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# NEXT WAVE OF TECHNOLOGY
(Based On Machine Intelligence)

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**Summary:** *The emphasis here is to build on the past breadth of applications for the discipline of mechanical engineering, develop a completely modern science base for intelligent machines (assembled on demand) in order to create a new wave of technology building on the success of the last wave associated with computers (see chart below). This wave will have a greater impact than that provided by computers over the past 40 years by modernizing all our basic systems (aircraft, ships, manufacturing and construction equipment, automobiles, household appliances, etc.) moving into the field of robotics, reducing human drudgery, and enhancing the relationship between man and machine. A strong position on this technical option at this time would position the U.S. to take leadership in a whole new economic activity of enormous magnitude (more so than computers). This new wave will be made of two major components. The hardware component is actuators (just as the computer chip is for computers – Intel Corp.) and the software component operates all machines made up of these actuators (just as Microsoft's Windows runs all P.C.'s). Electro-Mechanical actuators will drive anything that actively moves on cars, airplanes, ships, manufacturing systems (see chart below), space systems, human orthotics, prostheses, etc. It is more important than computer chips in the future economy. The software component enables intelligent control of these dexterous systems under direct human management and oversight (i.e., the emerging field of robotic surgery). The software for each application domain is universal; it provides for maximum performance (norms and envelopes prioritized by the human operator), condition based maintenance for timely repair (plug-and-play actuator replacement), and fault tolerance (on-line recovery from a fault to prevent loss of life or large economic-loss). Strong technical positions support this new wave argument, there is no uncertainty of purpose, a national resurgence in the core of mechanical engineering is feasible in the near term., etc. As suggested by the chart, we are just entering the new wave based on machine intelligence as described on the next page. In fact, it is claimed that now is the best time to be a young mechanical engineer in the past 100 years.*

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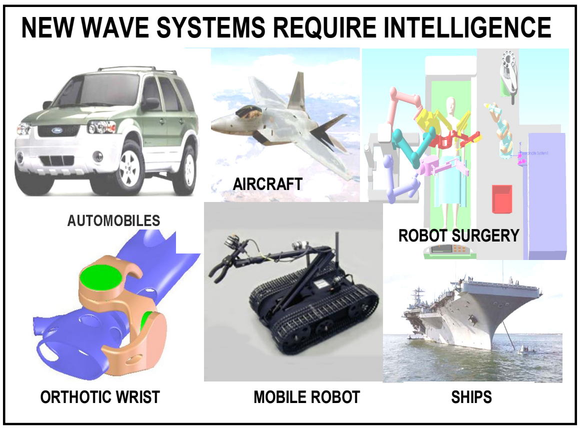
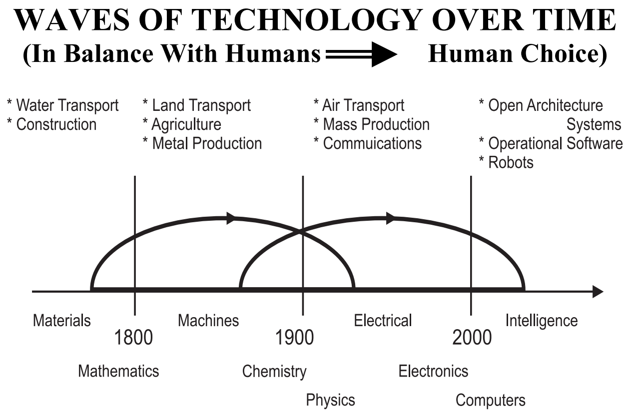



40 DOF Precision/High Load Manuf. Cell
(assembled on demand, reconfigurable, no fixtures)




## MECHANICAL SYSTEMS OF INTEREST

1. **AUTOMOBILES**
   - Continuously Expanding Intelligence
   - Condition-Based Maintenance
   - Maximum Performance
2. **AIRCRAFT**
   - Non-Fault Tolerant Actuators
   - Virtually No CBM
3. **SMART SHIP** (Closed Architecture)
   - Carrier Cost of $50 Billion Over 50 Years
   - Communications, Power, Actuators, Automation
4. **MANUFACTURING CELLS**
   - Primary Cost Is Integration (Reduce By 50%)
   - Assemble 40 DOF Systems On Demand
5. **CONSTRUCTION EQUIPMENT**
   - Worker Safety
6. **MEDICAL EQUIPMENT SYSTEM**
   - In-Situ Patient Exams/Rehabilitation
7. **CLOSED MINI-ENVIRONMENTS**
   - Absolutely No Human Physical Involvement
   - Automate Glovebox
8. **ENTERTAINMENT EQUIPMENT**
   - Entertainment Parks, Educational Equipment, Robots
9. **HUMAN AUGMENTATION**
   - Create Larger Forces/Increase Endurance
   - Motion With Greater Precision/Filter Input Errors
   - Surgical Tele-operation/Exoskeletons
10. **MARS HABITAT**
    - Long-Term Application
    - Assemble Machines On Demand
11. **SEMICONDUCTOR MANUFACTURING**
    - Highly Repetitive Precision Tasks
    - Requires Complete Production System Model
    - Flexible Handling Systems

Fig. 1

## NATURE OF THESE SYSTEMS

1. **HIGH NON-LINEARITY**
   - Non-linearity is Basis For Their Usefulness
   - Leads To Incredibly Complex Models
   - Described By 100+ Operational Criteria
2. **ACTIVE RESPONSE**
   - Rapidly Changing Output Demands
   - Linearization Is No Longer Acceptable
3. **CRITERIA-BASED CONTROL**
   - Hundreds of Criteria For Good Operation
   - Usually Found Through Experimentation
   - Criteria Fusion
4. **MAXIMUM PERFORMANCE ENVELOPE**
   - Increase Size Of Envelope
   - Aggressive Operation
5. **CONDITION-BASED MAINTENANCE**
   - Monitor Performance History
6. **FAULT TOLERANCE**
   - Fault Detection and Identification
   - Operates Within A Finite Fault Tree
7. **OPEN ARCHITECTURE**
   - Open Structure/Standardized Modules
   - Concentrate On Standardized Modules
8. **UNIVERSAL OPERATIONAL SOFTWARE**
   - One Software For All Assembled Systems
9. **PROVIDE FOR HUMAN INVOLVEMENT**
   - Augment Human Physical Capacity
   - Integrates Human Judgment

Fig. 2

## 1. Machine System Intelligence

**Objective:** The goal is to widen the breadth of functions that can be performed by mechanical systems under human management in terms of an increasing number of input variables. This MIMO[1] structure requires conflict resolution in milli-sec. by means of a new decision making framework which manages uncertainty while maximizing performance.

**Background:** Humans have a remarkable capacity to sense a wide range of phenomena, to train themselves to perform a variety of complex operations, and to use human judgment in resolving conflicts and setting priorities. By contrast, machines excel in creating large forces, maintaining high accuracy under disturbances, repeating a given task, providing continuous operation, etc. Other mechanical systems provide safe transportation under hazardous conditions (automobiles, aircraft), some are increasingly autonomous (UAV's, ground vehicles), and others are in balance with humans (orthotics, prosthetics). This new wave of technology (Tesar, 2004a) will be harnessed to better meet human needs (health care, sustenance, security) and to reduce human drudgery (repetitive production tasks, heavy object handling, work in hazardous environments, etc.).

[1] MIMO – Multiple Input/Multiple Output

The reality of all mechanical systems is that they are inherently nonlinear (Tesar, 1978). That nonlinearity enables their wide flexibility in task performance (multiple distinct output functions). In the past, these devices were driven by the simplest of input commands (constant velocity flywheels, error management by feedback control, on-off sensor signals, etc.). Complex coordinated functions such as in sewing machines, automobile engines, and processing machinery were achieved only through the use of an unchanging crankshaft. Either these systems maintained their operation with minor adjustments or they did so through failure avoidance. The concept of performance availability in terms of multiple output objectives only began to emerge in the field of robotics about 1960-70. This desired flexibility is finally being achieved at the beginning of the 21st century, primarily because of the huge computational resources now available at low cost. It is well known that computers can now be assembled on demand from certified components in a worldwide supply chain. The equivalent of this open architecture for mechanical systems is now just being investigated and formulated in terms of standardized modules (actuators, end-effectors, power supplies, links and platforms, drive wheels, active suspensions, ultra-cap storage units, communication packages, etc.). The ultimate goal is to assemble the maximum number of systems of increasing functional capacity in terms of the minimum set of highly certified, mass produced, and cost effective modules. *This increasing openness, reprogramability, reconfigurability, refreshability, etc. now requires and demands a new level of decision making, which we call here mechanical system intelligence.* Some of the devices/systems that require this level of intelligence are:

**Electric Wheel Drives**
**Unmanned Ground Vehicles**
**Battlefield Operations**
**Condition-Based Maintenance**
**System Power Management**
**Smart-Car Operation**
**Wind Farm Operation**
**Human Rehabilitation**
**Multi-Function Actuators**
**Actuator and System Level Design**

**Development of Mechanical System Intelligence:** New wave mechanical systems will remain nonlinear, have multiple inputs under human control, and will provide for increasingly complex and changing output functions. Statistical decision tools or mathematical optimization cannot manage this complexity and inherent uncertainty in real time (milli-sec.). The approach recommended here is to provide precise parametric modeling (either analytically or through metrology) of every component in the system (i.e., in-depth certification). This process will generate a finite number of performance (or capability) maps for each component which, hopefully, will be monotonic and represent a finite level of uncertainty. Then, every system will be represented by a collection of these component maps (say up to 100). Combinations of these maps will result in numerous envelopes (or decision surfaces). Further, each system's operation will require its own decision structure based on system criteria. This means that each system application domain will require its own unique criteria and operational software. As decisions are made, conflicts resolved, priorities met, etc., there is a real possibility that error propagation will occur (and, in some cases, reduce the effectiveness of the decision process). The primary goal of this intelligence is to manage the system's performance (what may be called performance availability) in response to human intervention and goal setting. A lesser but necessary objective is failure avoidance (especially when human life or very high economic cost is at stake). This class of machine intelligence has recently been documented by Ashok & Tesar (2008).

