designed, fabricated, and tested a miniature (6" long) manipulator of enough resolution to be useful (see Fig.3a) [14]. Another surgical task which requires high forces and stiffness is the cutting of bone (see Fig.3b) [15]. Carnegie Mellon University researchers have shown that this is feasible using a high quality Adept industrial robot manipulator. This Adept system uses direct drive motors to improve its tracking capability to meet the requirements of this demanding physical task. Finally, Joe Engelberger, the father of American robotics has developed a system called HelpMate (see Fig. 3c).



a) Underwater platform for and oil field service [18].



b) Robonaut concept as dual of astronaut in space [19].



c) JPL rover for deployment on Mars [20].

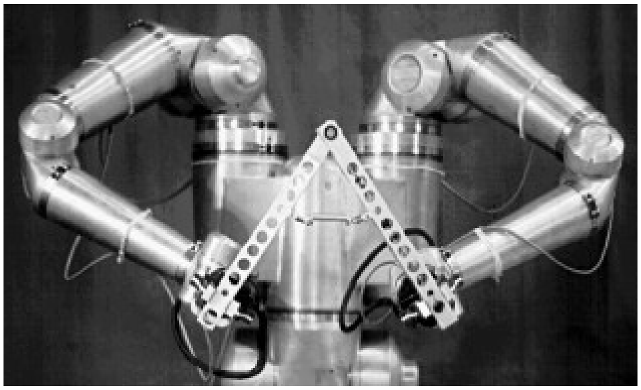
Figure 4: Mobile platforms for remote operations.

The initial use of this system is for transport in hospitals. A future use will be to add two manipulators to the platform to enable it to become the nurse's aid and companion to incapacitated humans [16].

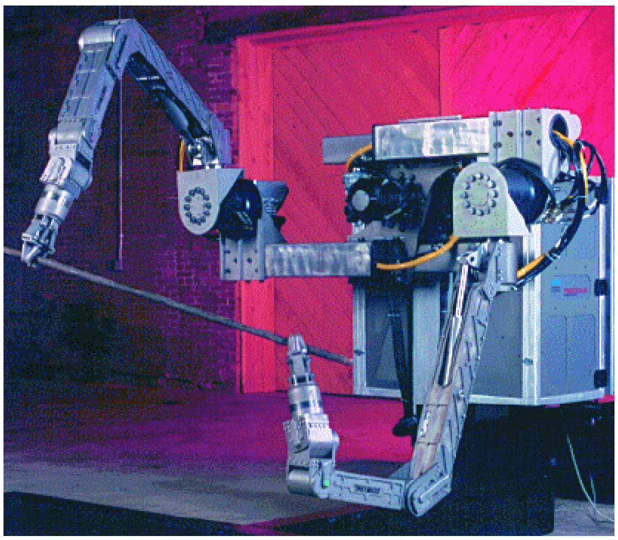
Figure 4 illustrates a range of mobile platforms to carry out remote tasks. The platform in Figure 4a represents an underwater system for ocean exploration or for oil field service functions [18]. That in Figure 4b is an emerging concept by the Johnson Space Center robotics division to create an astronaut assistant to augment his capability [19]. The goal is to reduce astronaut EVA by 50%. Finally, to survey unknown planetary surfaces, JPL is sending rovers to Mars and other planets (see Fig.4c) [20]. These devices are miniaturized to reduce weight.

Systems of higher complexity are increasingly becoming feasible. The 17 DOF dual arm system was built by Robotics Research Corporation as a prototype system for a major robot development in the mid 80's* [21]. It represents a very high level of dexterity and motion flexibility and I s an exceptional laboratory demonstrator. The dual arm system in Figure 5b is being used to dismantle the Chicago Pile 5 at Argonne near Chicago. This is an example of a future need that faces the U.S. and other industrialized nations; i.e., the dismantlement of most of our nuclear facilities and reactors. The basic requirement is to make it unnecessary for humans to enter a high radiation environment. Finally, Figure 5c shows a concept of a 10 DOF, 50 ft long dexterous "crane" manipulator capable

