NEW WAVE OF TECHNOLOGY
Built On The Core Of Mechanical Engineering

PRESENTATION TO:
DoD Maintenance Symposium
October 27, 2008
Denver, CO
by
Prof. Delbert Tesar
Carol Cockrell Curran Chair
Robotics Research Group
The University of Texas at Austin
MILITARY APPLICATIONS

- Ships/Submarines
- Aircrafts/UAV
- Tanks/Off Road Vehicles
- Anti-Terrorism Robots
- Trucks (Hybrid)
1. RECOMMENDATIONS TO PRESIDENT-ELECT
   • Global Trends 2025
     - Aging Workforce
     - Climate Changes
     - Water Shortages
   • American Dominance Eroding
     - Political
     - Economic
     - Cultural
     - Exception Is Military
   • Aging Populations (1 to 3)
     - Europe
     - Japan
     - China
   • Increasing Life Spans
     - Biogerontotechnology
     - Higher Health Care Cost

2. POTENTIAL DISRUPTIVE TECHNOLOGIES
   • Energy Storage Systems
     - Fuel Cells
     - Ultra-capacitors
     - Replace Fossil Fuels
   • Crop Based Bio-fuels
     - Reduce Gasoline Dependence
   • Clean Coal Technology
     - Reduce Pollutants
     - Improve Power Generating Efficiency
   • ROBOT TECHNOLOGY
     - Reduce Humans In Industry
     - Military Applications
     - Health Care
   • Internet to be Pervasive
     - Streamline Supply Chain
     - Science Has No Boundaries
Defense Science Board Recommendation

1. RELEVANT RECOMMENDATIONS
   • Invest In Energy Efficient Tech.
     – Alternative Energy
     – Disruptive Technologies
   • Accelerate Development
     – Prime Mover Platforms
     – Potential to Impact Con Ops

2. DISRUPTIVE TECHNOLOGIES
   • Blended Wing Body Aircraft
   • Variable Speed
     (Tilt Rotary/Vertical Lift)
   • ADVANCED ELECTRO-MECH. ACTUATORS
   • Blast-Bucket Tactical Vehicle
   • Advanced Micro-Generators
   • Etc.

3. BRIEFING BY D. TESAR (May 2006)
   • EMA's Are Universal
     – All DoD Systems
     – Replace Hydraulics
     – Improve Efficiency (75%)
     – Reduce Weight (50%)
   • Major Technology Push Feasible
     – Performance Maps/Envelopes
     – Full EMA Architecture
     – Fault Tolerance
     – No Single Point Failures
     – Condition-Based Maintenance
     – High Torque Density
     – High Acceleration Response
     – Standardized Interfaces
     – In-depth Certification
Figure 1: EOD Components and Systems
<table>
<thead>
<tr>
<th>DOF</th>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Tesar 3 DOF Wrist (Spherical Linkage)</td>
<td><img src="image1" alt="Image of Tesar 3 DOF Wrist" /></td>
</tr>
<tr>
<td>1</td>
<td>One DOF Elbow (Antagonism)</td>
<td><img src="image2" alt="Image of One DOF Elbow" /></td>
</tr>
<tr>
<td>3</td>
<td>Three DOF Shoulder (Spherical Linkage)</td>
<td><img src="image3" alt="Image of Three DOF Shoulder" /></td>
</tr>
<tr>
<td>2</td>
<td>Industrial Wrist (Bevel Gears)</td>
<td><img src="image4" alt="Image of Industrial Wrist" /></td>
</tr>
<tr>
<td>2</td>
<td>Two DOF Knuckle (Antagonism)</td>
<td><img src="image5" alt="Image of Two DOF Knuckle" /></td>
</tr>
<tr>
<td>6</td>
<td>Six DOF Micromanipulator (Stewart Platform)</td>
<td><img src="image6" alt="Image of Six DOF Micromanipulator" /></td>
</tr>
</tbody>
</table>

Early Actuator Development (Tesar ~1975-85)