**EMERGING APPLICATIONS FOR MSI**

| System Design | System Operation |
|---|---|
| 1. Intelligent Actuators | 1. Smart Car Operation |
| 2. Electric Drive Wheels | 2. Wind Farm Operation |
| 3. Active Vehicle Suspensions | 3. Human Rehabilitation |
| 4. Intelligent Tire | 4. System Power Management |
| 5. Open Architecture Rehabilitation | 5. Condition-Based Maintenance |
| 6. Reconfigurable Manufacturing Cells | 6. Unmanned Ground Vehicles |
| 7. Surgeon Controlled Surgical Cells | 7. Battlefield Management |

Fig. 1.1

**APPLICATIONS OF DECISION MAKING FOR INTELLIGENCE**

1. **Multi-Function Actuators**
   - Fault Tolerance
   - Layered Control
   - Force/Motion Control
2. **Actuator Design**
   - Design Rules
   - Parametric Maps
   - Performance Envelopes
3. **Electric Wheel Drives**
   - Multi-Speed Operation
   - Active Suspension
   - Efficiency/Acceleration
4. **Unmanned Ground Vehicle**
   - Terrain Operation
   - Power Management
   - Task Performance/ Reconfiguration
5. **Active Robot Shield**
   - Platoon Level Protection
   - Capability Maps
   - Asymmetric Threat Ops.
6. **Condition-Based Maintenance**
   - Performance Maps/Envelopes
   - Residuals For RUL
   - Reduced False Alarms
7. **System Power Management**
   - Aircraft, Ships, Vehicles
   - Needs/Supply Balancing
   - Margins/Reserves
8. **Smart-Car Operations**
   - Automated Braking
   - Weather Condition Management
   - Evasive Actions
9. **Wind Farm Operation**
   - Maximize Efficiency
   - Wind Speed Management
   - Durability/CBM
10. **Human Rehabilitation Orthotics**
    - 6 to 24 Coordinated Actuators
    - Bilateral Torso Undergarment
    - Use in Clinic and ADL

Fig. 1.2

## 2. Machine Equivalence To Biological Systems

**Objective:** The ultimate goal of machine systems is to benefit from and integrate the intelligence structure in biological systems to govern the motor capacity represented by machines (their control, dexterity, reconfiguration, learning, self-healing, and refreshment) in order to perform complex human functions (shooting a basketball 30 ft. from one's fingertips within 100 to 300 milli-sec.) or to augment those capabilities (precision, endurance, load capacity, etc.).

**Background**: Much has been written about the concept of artificial intelligence. Our present day computers may still only be able to solve a simple set of logical decisions, but they are able to contrast truly complex alternatives if given the correct norms, criteria, and processing algorithms. By contrast, the biological equivalence in motor capacity (moving from complete softness in a delicate touch, to high forces in a chopping action, to exceptional rigidity by using antagonism, to surgical precision using a specialized tool, etc.) for machine systems is in its infancy. This lack of progress is primarily due to our inattention to the essential ingredient between the computer and the physical task—i.e., the intelligent actuator. The actuator is the exact equivalent as a driver of machines to the electronic chip as a driver of computers. The level of standardization, depth of technology, investment strategy, etc. in electronics has accelerated during the past 30 to 40 years where truly unprecedented (also quite unbelievable) progress has occurred. The driving force behind this progress was the continual benefit for measurable predicted (and self-fulfilling) progress on a yearly basis but also the forecast as to how much further progress could occur with continued scientific and commercial development.

The question is, what is the equivalent potential for intelligent Electro-Mechanical Actuators (EMA)? The simplest perspective is to put EMA's in a timeline similar to that which we have seen for electronic switching; i.e., where electrical valves (analog tubes) were in 1950 is where EMA's are in their potential development today. The analog tube valve was standardized (but the exceptional population did not lead to rapid technology progress, cost reductions, endurance, etc.), it had some standard plug-end connectors, it used standard voltage levels, etc. but almost nothing more. This is where EMA's are today. There are literally thousands of devices on the market, each produced for its niche market. Their level of standardization is minimal (interfaces haven't changed for 50 years), integration (motors, brakes, buses, gear trains, sensors, etc.) almost doesn't exist, their control is based on not failing (the only question is stability), and a true sense of intelligence in a full architecture is non-existent in the trade. Yet, the worldwide market for actuation devices is said to be $75 billion and growing at 50% every three years. The need is there. The question is, what is the technical future for EMA's?

**Proposed Long-Term development:** To achieve (more correctly to exceed) the intelligent motor capacity of biological systems will require the same technical and investment strategy we have witnessed for computer electronics over the past forty years. Every function of the human, or the support and extension of humans, requires this improved motor capacity as represented by an intelligent EMA* Intelligence can only occur in a set of actuators which have enough internal resources** to be managed by that intelligence. The biological system can be reconfigured on demand (softness, rigidity, force, speed, etc.) to perform an exceptional range of tasks. Today, our mechanical systems (say, industrial robots) are far removed from this remarkably important goal. We must establish a finite number of actuator classes, make them intelligent,*** standardize their size and interfaces, manage their assembly on demand in completely reconfigurable systems, operate them with one universal system software, permit human intervention, and continue to work the performance/cost ratio. Doing so is not a dream (i.e., science fiction). It is a commercial opportunity dependent on leadership and a commitment of adequate development resources.

**ATTRIBUTES OF UNIVERSITY OF TEXAS ACTUATOR TECHNOLOGY**

1. FULL INTEGRATION
   - **Self-Contained/Compact Package**
     - No Vulnerable External Utilities (piping, hoses, connectors, pumps,etc.)
   - **Contains Only Five Basic Parts**
     - Brake, Motor, Gear Train
     - Principal Bearing
     - Electronic Controllers
   - **Actuator Also Acts As System Joint**
     - Joint Bearing Already In Actuator (No additional bearings, shafts, or attachments)
2. HIGH PERFORMANCE
   - **8 Orders Improvement By Year 2010**
     - Minimum Weight/Volume
     - Maximum Torque Density
     - Exceptional Stiffness
     - Temperature/Tolerance Insensitive
3. EXCEPTIONAL GEAR TRAINS
   - **Star Compound**
     - Great Simplicity
   - **Hypocyclic**
     - Extraordinary Load Capacity
   - **Wide Range of Reduction Ratios**
     - 5 to 1 up to 5000 to 1
     - Prime Mover Speeds (2 to 30K RPM)
4. INTELLIGENCE
   - **Full Array of Internal Sensors**
     - Temperature, Position, Torque, Current, Etc.
     - Monitor Condition In Real Time
     - Enables Max. Performance (Reduces weight)
   - **Permits Condition-Based Maint.**
     - Timely Repair/Replacement
   - **Emergency Response**
     - Uses Performance Reserve for Survival
   - **Conserves Performance Reserve**
     - To Extend Live
     - To Reduce Noise
     - To Operate In Stealth Mode

Fig. 2.1

**ATTRIBUTES OF UNIVERSITY OF TEXAS ACTUATOR TECHNOLOGY (Cont.)**

5. STANDARDIZED INTERFACES
   - **Quick-Change** (Plug-and-Play)
     - Rugged (4 to 60x Stiffer Than SOA)
     - Accurate (22x Better Than SOA)
   - **Enables Rapid Change-Out**
     - Battlefield Repairs/Tech-Mods
6. STANDARDIZATION
   - **Perhaps 10 Sizes** (1" up to 20" Diameter)
     - Maximum Simplicity
     - Exceptional Ruggedness
     - 5 Up to 100,000 ft-lb. torque capacity
   - **Min. Number of Distinct Actuators**
     - Reduces Need for Spares
     - Reduces Distinct Training Regimes
     - Enables Spiraling
     - Enables Cannibalization
7. CERTIFICATION OF PERFORMANCE
   - **Performance Fully Certified**
     - Durability/Shock Resistance
     - Torque Density
     - Duty Cycle Capacity
     - Temperature Tolerance
   - **Embedded Performance Maps**
     - Feasible Performance Envelopes (For Max Torque, Stealth, Efficiency, Etc.)
     - Response To Operator (High Acceleration, High Power, Etc.)
     - Criteria Based Decision Making (Embedded/Extensible SFW)

Fig. 2.2

## 3. Intelligence Is Essential To The Goal of A Full Electro-Mechanical Actuator Architecture

**Purpose:** The goal is to establish a fully responsive actuator whose intelligence manages a sufficiently broad set of choices (performance, duality, layered control, force/motion, etc.) using carefully documented criteria (for prime mover, bearings, gear trains, power supply, and electronic controller) which when combined by fusion mathematics enables deployment to the widest range of systems (aircraft, ships, battlefield, space, manufacturing, surgery, etc.).