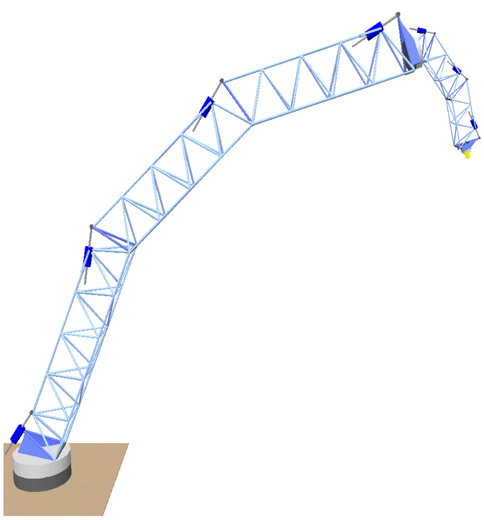
. This device was recently donated to The University of Texas at Austin by Northrup Grumman.



a) Robotic Research Corporation's dual manipulator of 17 DOF.



b) 16 DOF Dual arm system for nuclear facilities dismantlement.



c) Long reach arm (50 ft.) of 10 DOF for construction industry.

Figure 5: Unique prototypes of 10 or more DOF.

of precision placement of building components with minimal human involvement thus dramatically improving worker safety which is a major issue in this industry. One requirement here is a special light weight, high force, and high resolution actuator to drive this large structure.

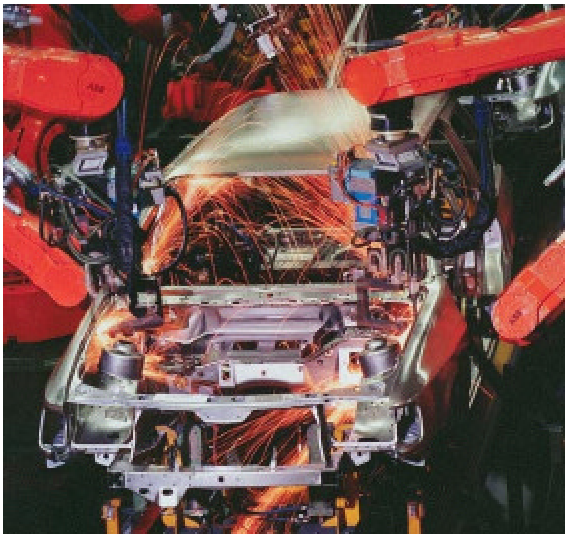
The market for industrial robots in the U.S. has tripled in the last three years, now exceeding $1 billion per year [22]. General Motors purchases 4,000 robots per year. These systems are extraordinarily smooth with a reliability exceeding 20,000 hours (recall that cars may now be considered to be 3,000 hour machines). One of the most common applications is spot welding (see Fig.6a) as well as spray painting and some assembly. The most important reality is that the cost to integrate (make it work) a robot into the factory is four times the cost of the robot itself. Also, time of integration makes rapid product model changeovers virtually impossible. In order to make rapid integration feasible, it will be necessary to improve the absolute accuracy of industrial robots from 0.2 inch to 0.01 inch (a factor of 20) and to have computer control directly from the product database. No industrial robot technology is prepared to meet this dominant requirement at this time. Another important application is electronic assembly. The Hirata manipulator (Fig. 6b) uses high accuracy direct drive motors to maintain the level of speed and precision required. This Japanese made manipulator is also used by Adept in the U.S. It is the only U.S. based industrial robot system manufacturer of any magnitude, leaving the enterprise open to the entry of vigorous technology based start-ups.

III. What is Robotics?

The concept of a machine equivalent to humans has always intrigued mankind and is frequently represented in various forms in the literature. It was crystallized for us by Karel Capek who coined the word robot* in the sophisticated tale of the gradual rise of a robot society, the reduction of the role of humans, and the eventual genocidal destruction of the robot population to follow by its rebirth in terms of two surviving individuals.

