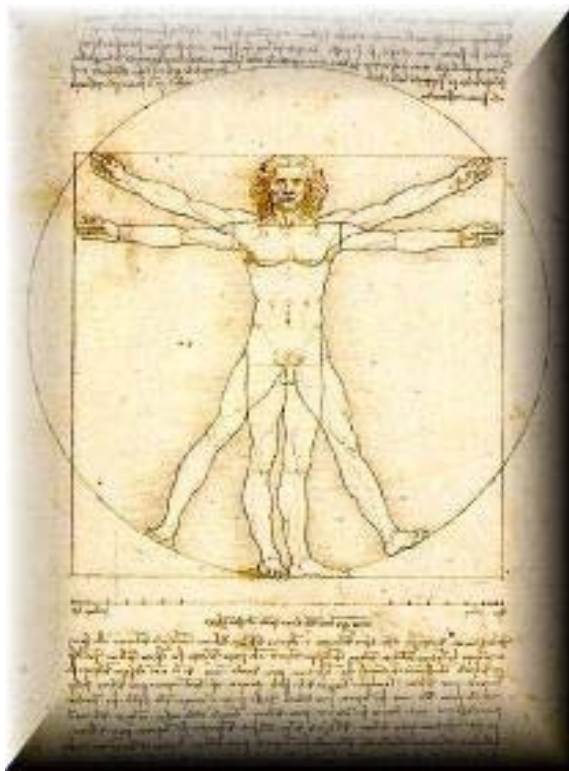


# **NEW WAVE OF TECHNOLOGY**

## **Built On The Core Of Mechanical Engineering**



DA VINCI

PRESENTATION TO:  
**CBM Workshop**  
**TARDEC**  
**Detroit, Michigan**  
November 28, 2007

by

**Prof. Delbert Tesar**  
Carol Cockrell Curran Chair

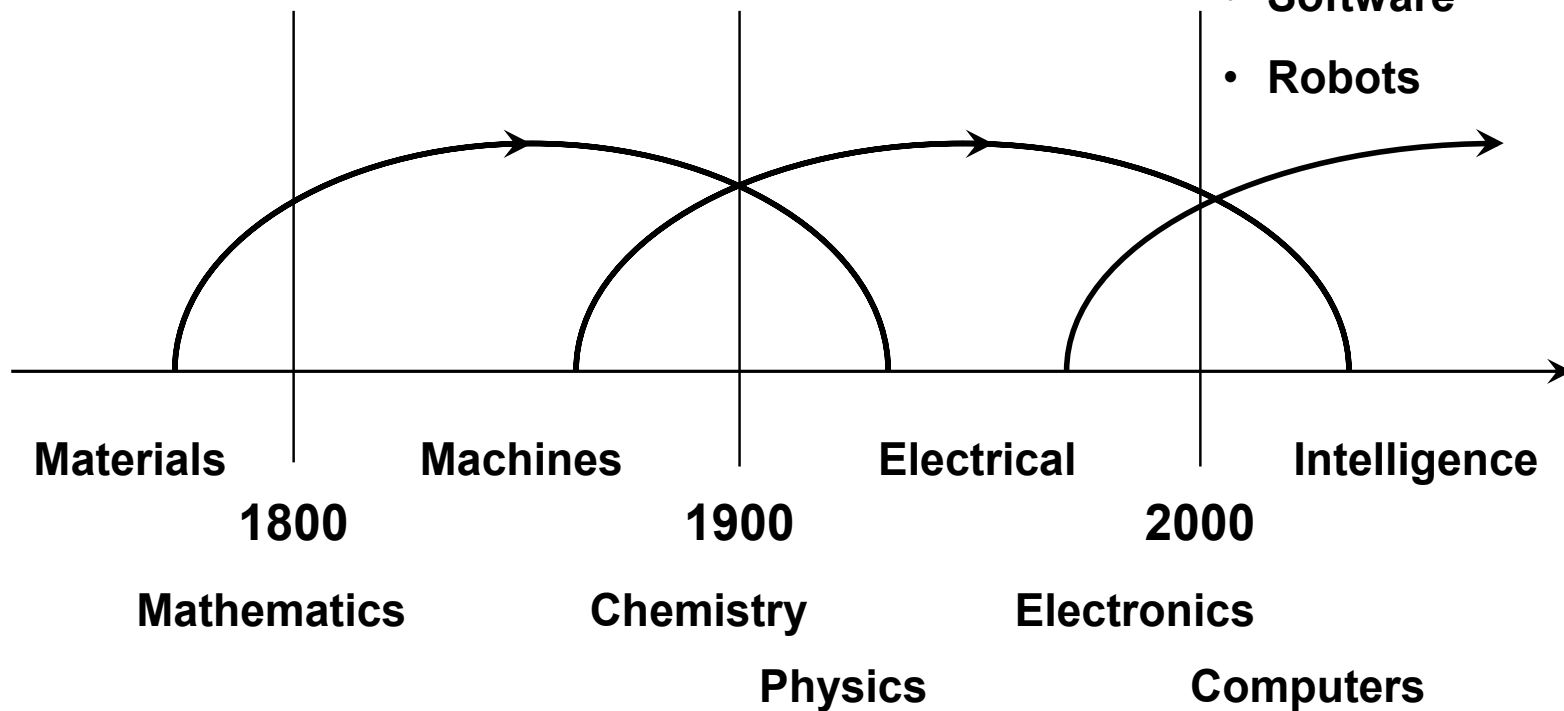
Robotics Research Group  
The University of Texas at Austin

112807

# WAVES OF TECHNOLOGY OVER TIME

(In Balance With Humans  $\Rightarrow$  Human Choice)

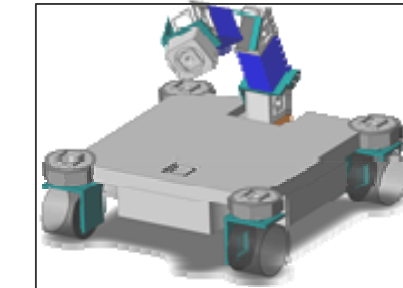
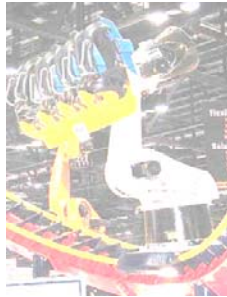
- Water Transport
- Construction
- Land Transport
- Agriculture
- Metal Production
- Air Transport
- Mass Production
- Communications
- Open Architecture Systems
- Software
- Robots



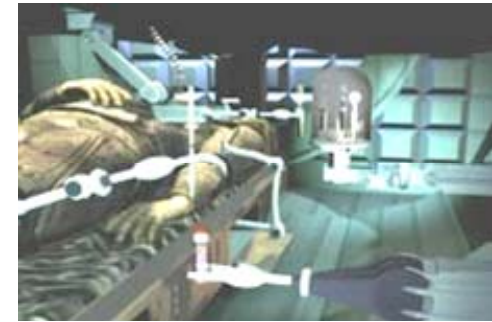
# EMERGING APPLICATIONS



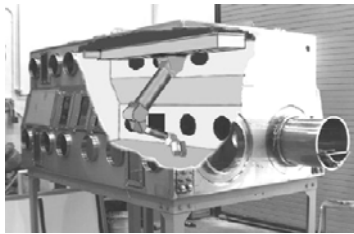
Entertainment Systems



Educational Robots



Surgical Systems



Glove Box Systems



Farm Machinery



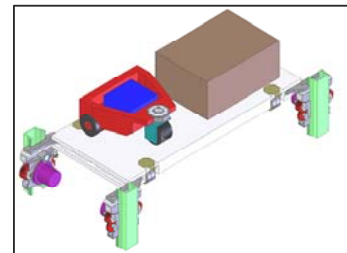
Construction Machinery



Busses (Hybrids)