**Background:** We have established a full architecture of 10 classes of rotary and linear actuators which embody all the possible physical choices now considered necessary for an

* Attached, find a one-page description of our present concept of EMA intelligence.

** The attached presentation chart describes the potential for diverse functional regimes in a full EMA architecture.

*** Attached is a presentation chart of the functional complexity necessary to make an actuator intelligent.

extremely broad set of applications. We have energetically pursued the design of these actuators, and are formulating a science of design for that purpose (parameter definition, design, criteria, configuration management, scaling procedures, parameter reduction by synthesis, etc.). We have established strong position statements for deployment of these actuators in virtually every application of mechanical systems. Because these systems are nonlinear, the deployed actuators are highly coupled, and the actuators themselves are highly nonlinear (perhaps 40 criteria are necessary to describe their operation), it becomes necessary to develop a specific scientific approach to manage these actuator resources by means of criteria fusion, ranked and normalized criteria (prioritized based on their physical meaning and relevance), with priority setting done primarily by human judgment. Figure 3.2 illustrates the expansion of the proposed EMA architecture, the internal decision making management (and complexity), and a framework for developing the required actuator software for intelligence to be labeled AMOS (Actuator Management Operating Software).

**Technical Development:** Now that we have a fully established actuator architecture, a well defined set of operational criteria, and an emerging decision making process, the underlying science can flourish and we can work towards the following:

| | |
|---|---|
| **1. Maximum Performance Envelope** | The most basic need for intelligence is to combine available resources within an actuator which provides the best performance envelope to meet the present needs of a given application (force, accuracy, speed, response, etc.) on demand. |
| **2. Condition-Based Maintenance** | The broadest possible early need for actuator intelligence will be the condition monitoring of the actuator to advise the system if the performance envelope has diminished and whether maintenance is required. |
| **3. Fault Tolerance** | Where life is a stake (aircraft) or where high economic losses might occur (nuclear reactors), then fault avoidance becomes necessary. Here, we have equal (dual) subsystems (performance maps) which must be balanced in real time to ensure continued operation under a fault (full or partial) on one side. |
| **4. Layered Control** | Here, we mix the physical scales of the system (say 100%, 10%, 1%, etc.). Unique criteria exist at each scale, mixing criteria between scales must be developed, and performance objectives (norms) must be set at each scale. |
| **5. Force/Motion Control** | Here, we mix physically distinct phenomena to enable a whole new class of output functions to be met where a basic motion must be achieved without being impacted by a superimposed force disturbance. |

The criteria for this intelligence are built on the physical nature of electro-magnetic prime movers, rolling element bearings, tooth mesh reducers, and electronic power supplies. Using other basic components (piezoelectric drivers; jeweled, air or magnetic bearings; or screw transmissions or fluid reducers) would add a new range of criteria to our concept of actuator intelligence.

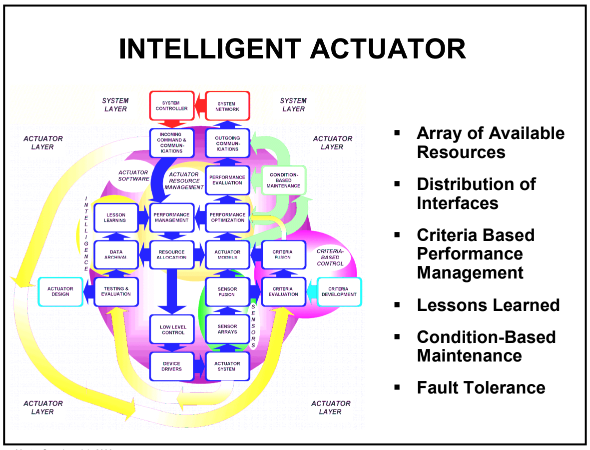



Fig 3.1

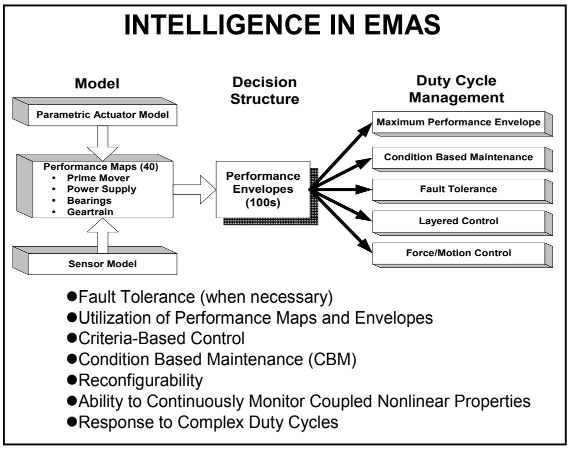



Fig. 3.2

## 4. Precision Connection Interface For Open Architecture Mechanical Systems

**Purpose:** The goal here is to make it possible to assemble precision machines on demand and to make their rapid repair possible by quick module change-out by creating a new standard precision connection interface. This interface must simultaneously account for internal forces, deformations, and tolerances to ensure sufficient accuracy of the resulting connection assembly.

**Background:** Most mechanical systems represent intensive design of singular purpose machines with a closed or monolithic architecture. This closed architecture is difficult to update as new technology becomes available or to repair without specialized training, resulting in a long logistics trail. The University of Texas at Austin has long proposed making robot manipulators, mobile platforms, processing equipment, etc., modular and reconfigurable; where a minimal set of modules (actuators, links, tools, etc.) are necessary to build a large population of systems. This suggests that, especially at the actuator level, standardized interface connections are essential to make this open architecture feasible. The most common interface today is a regular geometric array of bolts/holes to form a strong physical assembly. Except for the use of some guide pins, or circular mating grooves and ridges, this bolted assembly provides for very little in predictable assembly accuracy. Hence, to gain any semblance of machine accuracy, the whole system is assembled and then calibrated by careful measurement to back out the assembly errors that always occur. This calibration step may be expensive and difficult to perform in the field without dedicated equipment and well-trained personnel on hand. This means that should a repair (by disassembly/reassembly) be necessary, much of the factory documented accuracy will be lost and difficult to retrieve in the field. This is what is meant by an extended logistics trail.

If we are to achieve a true openness to mechanical systems as the computer industry has, we must establish a new class of mechanical connection interfaces which can maintain a desired level of accuracy under repeated assembly cycles at those connections. This connection interface should, in general, be passive – i.e., no internal sensors are required to determine the resulting connection accuracy after assembly has been achieved (active sensing may be useful to further enhance the accuracy of a high quality mechanical interface to be described below). Recently, Slocum has studied and further developed a precision interface based on purely kinematic geometry. Even though that device has merit, our concern is that it is not sufficiently stiff and that it requires heavy back plate structures to reduce the internal deflections. The kinematic coupling provides a theoretical accuracy based on a highly symmetric geometry where all forces are essentially decoupled. This means that tolerances are not central in its design concept.

Here, we wish to introduce a whole new class of quick-change interfaces which can passively maintain a high level of accuracy under repeated assembly cycles. To do this, we have created a new design theory which mathematically combines internal interface forces, deformations, and tolerances. We statistically integrate the affect of tolerances on internal interface forces to control the local deformations by means of compatibility equations in order to ensure the resulting assembly accuracy in all six directions. Essentially, the internal deformations must be managed to ensure this assembly accuracy based on a known level of manufacturing tolerances. So far as we know, this has never been done before. The deformations must be larger than the available tolerances (perhaps by a factor of 5 or more), and these deformations must be programmed to occur due to a sufficient level of closing clamping force without significantly reducing the assembly's resulting stiffness in any direction.