Today, this fascination continues in our science fiction and in game competitions such as the recent contest between Deep Blue (of IBM) and chess master, B. Kasperov. While these manifestations are fascinating, they have very little to do with reality. Think of the exceptional ability of the eye-brain combination to accurately distinguish a face among hundreds, thousands, or millions of similar "shapes" that differ only by small nuances. Consider the exceptional accuracy and fingertip control necessary by a basketball player to shoot a 3-point shot. These human capabilities are obtained through trial and error perceptions and corrections obtained through rigorous training, none of which the technical field of robotics is approaching in its most aggressive development. The Deep Blue - Kasperov chess contest is not representative of these highly integrated multi-sensory, multi-motor responses which are best described as highly coupled nonlinear functions which are always in conflict to result in a refined and delicate balance. They are not simple digital (discrete) alternatives. It is the differencing (conflict resolution) which makes it possible for humans to be trained at an exceptionally high level. In fact, antagonistic control of large forces to provide a refined small force output has long been known to be a difficult technical task. Yet, the motion of the human eye is governed by a number of parallel acting muscles which antagonistically move the eyeball in a slewing mode at high speed and, just before focusing, changes to a high accuracy slow motion to prevent overshoot and jitter. In fact, these systems begin to fail when the antagonistic error exceeds the corrective decision making of the "analog" control system. This is a lesson of greatest importance technically. We know there are measurement limits for many physical phenomena. There will also be similar limits on the control of highly nonlinear-coupled man-made systems. The human/biological system is basically analog (a continuous relationship between input command and output response) while the man-made system is increasingly digital (discrete steps in the input-output relationship). We are on the verge of a revolution in the digital control of machines. Why? Because by the year 2000, there will be available computer technology producing a gigaflop of computational power as a $5000

*Robota (Czech) was the number of days of work per year the serfs owed the local baron for his protection and governance



a) Spot welding in an automobile assembly plant.

b) Precision high speed electronics assembly.

Figure 6: Common applications for industrial robots.

commodity [25]. This is equivalent to three or more 1980 super computers. Hence, the architectural generality described in [26] and the forecast of a super-robot discussed in [27] now become truly feasible. The fields of computer science, micro-electronics, and materials science are yielding support to this revolution. But the real demand on the technology comes in the field which the Japanese have called mechatronics - an intimate combination of mechanical and electrical technologies. The mechanicals must generate the physical embodiment of the system - in other words, they must create the best possible parametric representation of the system. The electricals, by means of exceptional decision making software, must resolve demand/response conflicts through criteria fusion at several hierarchical levels. In fact, as the speed of digital decision making increases, the more analog the control response will appear. Today, the field of robotics is moving rapidly to a blending of these fields into a new discipline. Those young people who wish to be leaders will strive to excel in this emerging science of mechatronics.

IV. What is the Future of Industrial Robotics?

The robot industry (and most machines in general) has concentrated on a monolithic design of manipulators (4 to 7 DOF arms) which are one-off designs in much the same way we built and operated our earliest computers. A massive lesson from computers has been learned from the last two decades on the commercial development of an open architecture for the hardware system (Dell Computers) and a generalized software for the operating system (Microsoft). In other words, these systems are so open that they can be assembled on demand and integrate virtually all technical modifications from a broad range of sources (because of standardization) without disturbing the remainder of the system. The widespread awareness of this standardization encourages investment to organically occur from a variety of sources. This concentration on an open architecture enables

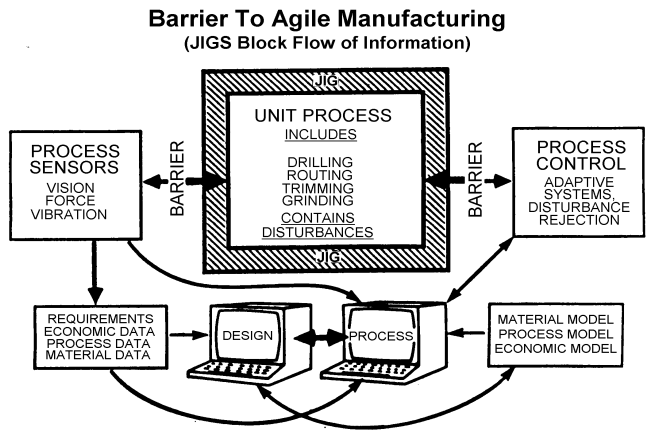


Figure 7: Agile manufacturing barriers

a continuous improvement on performance while reducing cost - quite a contrast to the paradigm of most existing production machine technologies.