Trucks (Hybrids)



Elevators (Industrial)



Wind Turbines

# MILITARY APPLICATIONS



Ships/Submarines



Aircrafts/UAV



Tanks/Off Road Vehicles

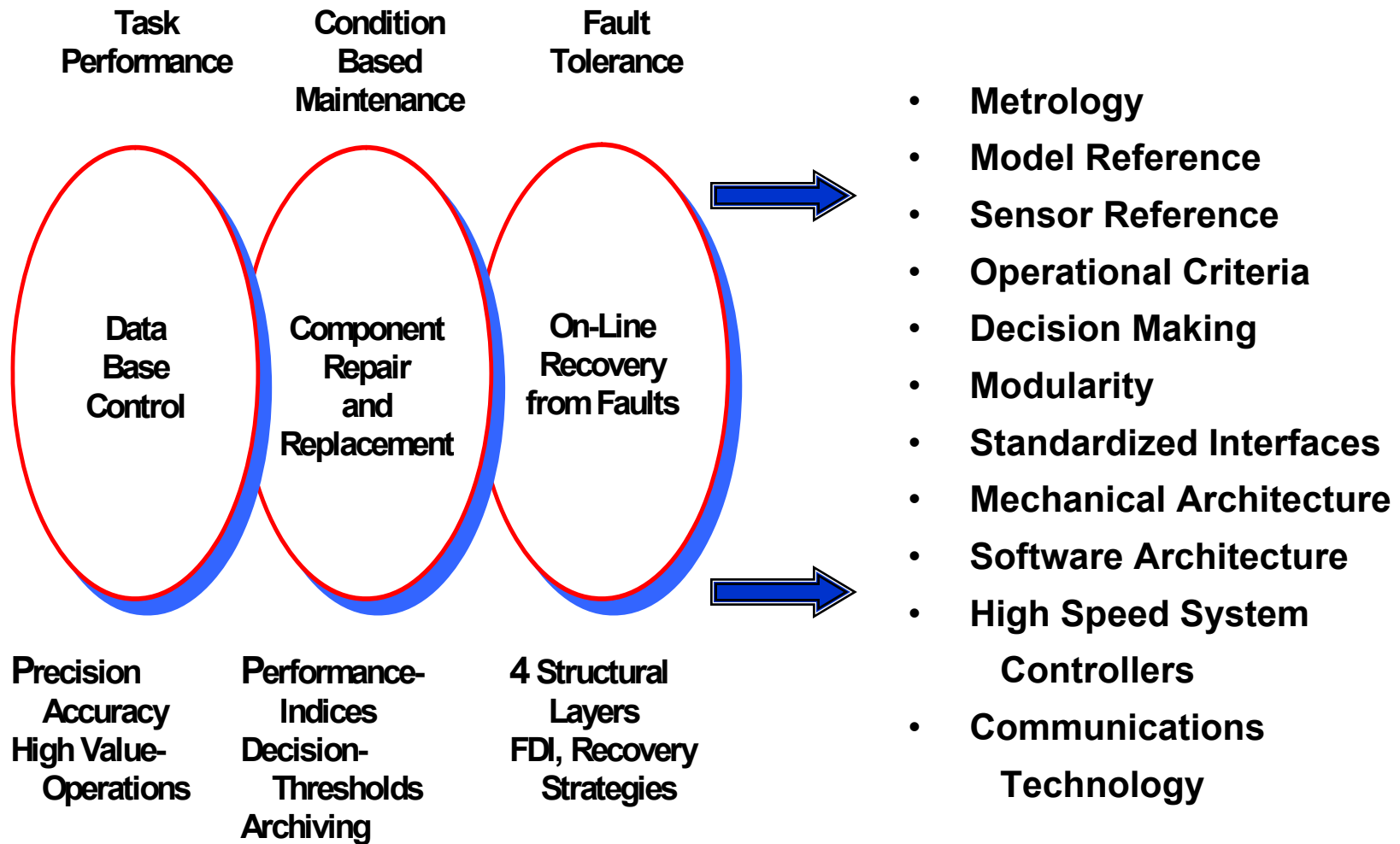


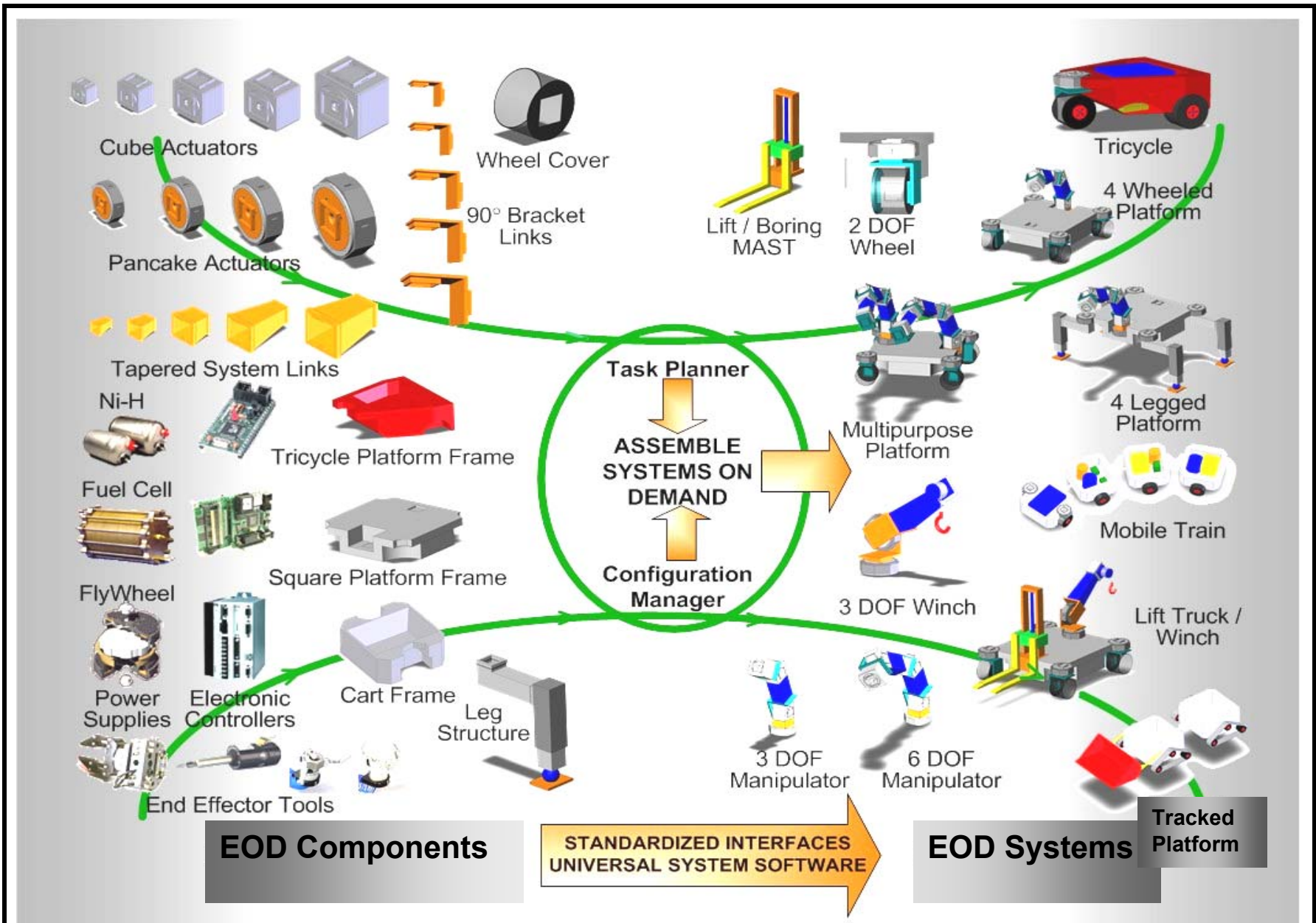
Anti-Terrorism Robots



**Trucks (Hybrid)**

# CONTINUUM for ADVANCED MACHINE OPERATION





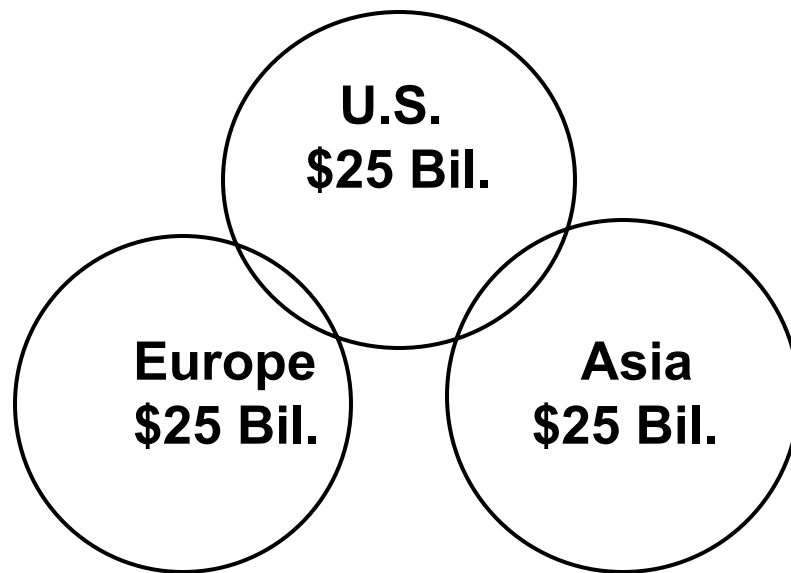
**Figure 1: EOD Components and Systems**

# ACTUATOR/MOTION CONTROL SALES

## 1. WORLDWIDE SALES (Forbes, Nov. 2004)

**\$75 Billion/Year**

- 40% Controller/Electronics
- 60% Motor, Gear Train, Etc.



## 2. 50% GROWTH IN 3 YEARS

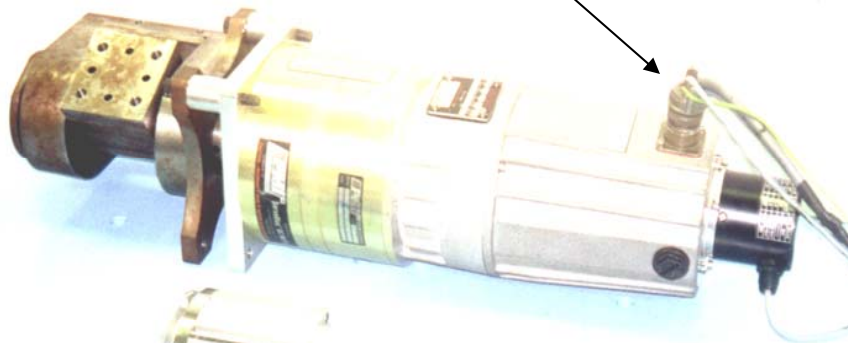
- 3.5X in 10 Years (≈\$250 Bil/Yr)