**Interface Design:** One version of the interface design is shown in Fig. 4.2. This figure shows the CAD rendering of the interface made up of an upper and lower body which is clamped together using two or more wedged c-clamps which are held in grooves in both interface bodies by a band-clamp to create the required closing force. A wedge assembly repeats itself an even number of times along the outer rim of the connection. Generally, the higher the number of these wedge assemblies, the more accurate the whole interface becomes. The minimum is four, but up to 16 is feasible (in increments of 4). The fiture gives a layout of the lower body which contains the symmetric pairs of deformable wedges. These wedges must allow sufficient deformation to permit the closure of the interface (with the available closing force), such that large (and stiff) contact flats come into contact. The figure also shows the upper body which contains the mating wedge surfaces and the corresponding contact flats. Both the upper and lower body interfaces contain utility ports (for power, communications, fluids, etc.) for transport of all necessary utilities through the interface. The utility ports are designed to achieve their connections automatically as the connection closes. In the work done to-date, it is possible to compare the assembly accuracy of this new connection with the recently developed connection called the kinematic coupling (with six grooves and six mating balls). The local manufacturing tolerances are taken to be the same for both connections (linear: ANSI 5, angular: 10 arc sec.). The developed analytical formulation inserting the

**QUICK-CHANGE INTERFACES**

1. **Enables Plug-and-Play**
   - Reduces Number of Actuators
   - Reduces Spares
2. **Enables Rapid Assembly**
   - Quick Spares Replacement
3. **Standardize**
   - For All Actuators/Links
   - Links Are Machine Geometry
4. **Interface Structure**
   - Largest Possible Diameter
   - Near Principal Bearing
   - Minimize Force Path
5. **Repeated Assembly Accuracy**
   - Analytical Balance Of Tolerances/Deformations
   - Detents/Compliance Contacts
6. **Matches Actuator Accuracy**
   - Precision Operations
   - Preserves Calibration
7. **Low Cost Production**
   - On Standard Machines
8. **Reduced Maintenance Cost**
   - Fewer System Modules
   - Reduced Training
   - In-Field Replacement
9. **Contains All Utilities**
   - Wiring
   - Coolant
   - Communications
10. **Enables Open Architecture**
    - Assemble On Demand
    - Minimum Set of Modules
    - Maximum Population of Machines

Fig. 4.1

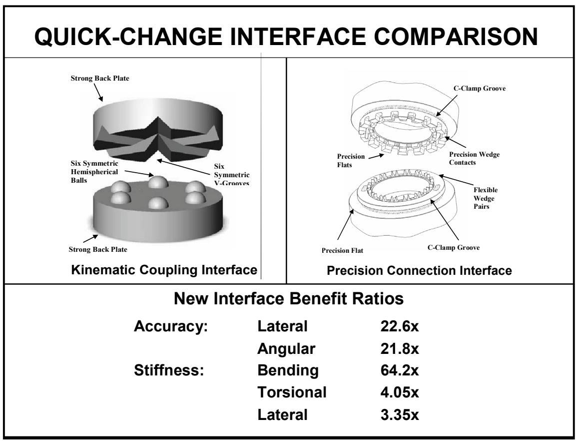



Fig. 4.2

influence of these tolerances shows that the new connection (with 16 wedge pairs) is 22 times more accurate and 3.5, 4.0, 64 (lateral, angular, bending) times more stiff than the existing kinematic coupling. *These results show that sufficient connection accuracy and stiffness is now available to warrant the aggressive development of open architecture machines.*

**5. Comparative Analysis of Advanced Gear Train Technology With Best Practice** (SOA)

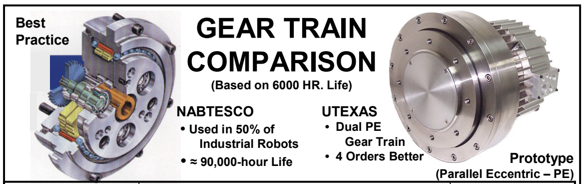
**Objective:** Here, we wish to compare the design and performance parameters of an existing "best practice" gear train transmission used in many machine systems (including robotics) with our most recent transmission concept based on a hypocycloid gear train. We wish to show that our concept is two to four orders of magnitude higher in overall performance than existing best practice, dramatically changing the framework for opening up the architecture of robotics, manufacturing cells, naval ships, aircraft, surgical systems, etc.

**Background**: Most gear train transmissions are designed to transmit high loads at high velocities. Rarely do manufacturers concentrate on gear trains for servo applications beyond the simple question of precision. Extremely important issues associated with volume, weight, torque capacity, torsional stiffness, etc. are treated as secondary considerations. Here, we want to make these issues central to our development program. To do so requires the judicious choice of the best possible components (gear tooth geometry, gear train architecture, bearings, force path, etc.). Our goal is to use the simplest possible configuration with a minimum set of design parameters that produces the highest overall performance for the transmission between the servomotor and the driven load. We want to do this so that the design process becomes transparent (no longer a mysterious black box approach) to even the nominally trained designer.

**Comparison:** The comparative analysis is presented here for a standard size gear transmission whose outside diameter is approximately 10 to 12" and whose gear ratio is 100 to 1. The first reality is that the commercial drive has many more parts than our hypocycloid concept (almost 5 times more). There is only one critical bearing in our gear train concept and it also acts as the bearing for the joint of the machine as well. This joint cross-roller bearing is exceptionally rugged, having a very high load capacity (radial, thrust, and out-of-plane moment) as well as exceptional stiffness in all directions (ideal as a joint bearing for heavy-duty applications). Because of the minimal set of parts involved in our concept, it has far fewer critical design parameters to manage in the design process (getting to the optimum is much more likely). Since there are fewer critical dimensions and because the hypocycloid geometry is so forgiving, the system is less expensive to manufacture and simultaneously less sensitive to changes in operating temperatures (certainly, both of these are major issues for the commercial drive used in this comparison).

But, the truly exceptional aspect of our concept is its torsional load and stiffness properties. The hypocycloid gear teeth (concave/convex mating surfaces) provide Hertzian stresses 8 times below the AGMA standard, shear stresses 4 times below the AGMA standard, and bending stresses 2.5 times below the AGMA standard. Under these conditions, our concept will carry 2.5 times the load at a comparative stiffness of 4 times relative to the commercial drive. Note, because the sliding velocity for teeth in this class of hypocyclic gear train is low, the friction power losses are also lower. We believe our losses are 50% of the commercial gear train. Finally, precision cut circular arc gear teeth should dramatically improve the accuracy of our gear train and significantly reduce lost motion during load reversals in comparison to the existing best practice commercial product.

All of these comparisons easily allow us to claim two orders of magnitude overall improvement based on our concept. We may even b be able to defend an improvement of four orders of magnitude. Results like this show that concentration on the design, prototyping, and commercialization of this gear transmission concept will, indeed, be rewarding. Use of all the sciences (materials, gear tooth surface treatment, gear tooth geometry, finite element methods, in-depth metrology, etc.,) should show further improvements in this concept. We contend that this technology is just beginning, having been forgotten for decades and ready for a rebirth in the field of intelligent open architecture machines.




| PROPERTY | COMMENT | BENEFIT |
|---|---|---|
| Torque Capacity | Rugged Crankshaft Bearings | 4.5X |
| Endurance | Contact Stresses In PE Are 3X Less | 3X |
| Output Stiffness | Internal Deformations and Length of Force Path in PE Are 2.5X Less | 2.5X |
| Pressure Angle | In PE $\gamma = 7^\circ$, While in the Nabtesco $\gamma > 30^\circ$ | 5X |
| Mesh Friction | PE Sliding Velocities Are 3X Less Than For Nebtesco | 3X |
| Lost Motion | PE Tooth Load Distribution is Central While Nabtesco is Not | 4X |
| Balancing Mass | Dual PE is Inherently Balanced | 1X |

Fig. 5.1

**ACTUATOR DEVELOPMENT AT UT AUSTIN**

1. FIRST PROTOTYPE RESULTS (1988)
   - Dual/Symmetric System
   - Frameless Configuration
   - Total Benefit Was 200x over SOA
2. PROJECTED BENEFITS FOR 1990 DECADE ($10^4$)
   - Weight 3 to 10x
   - Compactness 3 to 5x
   - Stiffness 3 to 10x
   - Interfaces 2 to 4x
   - No. of Bearings 3x
   - Redundancy 2x
3. PROJECTED BENEFITS FOR 2000 DECADE ($10^4$)
   - Performance 3 to 10x
   - Weight 3 to 5x
   - Stiffness 3x
   - Fault Tolerance 4x
   - Intelligence 10x
   - Standard Interface 4x
4. TWO DECADE ACHIEVEMENT

   Eight Orders of Magnitude ($10^8$) Similar to Moore's Law

Fig. 5.2

## 6. Actuator Criteria Based Decision Making In Terms Of Performance Maps/Envelopes

**Objective:** The reality of mechanical devices is that they are highly nonlinear and their operational parameters drift over time due to aging and extended operation. Increasingly, these devices are becoming more complex, and the user community wants continued improved performance at lower costs. This implies working closer and closer to the operational margins of the device (its torque, acceleration, temperature, endurance, etc.). This means that classical methods of control based on simplistic linearized models can no longer be the basis for continued growth in the technology. Because of our ever-improving computational capability, we can replace the antiquated analog approach with a digital approach based on quantitative parametric description (what may be called the "model" reference) of the mechanical system and its real time "sensor" reference derived from a full array of internal sensors. To do so means that we must create a new decision paradigm based on performance maps (norms), performance envelopes (chosen by the user), trends of device capacity, etc.

**System Performance Criteria:** The University of Texas has 20(+) years of work for criteria based decision making at the decision level, having created about 100 performance criteria with 50 operational in our system software (OSCAR). These criteria apply to dexterous machines such as robot manipulators (6 to 10 DOF) up to manufacturing cells (20 to 40 DOF). The controlling parameters at the joints (position, velocity, acceleration, torque, etc.) are well known and relatively precise. The system dimensions (links joining the actuators) are well known and precise. Hence, the math descriptions of the performance criteria are quite quantitatively precise and computationally reliable. These criteria, however, are volatile and have weak physical meanings, making judgment of the system's quality of performance difficult. Also, these criteria can be highly coupled and frequently in conflict.