It now becomes possible to open up the architecture of dexterous machines (robots). Actuators (the muscles) can be produced in a small number of standard sizes to populate a very wide range of systems to meet a diverse set of applications (seeTable1). These standardized actuators will contain sensors, motors, bearings, gear trains, brakes, electronic controller, wiring, communication buses, etc. In other words, a massive amount of technology. It has the same significance to machines as the electronic chip has to computers (i.e., it becomes one of the standards for investment). Perhaps 7 to 10 actuators in each of five distinct classes would be necessary to populate all the systems required by applications listed in Table 1. Adding links between the actuators makes up the manipulator. All that is necessary to complete the system is an open architecture system controller (now being offered by several suppliers) and a generalized operational software (which is under development at UT Austin) in the same format as offered for computers by Microsoft (the other standard for investment) [28]. Is this feasible? Can commercial entities make money in this manner? Yes, if they expand their markets to applications which are virtually untouched (food, textiles, apparel, agriculture, etc.) which are global in nature, and much larger than those already addressed (automobiles, electronics).

To do so, however, requires that a fully integrated technology be established which is not only responsive to market demands but reacts quickly (and at virtually no cost) to product design changes. This is a concept called agile manufacturing (see Fig.7). The high value added functions (drilling, routing, trimming, etc.) usually contain large force disturbances which are contained by a jig (or rigid frame). The jig maintains operational precision but it blocks all the information flow to the central computer and it certainly is not agile. Further, it can easily cost ten times more than the robot. Hence, a science of machines must be developed which makes it possible to eliminate the jig. To do so will require a whole series of new sciences (metrology, criteria fusion, performance norms, etc.) and a generalized decision making software (opportunities of real magnitude for young people to enter into the field) [29].

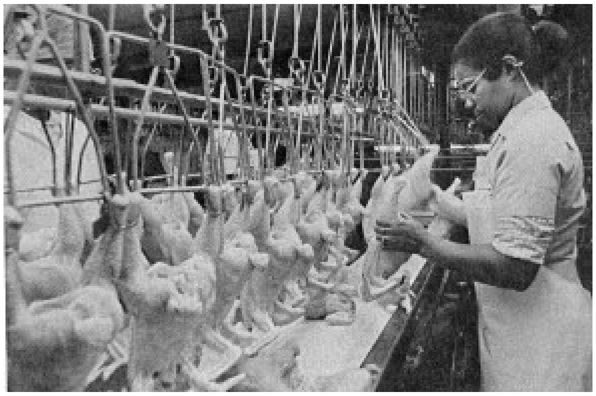
Some of the future applications in industry are shown in Figure 8. Figure 8a illustrates a very common dilemma in the food industry. Many onerous repetitive physical tasks exist that must

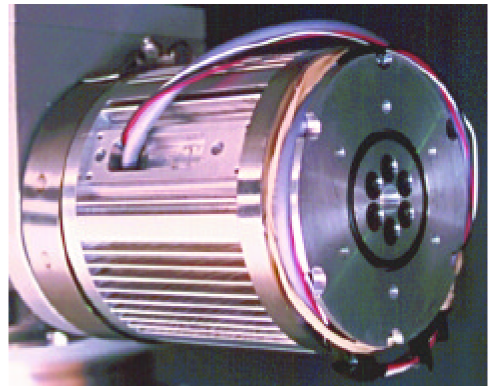
Industrial Automation	Precision light machining Microfabrication Complex assembly/flexible manufacturing/remanufacturing Batch processing Small-scale industrial processes Seam Welding Force fit assembly
Energy Systems	Utility nuclear reactor maintenance Offshore oil and gas exploration Nuclear waste site clean-up Coal production
Military Operations	Battlefield operations All-electric or hybrid vehicles Flight surface control Automatic ammunition loader Logistics operations Explosive ordnance disposal Maintenance and emergency repair
Human Augmentation	Hazardous duty missions Training and service machines Prosthetics and orthotics Microsurgery
Agriculture	Field mapping and harvesting
Space Operations	Space Station maintenance Assembly and construction of planetary surface systems