- More Important Than Computer Chips
- Drives Anything That Moves
- Commercialization Just Beginning

## 3. DIFFERENTIATE CLASSES of SALES

- Military (High End)
- Manufacturing (Medium Class)
- Trucks/Buses/Farm Mach. (Medium Class)
- Entertainment/Education (Low End)

# 1995 State of the Art Actuator Comparison

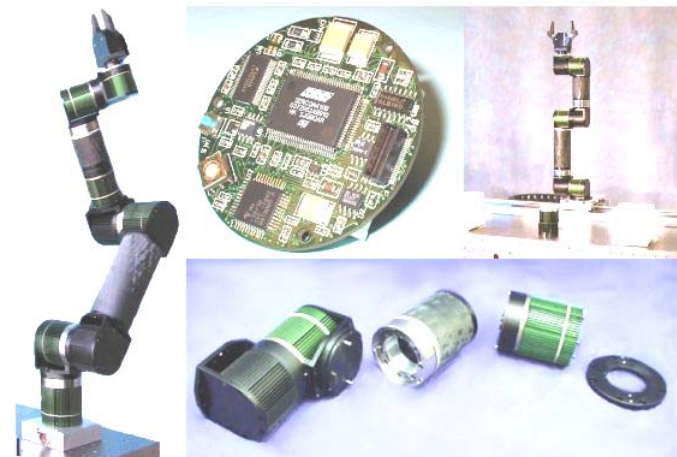
**1995 State of the Art  
Actuator Comparison**



**UT BASELINE PROTOTYPE**

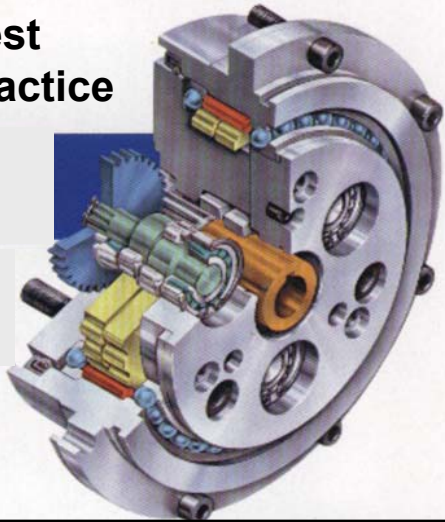


## MODULAR 6 DOF MANIPULATOR



- **Quick-Change Interfaces**
- **Commercial Buses**
- **Embedded Controller**
- **Integrated Joint Bearing**

Best Practice



# GEAR TRAIN COMPARISON

(Based on 6000 HR. Life)