**Actuator Criteria:** Actuators are the drivers of all dexterous machines. In this case, there will be a series of performance maps that are required to describe each component of an actuator (bearings, prime mover, gear train, and power supply). These maps may have to do with torque, losses, acceleration, noise etc. They are usually monotonic (the opposite of volatile). We usually have an excellent physical meaning for the map. Most of these maps are independent of each other. Unfortunately, most of these maps will be quantitatively imprecise. System level maps are dependent on 5 (up to 20) independent control parameters, making their quantification and storage unwieldy. Hence, their local values must be calculated as performance criteria in real time. By contrast, actuator maps are relatively simple, enabling their storage in simple computer chips. Hence, the nature of the system criteria (map) and those at the actuator level are complete inverses of each other.

**Actuator Performance Map Descriptions:** Each actuator will require numerous performance maps to provide for their adequate description (let's say 10 each for the power supply, bearings, gear train, and prime mover). We will label these as:

$P_g$ -- gear train map
$P_s$ -- power supply map
$P_p$ -- prime mover map
$P_b$ -- bearing map

Each of these maps will be described by two parameters which are distinct in their nature. These are:

$c_i$ -- These are the control parameters that are used to manage the actuator's operations. These may be voltage, current, turn-on/turn-off angles, etc.

$r_j$ -- These are the key reference properties to describe the actuator's operation. These may be speed, torque, velocity, acceleration, temperature, etc.

This means that each performance map will be labeled as: $P_{ij} = f(c_i, r_j)$ where i, j are the counters on the control and reference parameters. Either two $c_i$, two $r_j$, or one of each will be used to describe the performance map (which is clearly a surface in a 3-D plot of the map).

**Basic Performance Map Numbers:** Each performance map will require a norm to numerically measure its overall magnitude and relative physical meaning. The norm could be a root-mean-square value for the surface. Or, the norm could measure the range between its minimum and maximum values. Or, the norm could describe its volatility, or vice versa, how monotonic it is. Norms could be associated with how uncertain (imprecise) its data is. This uncertainty could have its own set of norms (min.-max., volatility) and have meaning relative to the maps' absolute norms.

**Performance Envelopes:** This means that the operator chooses to combine several performance maps into a unique envelope – say, one which combines all maps associated with losses, into an overall indication of efficiency. In this case, the envelope would be described as: $E = f(P_g, P_p, P_s, P_b) = f(c_i, r_j)$. Each envelope would use the same $c_i$, $r_j$ to describe each of its controlling performance maps. Clearly, there can easily be hundreds of feasible envelopes. These envelopes would be tested extensively to validate their meaning to describe the operation of the actuator. Then, these proven envelopes would be embedded in the electronic controller to be selected by the operator. It would be rare for the operator to define the envelope (select its map components). Rather, they would indirectly select an existing envelope by requesting:

| | | |
|---|---|---|
| Watch out! | Be stiff. | Etc. |
| It's a tight fit. | Don't make noise. | |
| Go slow. | Hurry | |

**Actuators With Extra Resources:** The standardized actuator has only a limited number of physical resources. The choices of various performance envelopes, however, will make it electronically reconfigurable and, therefore, capable of meeting a wide range of application requirements. Given more resources inside the actuator, such as further expands the breadth of functional capabilities any one actuator can represent.

Duality
Layered position, velocity, or acceleration
Force/motion combined
Etc.

It also makes for a more complex decision making environment. For example, the simplest of these would be a duality of equals. Both sides would have identical performance maps and envelopes. The only question would be the balancing criteria that occurs when one of the sides degrades.

For layered control, we mix two different scales of operation (10 to 1, 100 to 1, even 1000 to 1 or any combination) with two distinct sets of criteria/maps/envelopes and a new set of mixing criteria (hybrids) and envelopes. Now, we truly have a complex decision making environment. This is where the growth potential is for intelligent actuators. This is what is meant by the concept of biological equivalence*. We are only starting on the development of this technology. Relative to the computer chip (and the electrical control valve), the present actuator is technically referenced to the decade of 1950-60. We have the opportunity to accelerate the development of the whole field of machines by making actuators fully intelligent.

**ACTUATOR PERFORMANCE MAPS**

I. POWER SUPPLY MAPS
- Conduction Losses
- Turn-On Switch Losses
- Turn-Off Switch Losses
- Gate Drive Losses (2)
- Total Harmonic Distortion (2)
- Temperature
- EMI
- Response Time

II. PRIME MOVER MAPS
- Temperature
- Torque
- Flux Density
- Copper Loss
- Other Losses
- Torque (Turn On/Off Angle)
- Torque Ripple
- Torque (PWM Duty Cycle)
- Average Acceleration
- Acoustic Noise

III. BEARING MAPS
- Endurance/Life (2)
- Friction (2)
- Temperature
- Noise (2)
- Radial Stiffness
- Clearance
- Permissible Speed

IV. GEAR TRAIN MAPS
- Bending Stress
- Contact Stress (2)
- Gear Box Temperature
- Flash Temperature
- Efficiency
- Permissible Load
- Stiffness
- Backlash/Lost Motion
- Vibration/Noise

Fig. 6.1

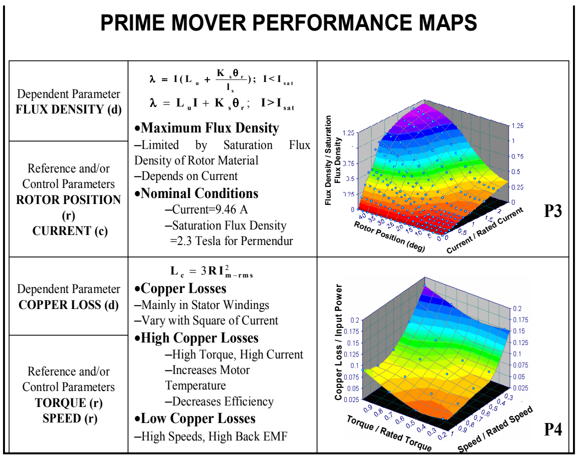


Fig. 6.2

* See "Machine Equivalence to Biological Systems," D. Tesar, March 24, 2005.

## 7. Condition Based Maintenance For Intelligent Actuators

**Objective:** The goal is to monitor the performance capability over time of intelligent actuators as principal drivers of mechanical systems. These actuators represent more resources to perform their function under human command (duality for fault tolerance, layered control, force/motion control, multi-speed operation, etc.). Because of this complexity (sensor array, power supply, electronic controller, prime mover, bearings, gear train, tooth mesh), sources of degradation can come from many components in the actuator. This degradation now demands a formal analysis for predicting performance reduction, reviewing useful life, time at which replacement is warranted, etc., with increasing accuracy and, therefore, reduced false alarms.

**Background:** Until recently, most actuators were informal assemblies of separately designed and produced components such that their integration into an actuator left uncertain results and certainly little chance to embed a significant array of choices (acceleration, efficiency, stiffness, lost motion, etc.) under human control. Today, the desired level of choice (intelligence) is increasing while improved performance to cost is also desired. Multiple resources (duality, layered control, force/motion control, multi-speed operation) combined with a full array of carefully integrated components (power supply/electronic controller, prime mover/brake, bearings, and gear train/tooth mesh) now requires a full management process (with real time software) to obtain best performance, durability, efficiency, etc. to match an ever-changing duty cycles.

This leads to the ultimate question for intelligent actuators: What is their durability and when should they be replaced (for maintenance reasons or to update the system) and how can this be done without false alarms?

**Proposed Development:** All components in an intelligent actuator can be represented by a finite number of performance maps obtained by extensive testing or physical modeling during the certification process. These performance maps (perhaps ten per component) can be combined into performance envelopes (losses, efficiency, acceleration, peak torques, power production, etc.). These envelopes (perhaps hundreds) become decision surfaces for the actuator. These envelopes must be reduced to norms (peak values, volatility, volume, physical dimensions, scales, etc.) which can be the basis for intelligent control; i.e., they represent an overall indication of the available performance (capability) of the actuator to meet any objective for the system's duty cycle demands.

The University of Texas has formulated a Decision Making Computational Mathematics (DmCm) process to manage this complexity and is developing an Actuator Management Operating Software (AMOS) for that purpose. AMOS will retrieve sensor data in real time from 10(+) distinct physical phenomena (measurands such as noise, vibrations, velocity, torque, voltage, current, etc.), analyze this data to control the actuator's response to system demands in terms of the envelope decision surfaces, use this real time data to update these decision surfaces to evaluate how these surfaces change in time (we expect degradation of performance), and establish measures of degradation to indicate available capability versus that required (differencing of required vs available maps and envelops). These differences (can be considered as volume difference norms) would be thought of as residuals on which to make fundamental decisions relative to command responses and remaining useful life. These residuals would be constantly updated by AMOS. Criteria for action would be chosen by the system's operator.

Once this capability is in place, then through extensive testing, a record of all degradation residuals and actual faults would be embedded in a finite fault tree that would be part of the decision structure of that unique actuator design. Each fault would be represented by a recommended action strategy (call for replacement, continue operation at lower performance, provide for duality to continue operation under a significant fault, etc.). Finally, the fault tree would represent lessons learned for improved component development, design, and production, provide guidance on performance-to-cost ratios, and maximize the responsiveness to any given complex duty cycle. Given this level of decision making, active actuator management software (AMOS), improved component design, etc., potential false alarms would be reduced. Also, spares management should become more predictable and therefore less costly. Finally, given severe duty cycle demands, it would be possible to measure and predict the reduction of the actuator's reserves to continue operation. Hence, the operator knows in real time how costly his/her operational decisions are.