Table 1: Listing of Robot Applications

be performed in high humidity, temperature extremes, chemical fumes, etc. It now becomes possible to build low cost, modular robots that can operate economically any where in the world. Further, nominally trained operators can replace failed robot modules (plug-and-play) and to do so from a small collection of spares (i.e., just as we now do for personal computers). The robot actuator module shown in Figure 8b is representative of the modularity required [31]. Figure 8c is a concept of an advanced micro-fab architecture which would make it possible to virtually remove the human from any entry into the clean room space. The inner cylindrical core would be occupied by modular handling robots and elevators all of which can be repaired by module replacement by other robots (see Fig.8d) [32]. The second inner cylindrical shell would be for storage of all work (wafers) in progress. Beyond that would be a cylindrical shell for dedicated production machines which could be moved to an outer cylindrical shell for major service, repair, or modification.

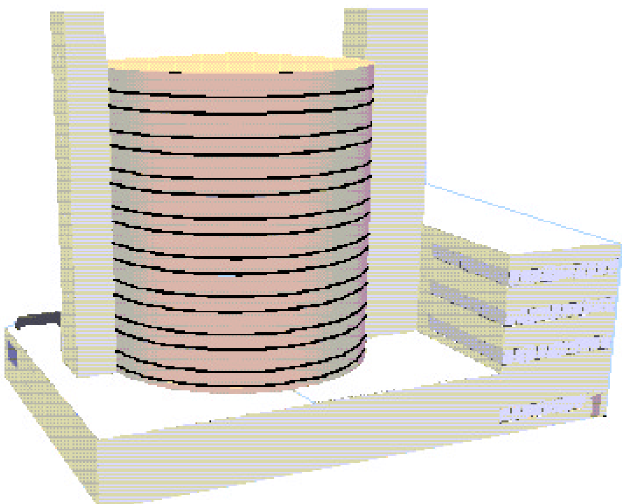
Finally, it now becomes feasible to address high value added functions such as airframe assembly. Figure 8e is the nose cone of a fighter aircraft. It contains 120 parts with hundreds of rivets now assembled by hand using expensive jigs and fixtures. It is proposed to design a finite number of link and actuator modules to be assembled, on demand, fully calibrated with integrating software to carry out this demanding assembly task. The result would be a precision assembly cell of 40(+) DOF [33]. Some of the manipulators would maintain precision under load of 0.01". Some would be force robots to prevent deformation of the product. Others would be dexterous fixturing devices. The whole would be a completely reprogrammable system whose operation would be based on commands derived from the data base of the product - a true representation of agile manufacturing.

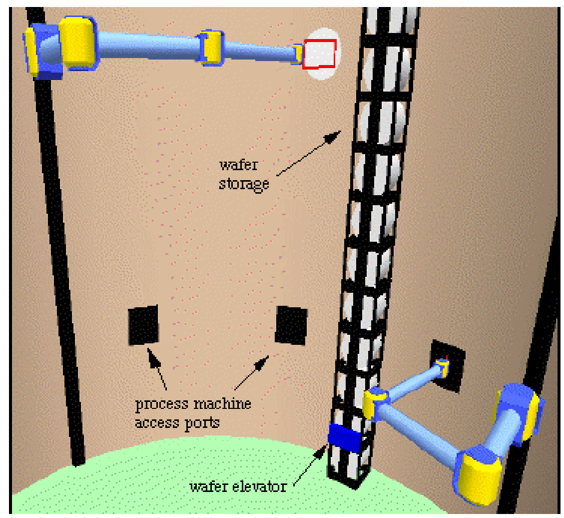




a) Humans face demanding and repetitive tasks in food production [30].