## NABTESCO

- Used in 50% of Industrial Robots
- $\approx 90,000$ -hour Life

## UTEXAS

- Dual PE Gear Train
- 4 Orders Better

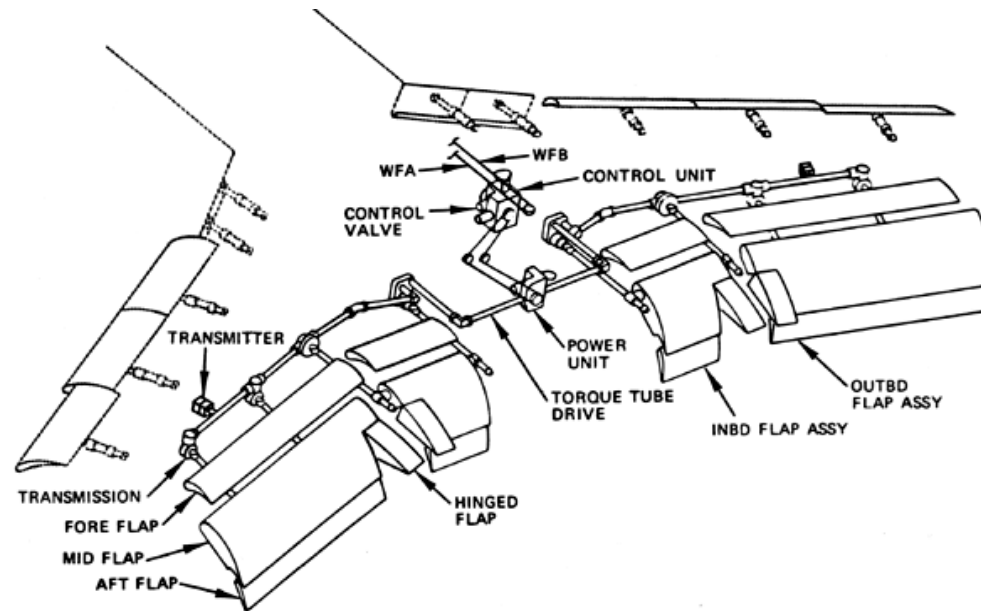


Prototype  
(Parallel Eccentric – PE)

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

# 737 TRAILING EDGE FLAP DRIVE SYSTEM

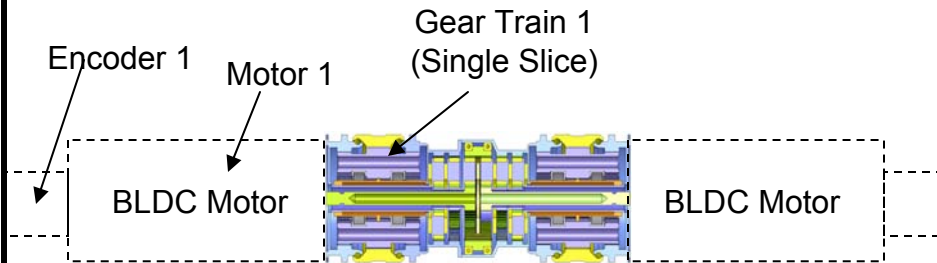
(From: Aircraft Flight Control Actuation, Raymond & Chenoweth, 1991)



## SYMMETRIC DRIVE GUARANTEES FLAP SYNCHRONIZATION

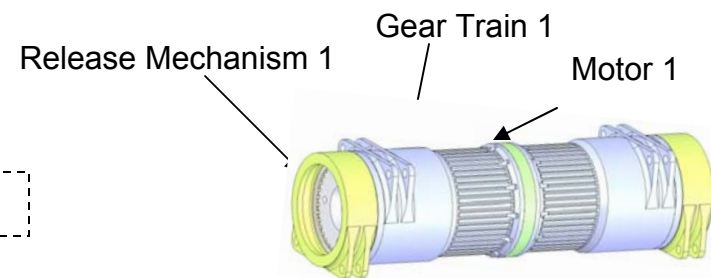
- **Each Flap Rides on Roller Carriages**
  - Mechanism Separates Individual Flaps
- **Power Unit Driven By Hydraulic Motor**
  - Drives Both Torque Tubes
  - Torque Tubes Rotate Bevel Gears
  - Bevel Gears Drive Screw Shaft
  - Screw Shaft Drives Flap on Carriage
  - Two Screw Shafts Per Flap

# Reconfigured Hingeline Actuator Comparison (Dual Motors and Gear Trains)



Weight: 37 [lb] (4" x 24")  
Nom. Torque: 660 [ft-lb]

**AiResearch**  
(Non Jam Tolerant)



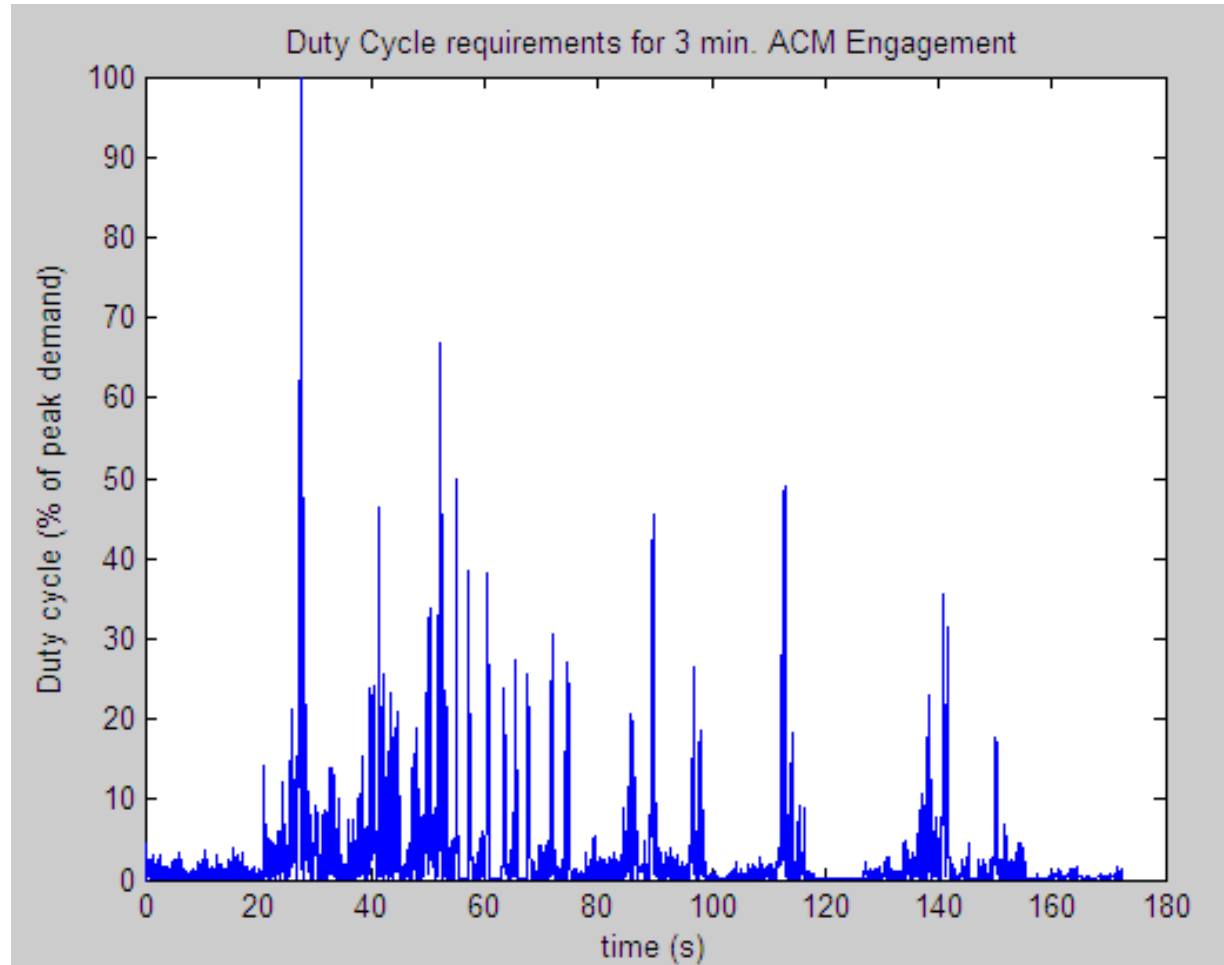
Weight 42 [lb]\*\* (4.62" x 17")  
Nom. Torque: 2537 [ft-lb]