Master Overview Sept. 23, 2008
1995 State of the Art Actuator Comparison

UT BASELINE PROTOTYPE

MODULAR 6 DOF MANIPULATOR

- Quick-Change Interfaces
- Commercial Buses
- Embedded Controller
- Integrated Joint Bearing
## GEAR TRAIN COMPARISON
(Based on 6000 HR. Life)

### NABTESCO
- Used in 50% of Industrial Robots
- ≈ 90,000-hour Life

### UTEXAS
- Dual PE Gear Train
- 4 Orders Better

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

1. Commonality to Reduce Cost
2. Minimum Set of Standard Sizes
3. Recommend Finite Number of Standard Sizes
   — Depends on application domain
4. Finite Number of Grades
5. Plug-and-Play
   — Throw Away
6. Enables Large Production Runs
7. Reduces Time To Market
8. Allows Rapid Tech Mods
9. Constant Improvement Of The Performance/Cost Ratio
10. Increasing Quality at Lower Cost
11. Rapid Diffusion/Multiple Suppliers
12. Certification of Performance
13. Perhaps 10% Must Be Super Quiet
   — Materials, high-end bearings, quality contact surfaces
14. Standard For Investment
   — Mechanical equivalent of Moore's law

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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
   - 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
   - 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
### CANDIDATE ARMY VEHICLES FOR ACTIVE SUSPENSIONS

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Quantity</th>
<th>Suspension Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>HUMVEE</td>
<td>4</td>
<td>- Independent Suspensions&lt;br&gt;- Short “Parallel” Arms&lt;br&gt;- Backfitted With Heavy Armor</td>
</tr>
<tr>
<td>STRYKER</td>
<td>8</td>
<td>- Front Wheels Articulated&lt;br&gt;- Independent Front Suspension&lt;br&gt;- Rugged, Rigid Rear Axle</td>
</tr>
<tr>
<td>BRADLEY</td>
<td>12</td>
<td>- 12 Wheels in Road Contact&lt;br&gt;- Short Arm Suspension&lt;br&gt;- Torsion Bar Spring (?)</td>
</tr>
<tr>
<td>M1 ABRAMS</td>
<td>14</td>
<td>- 14 Wheels in Road Contact&lt;br&gt;- Long Arm Suspension&lt;br&gt;- Torsion Bar Springs (?)</td>
</tr>
</tbody>
</table>
FOUR CLASSES OF ROTARY EMA'S FOR BATTLEFIELD SYSTEMS
(Robots, JLTV, HEMTT, Heavy Transport, Vertical Lift)
Common Features: Low Cost, Full Certification, Minimal Set

1. LOW COMPLEXITY EMA
   • Mass Produced
   • 3 Levels of Ruggedness
     − Light, Medium, Heavy
   • Exceptional Simplicity
     − Standard Components
     − Pancake/Coffee Can
     − SRM or D.C. Motor

2. MULTI-SPEED DRIVE WHEEL
   • Two Electrical Speeds
   • Two Mechanical Speeds
     − Maximize Efficiency
   • Four Operating Regimes
     − High Traction
     − Off-Road Maneuverability
     − Medium Road Speeds
     − High Road Speeds

3. ACTIVE SUSPENSION EMA
   • High Acceleration
     − Low Weight/Volume
     − High Torque
   • Permits Off-Road Operation
     − Emergency Maneuvers
     − High Speeds/Efficiency

4. HIGH TORQUE DENSITY
   • Heavy Lift Manipulators
     − Weapons Handling
     − High Payload/Weight Ratio
   • Mobile Platforms
     − Three Scales (24", 60", 120")
     − High Dexterity/Variable Geometry
   • Minimum Set For All Systems
     − 18 Distinct Actuators
Special Purpose Fielded Battlefield Robots

- Bulldozer Robot
- BAE Robot Vehicle
- BomBot
- Assault Robot
- Mine Clearing Robot
- Dragon Runner
- Gladiator Armed Robot
- PackBot (iRobot)
- Mine Clearing Robot
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