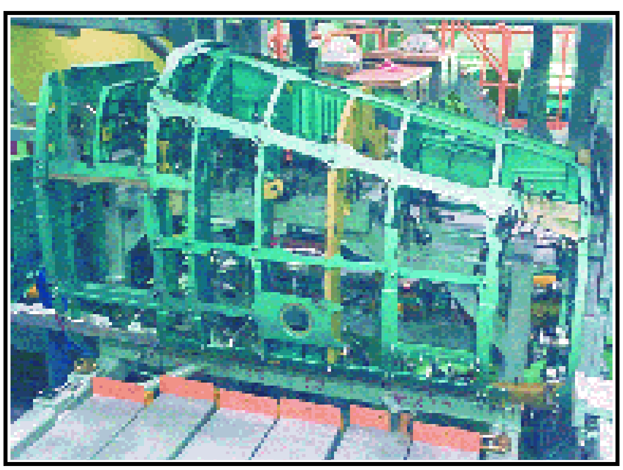
b) Standardized actuator as a basis for Plug-and-Play systems [31].

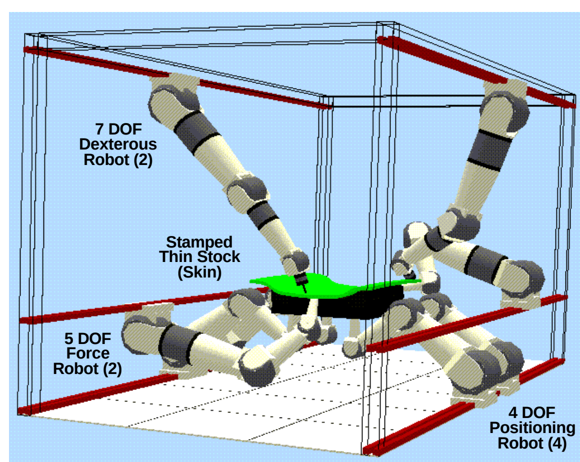




c) Revolutionary cylindrical micro-fab architecture [32].

d) Modular robot concept [32].





e) Nose cone airframe for an F-18 fighter [33].

f) 40 DOF handling cell for precision airframe assembly [33].

Figure 8: Demanding future applications of robotics in industry.

These industrial examples all indicate that open architecture (modular) systems of many degrees of freedom able to satisfy a broad range of applications will be the future of production machines that we need to be working on now. This architectural generality is what we classify as manufacturing cells.

V. Continuum for Advanced Machine Operation

The benefits of the massive technology associated with computers can now be expanded by changing the basis for machine control from analog and stability algorithms to criteria based decision making such that task performance, condition based maintenance, and fault tolerance become possible for complex production systems such as 40 DOF precision assembly cells for airframe manufacture. This generic approach would also apply to all intelligent machines such as aircraft, automobiles, harvesting equipment, medical equipment, etc.

Most mechanical systems are based on a control paradigm associated with the criteria of stability and a few ancillary criteria such as overshoot, settling time, and steady state error. Not only are these criteria irrelevant to the critical operation of most high value added production systems, issues such as task performance (precision, force, obstacle avoidance, etc), condition based maintenance (when should a component be replaced to maintain system performance) and fault tolerance (operation even under a fault) cannot be addressed by this out-dated approach to control. The successful fly-by-wire approach used in fighter aircraft shows that criteria based decision making not only works but that it is essential to generalize the architecture of production systems, make agile manufacturing feasible for high value added operations including advanced manufacturing cells, and to reduce life cycle cost.

Figure 9 describes what is meant by this new continuum of machine operation. Each operational concept (task performance, condition based maintenance, and fault tolerance) is based on a "residual" (or difference) between a predicted model reference (based on a parametric description of how the "as built" machine should perform) with a sensor reference (based on actual parameters measured by distributed sensors within the system). This difference model then can be used by the decision making software to maximize performance, to identify faults and to recommend the best configuration to mask the fault, or to recommend the replacement of a component which is adversely affecting the system's performance. To obtain these benefits, a massive development of foundation technologies such as metrology, operational criteria, decision making, modularity, communications technology, etc. (see Figure 9) must be undertaken. Little of these foundation technologies now exists or is being developed or taught in our academic institutions. It is also necessary to mention that federal research funding for manufacturing has provided virtually no support for this revolutionary but essential technology. For example, it can be forecast that condition based maintenance will be common to automobiles within this decade. Why not now also vigorously pursue this same technology for production systems and bring excitement back to our manufacturing industry and to the discipline of mechanical engineering.