**UTexas**  
(Fault Tolerant)

Performance Category	AiResearch (Baseline)	UTexas (RRG)	Benefit Ratio
Nom. Torque Density* [in-lb/lb]	216	725	3.4x
Stiffness [in-lb/rad]	4.66x10 <sup>6</sup>	66.2x10 <sup>6</sup>	14.2x
Lost Motion [deg]	0.25	0.050	5x
Reflected Inertia [lb-in <sup>2</sup> ]	0.0925	0.0289	3.2x
Number of Parts	132	80	1.7x
Single Point Failures	Yes	No	3x

\*Based on an allowable nominal contact stress of 214 [ksi]; \*\*Some parts use titanium

# Stabilator Actuator Duty Cycle (Power)



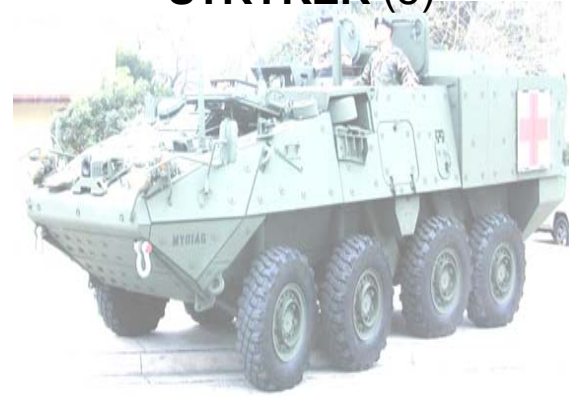
# CANDIDATE ARMY VEHICLES FOR ACTIVE SUSPENSIONS

**HUMVEE (4)**



- Independent Suspensions
- Short "Parallel" Arms
- Backfitted With Heavy Armor

**STRYKER (8)**



- Front Wheels Articulated
- Independent Front Suspension
- Rugged, Rigid Rear Axle

**BRADLEY (12)**



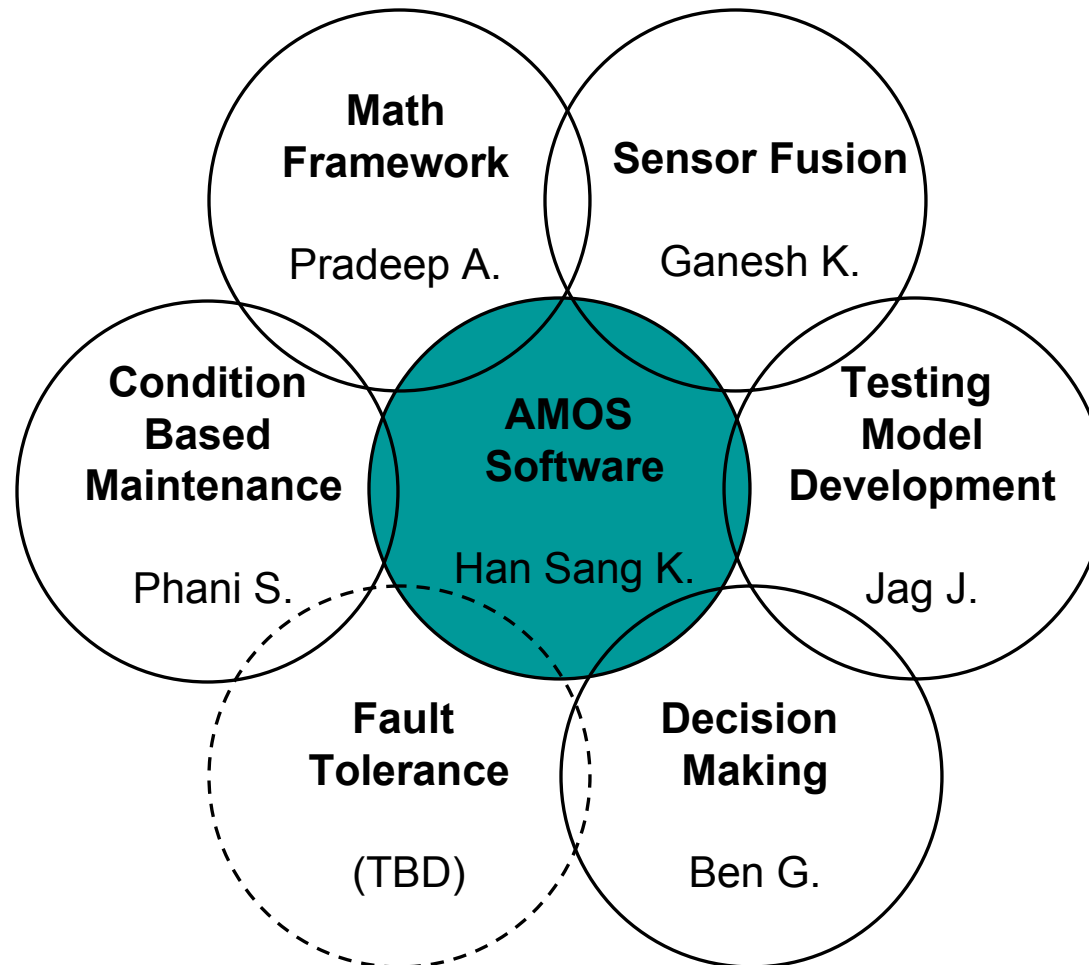
- 12 Wheels in Road Contact
- Short Arm Suspension
- Torsion Bar Spring (?)

**M1 ABRAMS (14)**



- 14 Wheels in Road Contact
- Long Arm Suspension
- Torsion Bar Springs (?)

# AMOS DEVELOPMENT TEAM STRUCTURE



# INTELLIGENT ACTUATOR

## I. CONTROL PARAMETERS ( $c_i$ )

- Current
- Voltage
- PWM Duty Cycle
- PWM Switching Frequency
- Turn-on Angle Advance
- Turn-off Angle Delay
- Load Duty Cycle
- Amplifier Modulation Depth
- Amplifier Dead Time
- Amplifier Sampling Factor

## II. REFERENCE PARAMETERS ( $r_i$ )

- Torque
- Speed
- Temperature
- Efficiency
- % Rated Load of Prime Mover
- Prime Mover Rotor Position
- Gear Train Tooth Mesh Cycle
- Torsional Load on Gear Train
- Out-of-Plane Moment Load
- Amplifier Output Power
- EMI Frequency