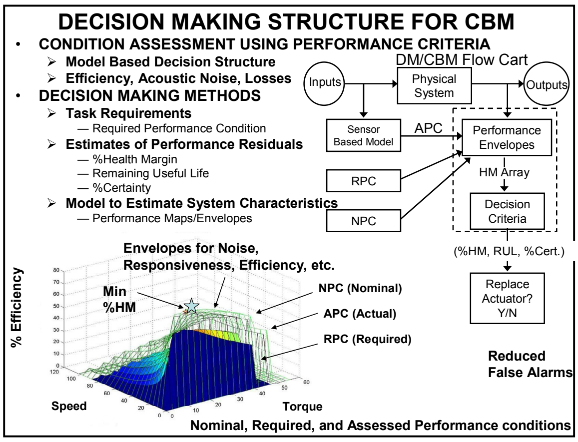



Fig. 7.1

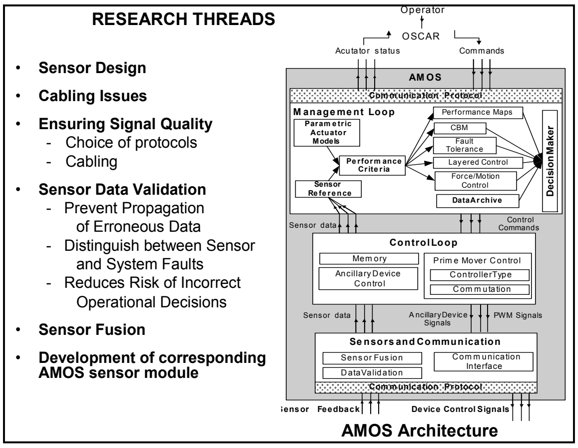
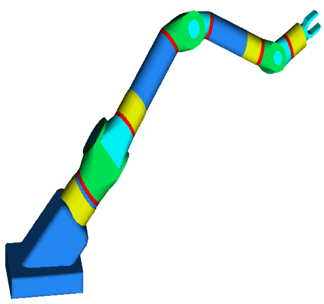



Fig. 7.2

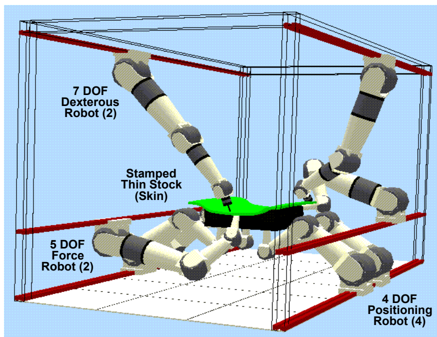
## 8. Intelligent Robot Systems And Control Software

**BACKGROUND:** The goal of the Robotics Research Group (RRG) at The University of Texas at Austin is to develop open architecture mechanical systems that exhibit increased performance at lower costs through the development of standardized building blocks. To achieve this goal, the RRG has pursued three key areas of development. The first is the development of Standardized Actuators and their associated component technologies. The second thrust of the RRG is the development of operational software and analytics for manipulators. The third is the development of manufacturing workcells and the associated software to design, control and integrate such systems.

Intelligent Actuators
(Self-Contained)



Manipulation Software
(Open Architecture)




Manufacturing Workcells
(Up to 40 DOF in Parallel)

Fig. 8.1

**8.1 Foundation Technology:**

The RRG has a 40 year history of analytical development in the field of robotic systems. The core of this development is in the establishment of generalized modeling of robotic systems in terms of kinematic, dynamic and compliance properties. Over the years, this has allowed us to analytically define independent performance criteria that can be used to optimize the control and design of robotic systems. In this area, over 70 different performance criteria have been developed, with 10 just in the area of obstacle avoidance. This basic development now acts as the foundation for our system-level research into six distinct areas.

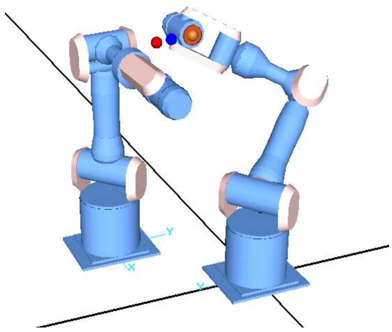


Fig. 8.2

**8.2 System Design & Configuration Management**: This research allows us to systematically design manipulator systems and processing cells from a limited set of standardized building blocks (actuators). Whereas, the traditional approach to such designs has been to treat actuators as black boxes, our approach involves using the actuator properties (gear ratio, motor inertia, etc.) actively in the design process. This research also addresses the configuration management issues faced due to the exponential explosion of choices when faced with modular systems (actuators, electronic controllers, end-effector tools, links, software, etc.).

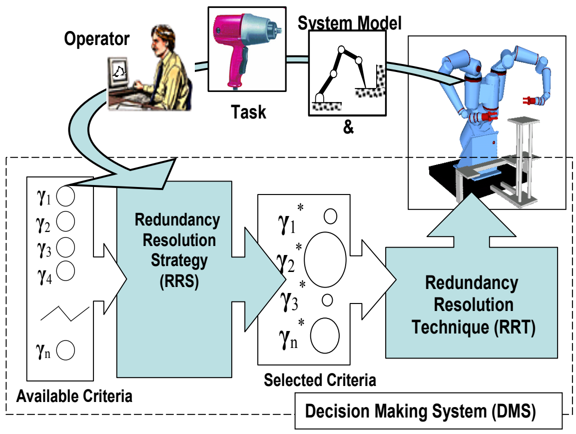



Fig. 8.3

**8.3 Motion Planning and Obstacle Avoidance**: Our research in motion planning focuses on the development of criteria that can be used to describe complex six dimensional paths in space while controlling the smoothness, accuracy, inflexion, etc. of the path. The eventual goal is to relate the path properties with the system capabilities and the constraints placed by the application environment (i.e., the process demands) to develop optimal motion plans. Obstacle avoidance is a key part of motion planning and we are developing first and second order criteria that are based on artificial potential forces. Obstacle avoidance is required for processing cells and can also greatly enhance the man machine interface by automatically guiding an operator towards obstacle free paths and/or towards specific targets.

There is an increasing use of mobile systems for remote operations, surveillance, bomb dismantlement, etc. Most of these systems are augmented by a manipulator for handling purposes, with the manipulator almost always treated as independent of the platform. The goal of this work is to scientifically study the interactions between a mobile system and the manipulator and to develop analytical techniques that improve the task performance of the complete system. Issues such as mobile system positioning versus manipulator accuracy, dynamics under high speed operation, etc. will be studied.

**8.4 Decision Making & Performance:** Manipulator systems are very nonlinear, uncertain, highly coupled, and implicit; thus requiring novel intelligent control methods that are different from conventional control approaches. As mentioned earlier, RRG's approach utilizes performance criteria (relative priorities set by human intervention) to better match manipulators capabilities with the task requirements. This research thread aims at developing techniques that allow the selection of appropriate criteria based on task constraints, methods to combine performance criteria, and conflict resolution strategies in the case of disjoint task goals, all while keeping the operator as the final arbiter.

Our decision making approach makes the assumption that the manipulator is redundant (i.e., it exhibits excess resources) and hence its performance can be improved by intelligently utilizing the redundancy. Unfortunately, there are few redundant systems commercially available and almost nonexistent in industrial use. One of our goals is to adapt our decision making system and develop new performance criteria that can be used to improve the performance of standard industrial systems (6 DOF or less). Our approach here will be to actively manage the task constraints faced by a manipulator and identify any underutilized resources that can be used to optimize the operation of the system.

**8.5 Human Machine Interfaces:** RRG's effort in this area has focused on the development of novel manual controllers and the actuators required for such a system. Additionally, we have developed a general software library for interfacing various categories of manual controllers into a telerobotic system. Realizing that a manual controller by itself is not a sufficient interface for an intelligent system, we plan to formally develop a generic human machine interface that can support various input mechanisms such as a manual controller, GUI, voice, etc. This interface will have to be semantically complete and will demonstrate its functionality in a hierarchical fashion. An important goal of this work will be to illustrate the increased capability of our decision making resource management system in an intuitive and user friendly way.

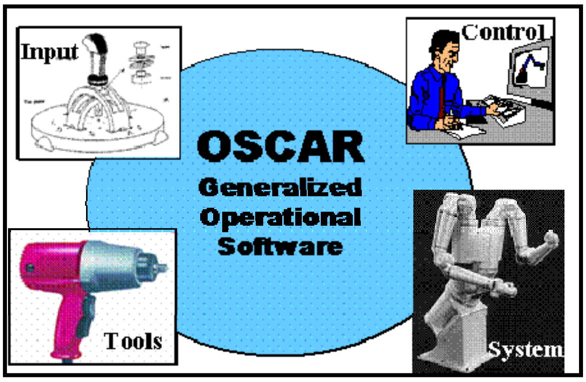



Fig. 8.4

**8.6 End Effector Tools:** The ability of a processing cell is directly related to its intelligent use of end-effector tools for specific tasks. This research addresses the generalized modeling of tools and how the tool model can be related to manipulator performance criteria. The goal is to provide the best match of the tool properties (usually invariant) to the full adaptability of all resources in the manipulator. As such, a procedure to formalize the parametric description of various tools is being developed.