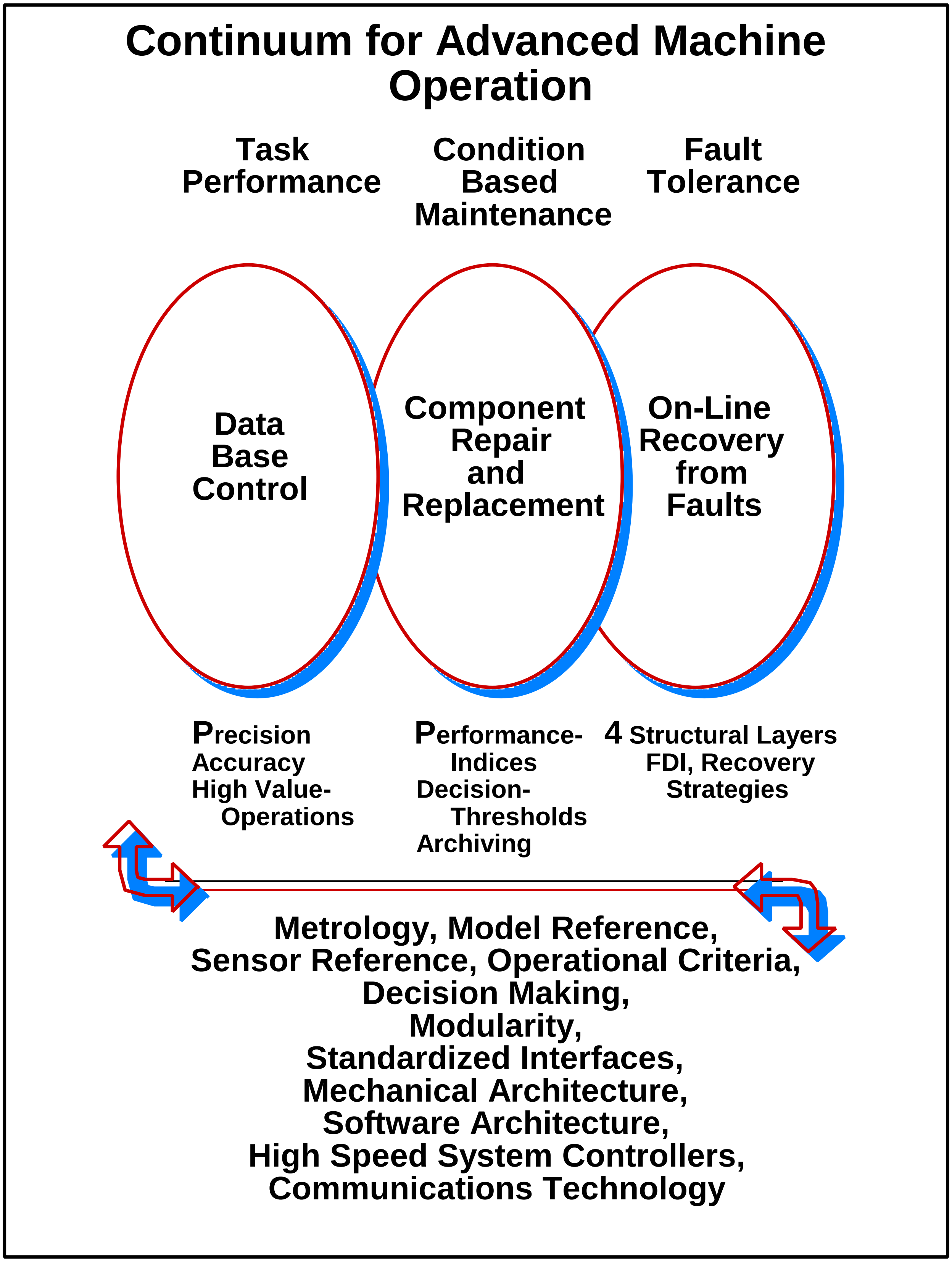

Continuum for Advanced Machine Operation
Task Performance
Condition Based Maintenance
Fault Tolerance
Data Base Control
Component Repair and Replacement
On-Line Recovery from Faults
Precision
Accuracy
High Value-Operations
Performance-Indices
Decision-Thresholds
Archiving
4 Structural Layers
FDI, Recovery Strategies
Metrology, Model Reference,
Sensor Reference, Operational Criteria,
Decision Making,
Modularity,
Standardized Interfaces,
Mechanical Architecture,
Software Architecture,
High Speed System Controllers,
Communications Technology

Figure 9.