# 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

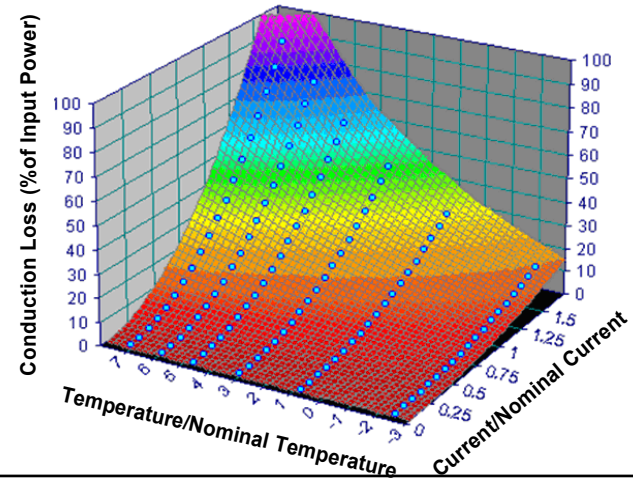
# AMPLIFIER PERFORMANCE MAPS

Dependent Parameter  
**CONDUCTION  
LOSSES (d)**

$$P_{\text{Cond}} = \frac{1}{2} \left( \frac{I_L}{\sqrt{2}} \right)^2 R_{\text{dson}}$$

- **Power Dissipation**
  - Inductors, Capacitors, etc.
- **Depends on Current/  
Temperature**
  - Losses increase
- **Nominal Conditions**
  - Current=12 A,
  - Temperature=25°C

Reference and/or  
Control Parameters  
**CURRENT (c)  
TEMPERATURE  
(r)**

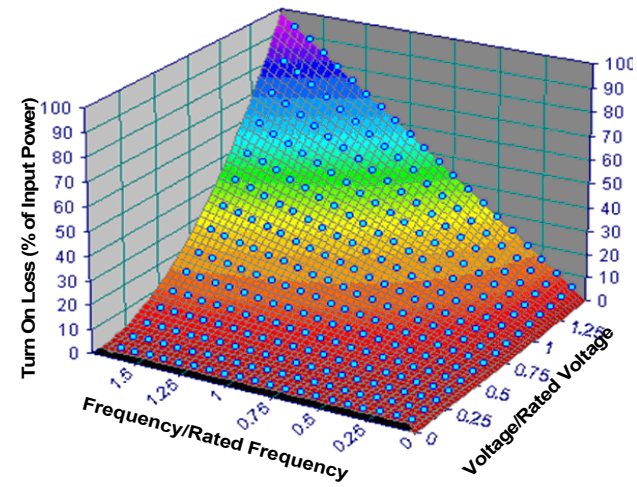


A1

Dependent Parameter  
**TURN-ON  
SWITCHING  
LOSSES (d)**

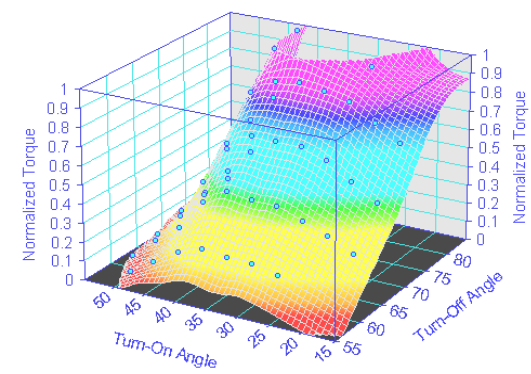
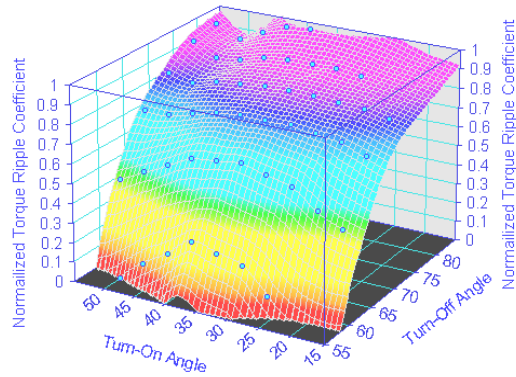
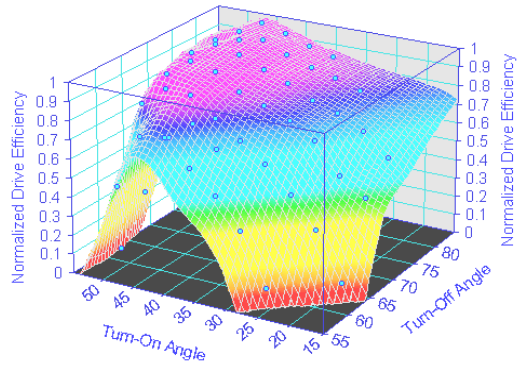
$$P_{\text{Off}} = \frac{1}{2} C_{\text{OSS}} V_{\text{dc}}^2 f_s$$

- **Principal Losses**
  - Crossover Power Loss
  - Capacitor Discharge Loss
- **Increased Losses**
  - Higher Frequency
  - Higher Voltage
- **Nominal Conditions**
  - Frequency=12kHz
  - Voltage=50 V