**8.7 Operational Software:** All analytical activity at the RRG is currently embedded in its system operational software framework called OSCAR.

OSCAR is an object-oriented library of C++ components that offer generalized kinematics, dynamics, performance criteria, obstacle avoidance, decision making and machine interfacing. This framework is based on well defined interfaces and allows easy substitution of OSCAR components with externally developed components. The generalized nature of OSCAR and the object oriented structure have led to reduced program development time by entry-level personnel and made possible the development of a universal processing cell controller.

While OSCAR provides the building blocks for intelligent machine software, the manner and mechanisms through which OSCAR components are composed remains manual and dependent on the software developer. This effort will develop formal operators (similar in concept to mathematical and logical operators such as +, -, and, or, etc.) that could then be used to construct OSCAR specific applications. These high level operators will lead to consistent programs with quantified performance and increased reliability. Key requirements that will drive this development will be integration, real-time capability, and machine independence.

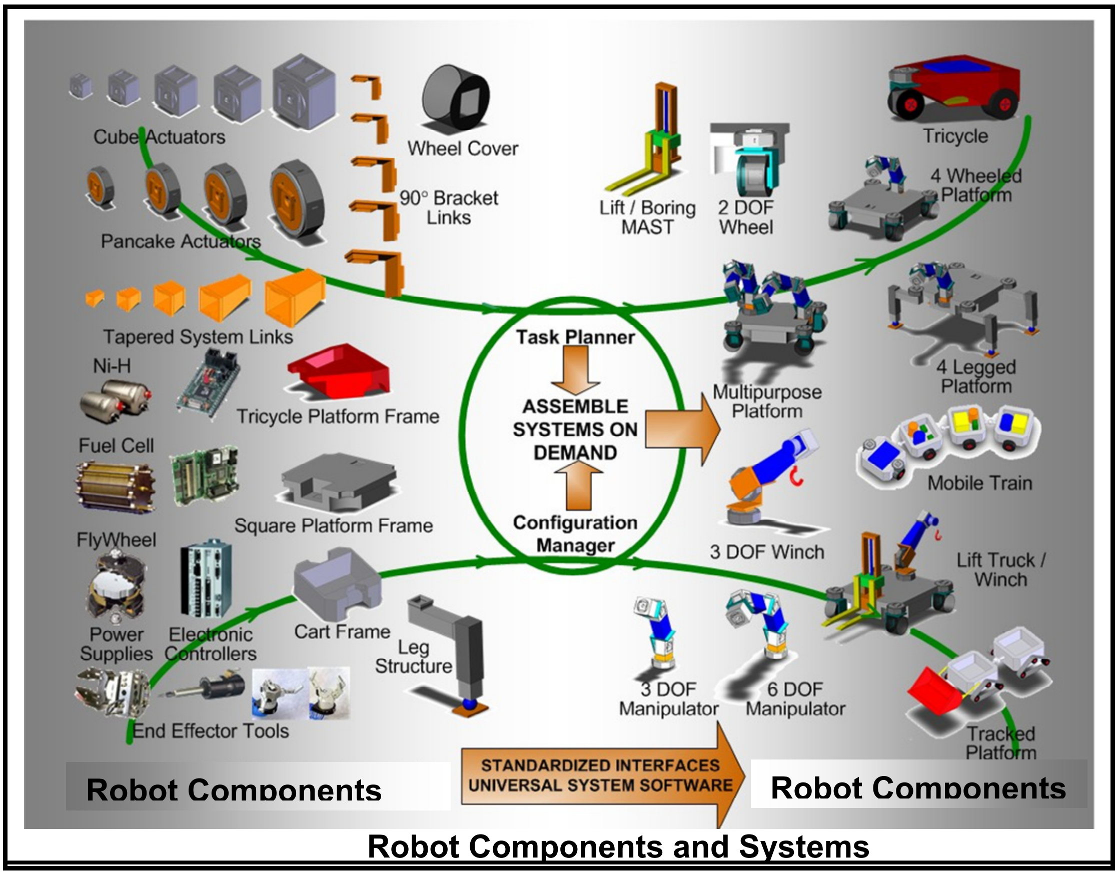


Fig. 8.5

## 9. Miniaturized Robotic Systems For Surgery

**Objective:** It is proposed to establish a framework for the development of modular manipulator systems to act as extensions of the human surgeon through a sophisticated visual and kinesthetic interface. The basic building block for this system is a newly conceptualized 2 DOF knuckle actuator module that can be scaled at ½", ¾", and 1" to then be assembled into any set of dexterous robotic systems from endoscopes (solid rods with a 2 DOF module at the end up to 10 DOF highly dexterous snake type systems). These ceramic based modules (which are magnetically lucent) would have standard interfaces, standard embedded software/ controller combinations, and four actuators in a symmetric array to give the module maximum structural integrity in the smallest possible package. This dexterous open architecture system would be combined with a set of ten smart surgical tools (with quick change interfaces) usable either directly by the surgeon or robotically as end-effector tools.

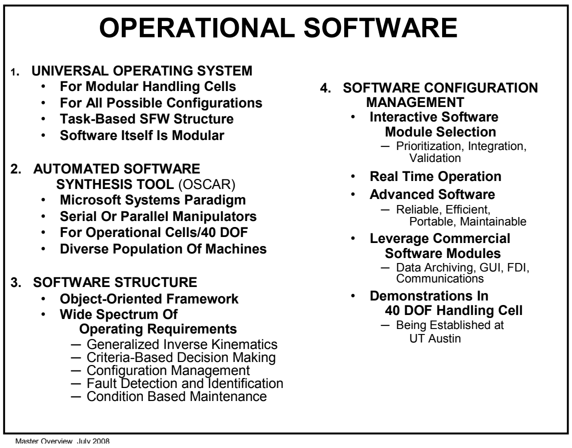



Fig. 8.6

**Background:** Miniaturized robotic systems have not experienced much development to-date primarily because of limitations of actuators of this small scale. The need for miniaturization derives from the functional spectrum associated with such tasks as assembly of micro-electronic devices as well as such human operations as micro-surgery. Micro-assembly involves delicate operations such as inspection, soldering, and placement of very small parts in electronic systems either in their manufacture or their repair. Similar activity is associated with operations dealing with processing of extreme hazard biologicals. Today, micro-surgery involves the use of a microscope to enhance the vision of the surgeon up to a factor of ten and to correlate this vision with preoperative visualization of the surgical site. This has been a major advantage in the fields of eye, ear, throat and brain operations.

In robot – assisted surgery, the primary objective is to augment the human surgeon’s motor capacity by at least a factor of 10 to complement his enhanced visual capacity. One of the goals of the system under consideration in this proposal is to lengthen the productive life of surgeons. The other immediate goal is to enhance his/her precision by a factor of 10 by high quality servo-controlled actuators in a dexterous manipulator, by changing scales of the operation through computer enhancement, and by filtering jitters, oscillations, or gross errors out of the input supplied by the surgeon’s fingers and hands.

**Long-Term Development Objective:** The University of Texas has proposed a ten-year development in two phases to create a revolutionary open architecture surgical assist system based on standardized actuator modules, smart tools, and a versatile surgeon’s cockpit, all operated with a universal software package (developed at UT Austin) to provide the surgeon a natural and organic means to operate the system. Phase I would be used to develop the critical component technologies (actuators, smart tools) and to carefully structure the full surgical system with continuous interaction with the user community. Phase II of the program would concentrate on the development (prototypes, clinical trials, training systems, etc.) of the full robot assisted system. It would be based on an open architecture which allows the system to be assembled on demand to meet any specific class of surgical tasks (just as we now do for computers). This openness means that multiple suppliers of the technology (actuators, tools, controllers, software, etc.) would be capable of continuously infusing advanced components without disturbing the larger system (thus reducing costs, eliminating the threat of obsolescence, and making repair feasible with a nominally trained technician). An early program to develop this technology is being funded by DARPA for their battlefield Trauma Pod concept with emphasis on system software and interaction with the surgeon. A future phase of the program will emphasize miniaturization, precision, modularity, plug-and-play maintenance, and cost-effectiveness.