<table>
<thead>
<tr>
<th>Dependent Parameter</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CONDUCTION LOSSES (d)</strong></td>
<td>( P_{\text{Cond}} = \frac{1}{2} \left( \frac{I_c}{\sqrt{2}} \right)^2 R_{\text{dson}} )</td>
</tr>
<tr>
<td><strong>Reference and/or Control Parameters</strong></td>
<td><strong>CURRENT (c)</strong></td>
</tr>
<tr>
<td><strong>Depends on Current/Temperature</strong></td>
<td>Current=12 A, Temperature=25°C</td>
</tr>
<tr>
<td><strong>Nominal Conditions</strong></td>
<td></td>
</tr>
</tbody>
</table>

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

### 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
BEARING PERFORMANCE MAPS

<table>
<thead>
<tr>
<th>Dependent Parameter</th>
<th>Reference and/or Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENDURANCE/LIFE (d)</td>
<td>LOAD (r) SPEED (r)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ L_I_b = \left( \frac{C}{P_{b-r}} \right)^n \frac{1}{\omega_b D C_b} \]; \( n = 3 \) for Ball Bearing \( n = 10/3 \) for Roller Bearing

- **Bearing Fatigue Life**
  - Inversely Proportional to Load Ratio and Speed Ratio
- **High Loads**
  - Higher Contact Stress, Reduced Life
- **High Speeds**
  - Reduced Running Time (Same Revolutions)
- **Optimum Loading Region**
  - \( 10\% < P/C < 50\% \)

- **Bearing Life**
  - Inversely Proportional to Temperature, Duty Cycle Ratio
- **High Temperatures**
  - Reduced Surface Hardness
- **High Duty Cycle**
  - Reduced Running Time For Fixed Speed

\[ C_{\text{reduced}} = f_h C \]

- **C: Bearing Load Capacity at 10^6 cycles**
- **f_h: Hardness Factor, 0 < f_h(T) < 1**

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PERFORMANCE ENVELOPE EXAMPLE NO. 1

Prime Mover

<table>
<thead>
<tr>
<th>Z Axis</th>
<th>X &amp; Y Axes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque(r)</td>
<td>1. Turn On Angle (c)</td>
</tr>
<tr>
<td></td>
<td>2. Turn Off Angle (c)</td>
</tr>
<tr>
<td>Torque Ripple (d)</td>
<td>1. Turn On Angle (c)</td>
</tr>
<tr>
<td></td>
<td>2. Turn Off Angle (c)</td>
</tr>
<tr>
<td>Drive Efficiency (d)</td>
<td>1. Turn On Angle (c)</td>
</tr>
<tr>
<td></td>
<td>2. Turn Off Angle (c)</td>
</tr>
</tbody>
</table>
Only 12% of the total operational region run on Efficiency above 70% and Noise less than 70 dB.
OVERVIEW OF ACTUATOR CONDITION-BASED MAINTENANCE

1. FRAMEWORK
   • Identify Faults During Operation
   • Continuous Assessment of System Condition
   • Provide Lead Time For Required Maintenance
   • Provide Timely Repair or Replacement
     − By Nominally Trained Technician

2. REQUIREMENTS
   • Spectrum of Sensor Readings
   • Reliable Fault Estimation Algorithms
   • Identification of Fault Origins
   • Continuous Assessment of System Condition
   • Forecast Expected Conditions
   • Record All Vital Parameters

3. DESIRED OUTPUTS
   • Assess Present and Future System Condition
   • Alert Operator of Detected Fault
   • Identify Suspected Component
   • Suggest Corrective Action

4. BENEFITS OF CBM
   • Reduces Maintenance Costs
   • Increases Equipment Reliability
   • Improves Equipment Availability
   • Extends Equipment Service Life
   • Provides Continuous System Awareness
   • Increases Operational Safety
   • Reduces Severity of Failures
   • Reduces Surprise Failures
   • Extends Maintenance Cycles
   • Reduces Technician Training Requirement
   • Reduces False Alarms
Performance Envelopes

Nominal Performance Condition

Assessed Performance Condition

Required Performance Condition

85% Torque
85% Speed
80% Efficiency