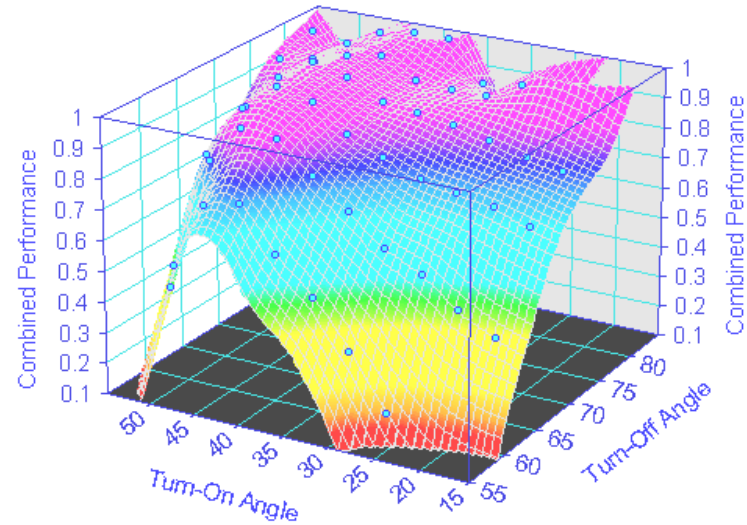


A2  
17

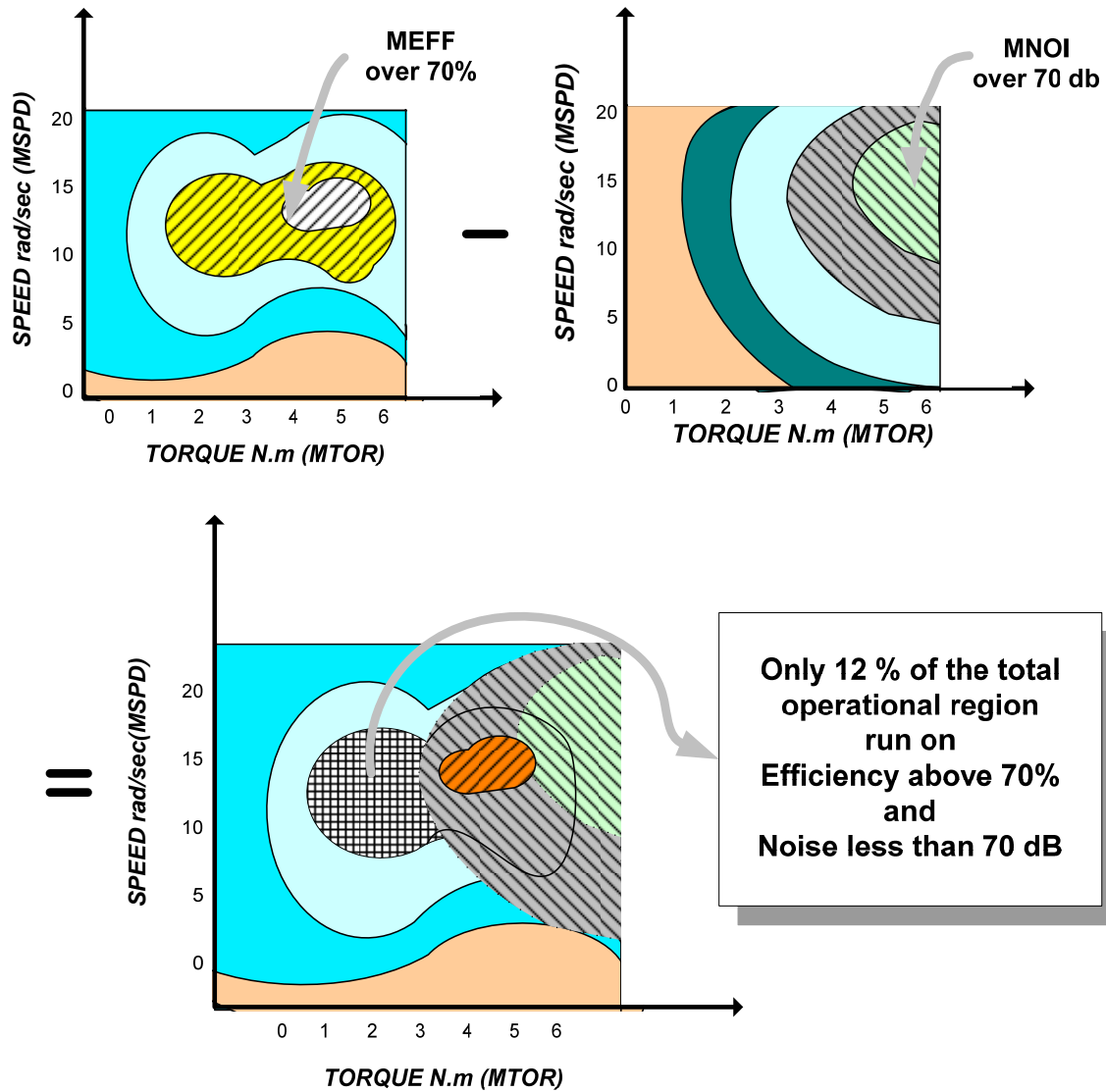
# PERFORMANCE ENVELOPE EXAMPLE NO. 1



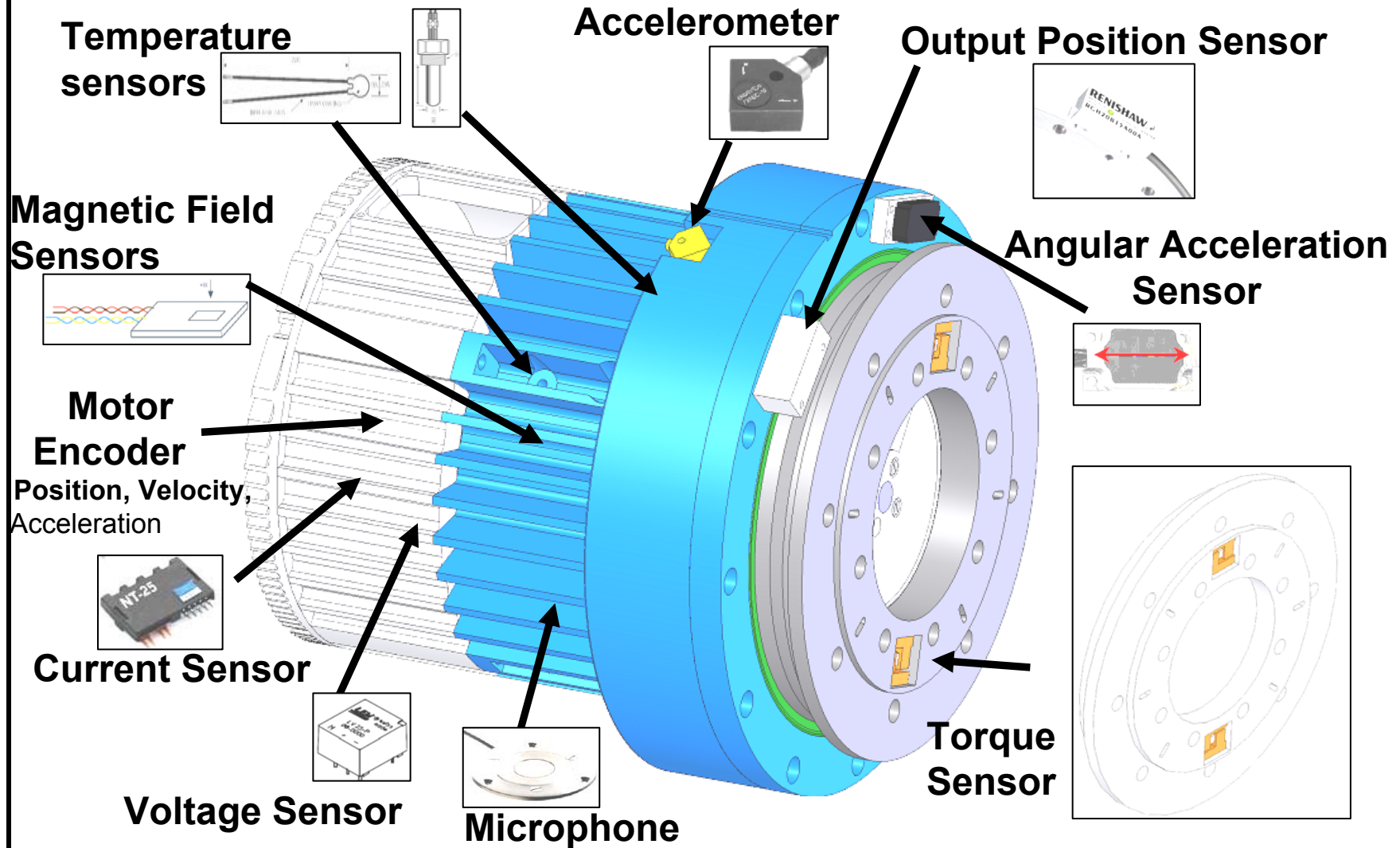
Prime Mover	
Z Axis	X & Y Axes
Torque(r)	<ol style="list-style-type: none"> <li>1. Turn On Angle (c)</li> <li>2. Turn Off Angle (c)</li> </ol>
Torque Ripple (d)	<ol style="list-style-type: none"> <li>1. Turn On Angle (c)</li> <li>2. Turn Off Angle (c)</li> </ol>
Drive Efficiency (d)	<ol style="list-style-type: none"> <li>1. Turn On Angle (c)</li> <li>2. Turn Off Angle (c)</li> </ol>