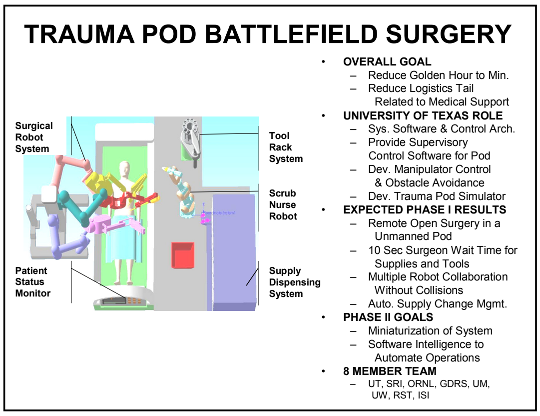



Fig. 9.1

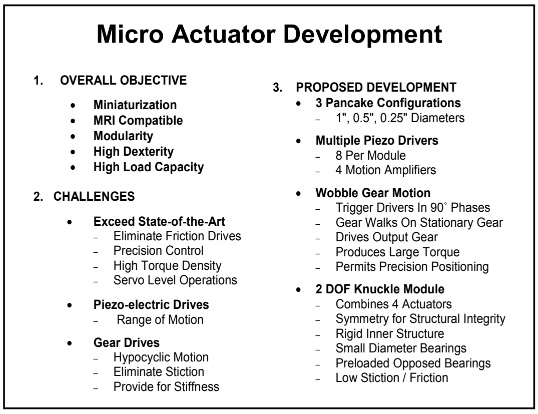



Fig. 9.2

## 10. Conclusion

This is not a normal assessment of the research publications of a community of scholars. It is, in fact, the collection of research objectives of a directed research team over the past 50 years as represented by the major position papers given in Sec. 11.1 over the past 30 years. The principal conclusion is that the discipline of mechanical engineering has not been sufficiently aggressive to maintain its relative position with other disciplines. In fact, because future intelligent machines are highly nonlinear where conflicts among numerous criteria must be resolved in milli-sec., it is not surprising that this expansion of the purpose and range of the required problem solving capability had to wait until the present wave of technology (computers) had reached its promise and effectiveness.

Increasingly, the most rewarding systems are those that move to accomplish tasks under human control or supervision (robot surgery, human rehabilitation, battlefield robotics, warehouse operations, entertainment systems, etc.). Increasingly, the human wants to issue very simple commands (be efficient, accelerate, watch out, be safe, be quiet, etc.), which requires a level of intelligence and decision making completely different from standard modern control methods (and certainly distinct from the concept of autonomy). Uncertainty is involved, conflicts among criteria and priorities, high levels of nonlinearity, the need for mission planning and situational awareness, all requiring a new class of decision making and operational software, as illustrated in some of the papers listed in Sec. 11.3.

This, then, leads to the question of open architecture, or the assembly, repair, and refreshment of these systems on demand, just as we now do for computers. It requires the development of a minimal set of highly certified components provided by a responsive supply chain to an integrator of the product (like Michael Dell). This will soon happen for most of our active mechanical systems (in particular automobiles). The basic building block of all these systems is the intelligent actuator with standardized interfaces (for hub drive wheels, active suspensions, human rehabilitation exoskeletons, reconfigurable manufacturing systems, surgical cells, etc.). I.e., the actuator is the basic building block for all active systems as the electronic chip is for computers. Today, the world market for actuators exceeds \$100 billion/year. It is predicted that this market will exceed the computer chip market in two decades. Also, there will be the equivalent of Moore's Law for actuators. In fact, this development is only beginning. That is why it is the best time in 100 years to be a young mechanical engineer (See Sec. 11.2).

## 11. References

### 11.1 Major Position Papers

Tesar, D., (1978), *Mission Oriented Research for Light Machinery*, Science, pages 880-887.

Tesar, D., (1980a), *Mechanical Technology, Part I: The Tragic Need*, Mechanical Engineering, Vol. 102, No.2, February 1980.

Tesar, D., (1980b), *Mechanical Technology, Part II: A Proposed National Program*, Mechanical Engineering, Vol. 102, No. 3, March 1980.

Tesar, D., (1989) *Thirty-Year Forecast: The Concept of a Fifth Generation of Robots – The Super Robot*, ASME Transactions on Manufacturing Review, Vol. 2, No. 1, pages 16-25, March 1989.

Tesar, D., M.S. Butler (1989) *A Generalized Modular Architecture for Robot Structures,* ASME Transactions On Manufacturing Review, Vol. 2, No. 2, pages 91-118, June 1989.

Tesar, D., (1990) *U.S. Robotics Technology*, Presented to the Democratic Caucus, U.S. House of Representatives, September 12, 1990.

Tesar, D., (1993) *Status of U.S. Manufacturing: A Proposed National Program,* Conference on a Sustainable Society, NUSP, Sao Paulo, Brazil.

Tesar, D., (1999) *Technology for Wealth Generation, Comments On A book by Lester C. Thurow,* Building Wealth Seminar, Technical University of Budapest, Hungary, September 7, 1999.

Tesar, D., (2001) *Meeting Human Needs While Reducing Human Drudgery,* Plenary Speech, IEEE Conference on Intelligent Systems, Istanbul, Turkey, October 2001.

Tesar, D., (2002) *Human Scale Intelligent Mechanical Systems,* Journal of Engineering & Automation Problems, Moscow Center for Scientific and Technical Information, Moscow, Russia, Vol. 4.

Tesar, D., (2004a) *Human Scale Intelligent Mechanical Systems,* Plenary Paper, 11th World Congress in Mechanism and Machine Science (IFTOMM), Tianjin, China, April 2004.

Tesar, D., (2004b) *Meeting Human Needs While Reducing Human Drudgery,* Proceedings, ASME Winter Annual Meeting, Anaheim, California, November 16, 2004.

Ashok, P. & Tesar, D. (2008) A Visualization Framework for Real Time Decision Making in a Multi-input Multi-output System, *IEEE System of Systems Journal 2(1), pp. 129-145*

### 11.2 Papers On Actuator Design

Grupinski, S. and Tesar, D., (1996) Design of Low Cost Robotic Actuators for a Modular, Reconfigurable Six-Degree of Freedom Robotic Manipulator, Report, UT Austin Robotics Research Group.

Smith, S., (1984) A compact Electromechanical Actuator, Proceedings, National Aerospace and Electronics Conference, Dayton, Ohio, Vol.1, pages 598-605.

Tesar, D., (2007) Electromechanical Actuator Architecture (EMAA), Compilation of work for years 2000-2007 for Mechanical Engineering, The University of Texas at Austin Robotics Research Group, 270 pages.

Dyson, A, Evans, H. and Snidle, R. (1986) Wilberhaber-Novikov Circular-Arc Gears: Geometry and Kinematics, Proceedings, Royal Society of London, Vol. 403, pages 313-340.

Roos, F. and Spiegelberg, C., (2004) Relations Between Size and Gear Ratio in Spur and Planetary Gear Trains, Royal Institute of Technology, Stockholm, Sweden.

Krishnan, R. (1987) Selection Criteria for Servo Motor Drives, IEEE Transactions on Industry Applications, IA-23, pages 270-275.

Krishman, R., Arumugam, R., and Lindsay, J., (1988) Design Procedure for Switched Reluctance Motors, IEEE Transactions on Industrial Electronics, Vol. 49, No. 1, pages 15-27.

Shuxing, Y. and Ping, Z. (1997) On the Parametric Design of Electromechanical Actuators, Journal of Beijing Institute of Technology, Vol. 6, No. 2, pages 138-144.

Mendez, P.F. and Ordonez, F., (2003) Scaling Laws from Statistical Data and Dimensional Analysis, Journal of Applied Mechanics, Vol. 72, Issue 5, pages 648-657.

Kanukolanu, D., Lewis, K., and Winer, E., (2006 A Multidimensional Visualization Interface to Aid in Trade-off Decisions During the Solution of Coupled Systems Under Uncertainty, Transactions of the ASME, Vol. 6, pages 288-299.

### 11.3 Papers on Actuator Intelligence

Denison, D.G.T., Mallick, B.K., Smith, A.F.M., (1998) Automatic Bayesian Curve Fitting, Journal of the Royal Statistical Society, Series B (Statistical Methodology) 60 (2), pages 333-350.

Druzdzel, M.J. and Leijen, H.V., (2001) Causal Reversibility in Bayesian Networks,Journal of Theoretical and Experimental Artificial Intelligence (JETAI), Vol. 13, No. 1, pages 45-62.

Golverk, A.A. (1995) Diesel Engine Performance Maps Under Variable Loading, ASME Internal Combustion Engine Division, Spring Technical Conference pages 1-12.

Isermann, R. and Ulrich, R., (1993) Intelligent Actuators – Ways to Autonomous Actuating Systems, Automatica, Vol. 29, No. 5, pages 1315-1331.

Nadkarni, S. and Shenoy, P.P., (2001) A Bayesian Network Approach to Making Inferences in Causal Maps, European Journal of Operational Research, Vol. 128, pages 479-498.

Omekanda, A.M. (2003) A New Technique for Multidimensional Performance Optimization of Switched Reluctance Motors for Vehicle Propulsion, IEEE Transactions on Industry Applications, Vol. 39, Issue 3, pages 672-676, May-June 2003.

Onder, C.H. and Geering, H.P., (1995) Model-Based Engine Calibration for Best Fuel Efficiency, Engine and Multidimensional Engine Modeling, SAE SP-1101, pages 213-230.

Pearl, J., (2000) Causality: Models, Reasoning and Inference, Cambridge University Press, March 2000.

Skelar, L. (2004) Bayesian Belief Network Propagation Engine in Java, CO600/CO620 Project Report, Computing at Kent, www.cs.kent.ac.uk/pubs/ug/2004/co600/bbn/reort.pdf

Thrun, S., Burgard, W., Fox, D., (2005) Probabilistic Robotics (Intelligent Robotics and Autonomous Agents, The MIT Press, September 1, 2005.