VI. Contribution by UT's Robotics Research Group

The Robotics Research Group at UT Austin has a 40 year history in machine development, 30 years specifically devoted to robotics. Since 1975, much of this effort has been to establish the general analytical and design infrastructure for an open (modular) architecture of systems with many degrees of freedom which are able to satisfy a broad range of applications for future production machines. This work has coalesced in two principal areas:

Standardized Actuators. We have defined five unique classes of actuators and have designed one or more actuators in four of these classes (high precision, high force, low cost, and backdrivable). We are pursuing all essential component technologies (gear trains, sensors, clutches, electronic controllers, communications buses, quick-change mechanical interfaces, etc.) as well as a complete test environment composed of four unique test-beds (endurance, condition based maintenance, control, and metrology) for these actuators. Finally, we are developing a ten sensor environment (torque, position, temperature, current, voltage, etc.) to create an architecture for an intelligent and reconfigurable actuator to maximize performance as well as make fault tolerance and condition based maintenance possible. The overall goal is to create a standardized set of advanced actuators whose production cost can be dramatically reduced by large production runs. This minimal set of actuators would then be available to create a very large population of open architecture machines and manufacturing cells which can be assembled on demand in the same manner that we now employ for personal computers.

Generalized Software. Once an open architecture structure for machine systems exists, it becomes necessary to provide a software architecture sufficiently general to operate any machine that can be assembled from these standardized machine modules. Our research program has laid the foundation for this software in an object oriented structure called OSCAR> This software is based on resource allocation by high speed (in less than 5 milli-sec) decision making among 100+ operational criteria (speed, force, precision, deflection, energy, etc.). this software can operate simple 6 DOF robot manipulators or complex 40 DOF manufacturing cells. Its decision versatility allows for a unified control for maximum performance (is there sufficient precision), condition based maintenance (does a module need replacement), and fault tolerance (can a fault be avoided even during operation). Much of this class of technology is being employed in the operation of our nuclear reactors, supercomputers, and even our modern automobiles. It now becomes possible to use this technology in our future production machines and to do so at reduced cost.

Based on this aggressive technical development, the Robotics Research Group is pursuing the following applications at this time:

Plutonium Processing: The operation of multiple robots in a glove box to handle and repackage highly radioactive plutonium. (Fig. 5a)

Dismantlement:	The operation of 16 DOF dual arm systems to decommission nuclear facilities and nuclear reactors. (Fig. 5b)
Airframe Manufacture:	The development of precision manipulators to create versatile assembly cells without the use of expensive jigs and fixtures. (Fig. 8e, f)
Robonaut:	The development of control software for the Operation of dexterous hands and dual arm Systems to assist the astronaut in space. (Fig. 4b)
Shipbuilding:	The design and development of low cost, modular Portable robots to weld ship structures at a cost/benefit ratio 50 times better than previous systems. (Fig. 8b)
Robot Crane:	The design of a 50 to 60 ft. long dexterous crane to assemble standard components of buildings with minimal human involvement, thereby increasing worker safety. (Fig 5c)

Other topics of interest are in the fields of food processing, handling and packaging; textiles; microsurgery; automobile assembly; microelectronics processing; and anti-terrorist operations.

VII. Comment

This is exciting business. A revolution is at hand. Just the thing to attract the brightest young minds. It does not have to lead to science fiction to be exciting. The goal is to move away from a simple concept of single purpose machines to those which can be assembled on demand to meet a wide range of applications at reduced costs. These systems will be fully integrated and reconfigurable, maintainable by a nominally trained technician, and repairable by module replacement from a limited number of modules that can be kept on hand at low cost. This architectural generality (standardized actuators and generalized operating software) is what we wish to consider as the basis for manufacturing cells. This approach to standards for investment is identical to the successful commercial model for personal computers (standardized computer chips and operating systems). Come and join us in this exciting development.

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