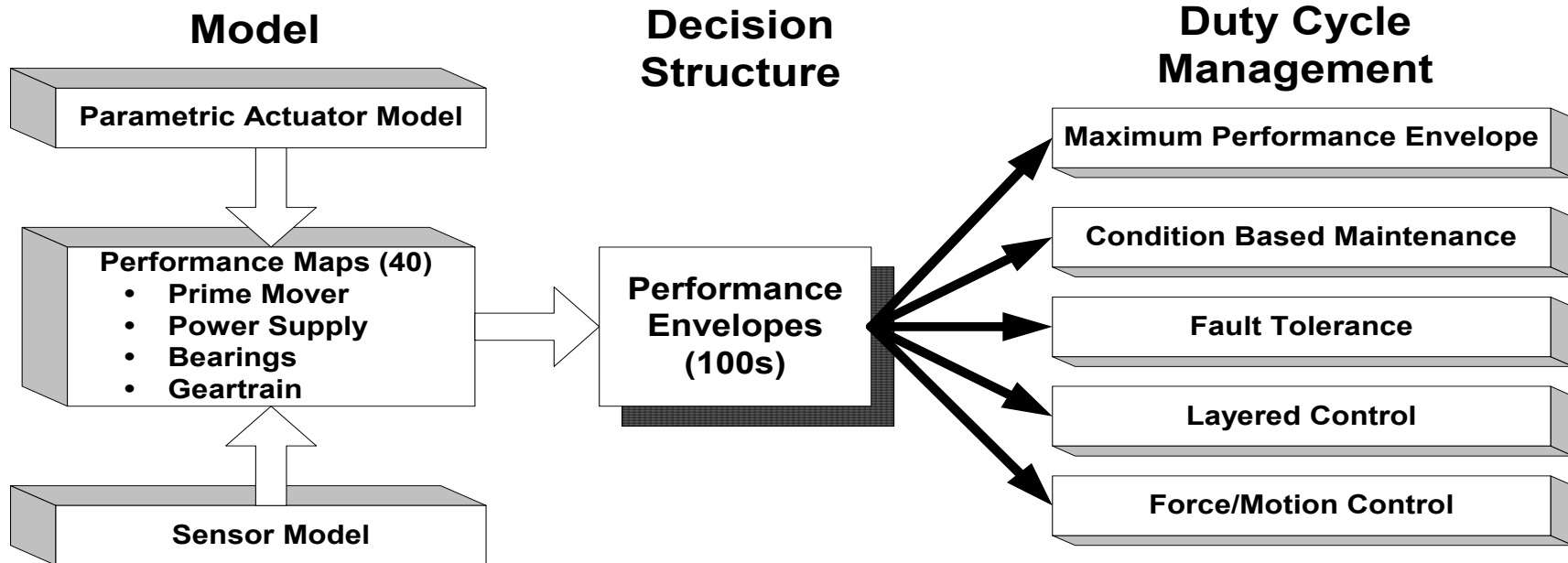
# NORM\_AREA(Z, X, Y)



# MULTI-SENSOR ARCHITECTURE



# INTELLIGENCE IN EMAS



- Fault Tolerance (when necessary)
- Utilization of Performance Maps and Envelopes
- Criteria-Based Control
- Condition Based Maintenance (CBM)
- Reconfigurability
- Ability to Continuously Monitor Coupled Nonlinear Properties
- Response to Complex Duty Cycles

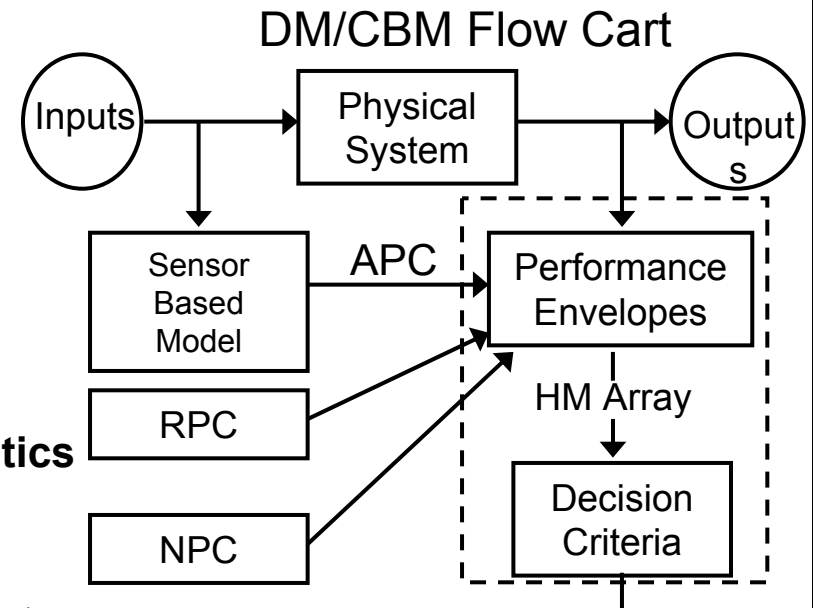
# DECISION MAKING STRUCTURE FOR CBM

- **CONDITION ASSESSMENT USING PERFORMANCE CRITERIA**

- **Model Based Decision Structure**
- **Efficiency, Acoustic Noise, Losses**

- **DECISION MAKING METHODS**

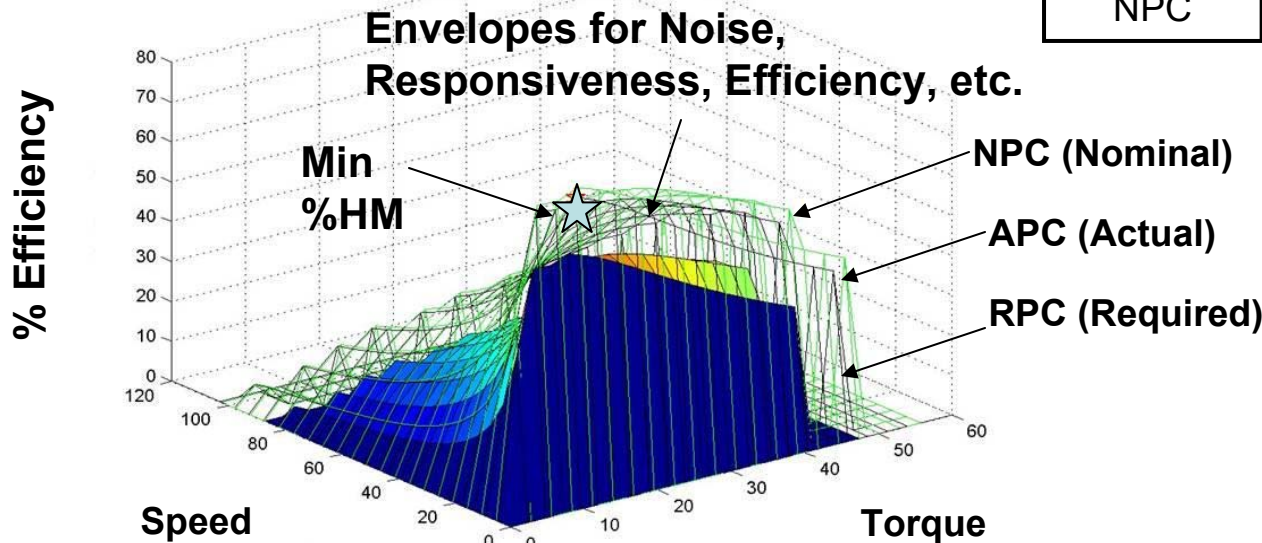
- **Task Requirements**
  - Required Performance Condition
- **Estimates of Performance Residuals**
  - %Health Margin
  - Remaining Useful Life
  - %Certainty
- **Model to Estimate System Characteristics**
  - Performance Maps/Envelopes



(%HM, RUL, %Cert.)

Replace Actuator?  
Y/N

**Reduced  
False Alarms**



**Nominal, Required, and Assessed Performance Conditions**