Control Systems Engineering Inc.

<ChuckR@ConSysEng.com>

Load & Motion Analysis For Mechanical & Electrical Engineer's

Chuck Raskin P.E. MSCS CMCS

Director of Engineering

Load & Motion Analysis

To Determine the requirements of the System Control Components

System Control Components

Motor
Amplifier (Drive)
Gear Box
Couplings
Slides & Linkages
Electronic Hardware
Operational Software

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Motion Control

*** IS ***

The Art of Controlling moving and Stationary Objects

Within the world of all things that move, there is a world of things that do not move.

Motion Control is knowing how to integrate these worlds to produce continuity within the motion process.

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The Motion Puzzle

How we Think is How we Design

Our habits follow us throughout our lives.

We must look carefully at the entire problem to correctly determine the required solution

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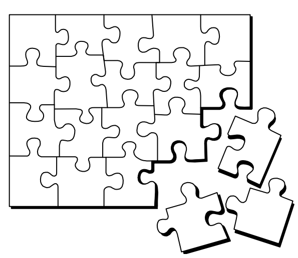
Motion Control Benefits

Shorter Positioning Times
Higher Accuracy
Improved Repeatability
Better Reliability
Coordinated Motion
Servo **Clamping**



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System

An Ordered Set of Relationships

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When Developing the Operation & Fault Sequences

Keep In Mind

Where you <u>were</u> and what just happened

Where you <u>are</u> and what is currently happening

Where you're <u>going</u> and what's about to happen

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How Many Ways Can Something be Moved

Motors & Mechanics
Hydraulics (Liquids)
Pneumatics (Gasses)
Cables & Pulleys
Magnetic's

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How Many Ways Should Something be Moved

How Stable is the Product

Is it Secure
Is it sensitive to or affected by Light
Is it sensitive to or affected by Magnetic Fields
What does it Look Like
What is it Made From
How Heavy is It
What is the Environment Like

Is It Being Worked on While in Motion

How Fast Does it Need To Be

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Types of Mover's

- ❑ **Motors & Mechanics**
- ❑ **Hydraulics (Liquids)**
- ❑ **Pneumatics (Gasses)**
- ❑ **Cables & Pulleys**
- ❑ **Magnetic's**

Motors & Mechanics

Reasons for Understanding Motors

- Budget Considerations
- Size Constraints
- Environment
- Reliability / Efficiency
- Style of Motion

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Types of Motors

- DC Permanent Magnet
- DC PWM Servo
- AC w/Variable Freq. Drive
- AC w/Servo Drive
- AC w/Vector Drive
- AC/DC Brushless
- Stepper

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DC Permanent Magnet

- Low to Medium Speed < 2500 RPM
- Light to Heavy Loads
- High Armature Inertia's
- VelMode
- Low Accuracy Positioning w/Gears
- Brute Force Operation
- Low to Medium Bandwidth
- 1.5 to 2:1Peak to RMS Power Ratio
- Poor Thermal Performance
- Low Power Density (High $/Watt)

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DC PWM Servo

- Good to 3000 RPM
- Low to Med Speed Short Moves
- Light To Med Index Moves
- Low to Med Armature Inertia's
- Good Thermal Performance
- 4:1 Peak to RMS Power Ratio
- Low Torque Ripple w/Skewed Armature
- Good Efficiency over Large Speed Range

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AC Motor

- Med to High Speed < 3600 RPM
- Low to Med Acceleration
- Light to Heavy Loads
- Med to High Armature Inertia's
- Brute Force Control (On/Off)
- VelMode
- Good Efficiency at FULL LOAD
- Poor Thermal Capability
- Med Power Density
- 1.5 to 2:1 Peak to RMS w/Blower

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AC Servo

- Low to High Speed < 3600 RPM
- Low to Med Acceleration
- Light to Heavy Loads
- Med Armature Inertia's
- Servo like Control
- VelMode
- Med Positioning Accuracy
- Good Efficiency at all Speeds
- Med Thermal Capability
- High Power Density
- 1.5 to 2:1 Peak to RMS w/Blower

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AC Vector

- ❑ **Low to High Speed < 3600 RPM**
- ❑ **Low to High Acceleration**
- ❑ **Light to Heavy Loads**
- ❑ **Med Armature Inertia's**
- ❑ **Servo like Control**
- ❑ **Good Positioning Accuracy**
- ❑ **Good Efficiency at FULL LOAD**
- ❑ **Poor Thermal Capability**
- ❑ **Med Power Density**
- ❑ **Able to Servo at Stop**

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AC/DC Brushless

- ❑ **Low to High Speed < 6000 RPM**
- ❑ **Low to High Acceleration**
- ❑ **Light to Heavy Loads**
- ❑ **Low to Med Armature Inertia's**
- ❑ **Servo Control Capability**
- ❑ **Good Positioning Accuracy**
- ❑ **Good Efficiency at all Speeds**
- ❑ **Good Thermal Capability**
- ❑ **High Power Density**
- ❑ **Hall / Resolver / Encoder Operation**

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Stepper Motor

- Low Speed < 2000 RPM
- Low Acceleration
- Light to Heavy Loads
- Med Armature Inertia's
- Servo Control Capability
- Good Positioning Accuracy 3%-5%
- High Accuracy W/Microstepping
- Low Efficiency at all Speeds
- Poor Thermal Capability
- High Power to Size Ratio
- No Encoder Required
- Current FdBk for Move Knowledge

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Types of Motor Amplifiers

- **AC:**
  - Variable Speed
    - Freq & Voltage
  - Vector
  - Brushless

- **DC:**
  - Fixed Voltage
  - Regenerative
    - SCR, Transistor
  - Linear
  - PWM
  - Brushless

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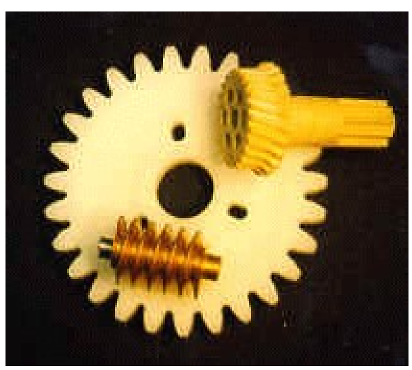
Why Use Gearing

- ❑ **Amplify Peak Speed**
- ❑ **Amplify Peak Torque**
- ❑ **Alter FdBk Freq. or Resolution**
- ❑ **Reduce Load Inertia**
- ❑ **Reduce Mover Size, Weight, Cost**
- ❑ **Improve Low Speed Operation**



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Gearing Problems

- ❑ **Backlash**
- ❑ **Added Friction**
- ❑ **Added Inertia**
- ❑ **Gear Errors**
- ❑ **Torque Ripple (Tooth Profiling)**
- ❑ **Stiffness**
- ❑ **Motion Hysteresis**

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Gear Types / Performance

- **Screw Jack**
  Med Bklsh, Med Stiffness, Smooth Otp Torq., 85% Eff, < 3000 RPM, High J
- **Worm**
  Low Bklsh, High Stiffness, Smooth Otp Torq., 40% Eff, < 2000 RPM, Med J
- **Planetary**
  Low Bklsh, VHigh Stiffness, Smooth Otp Torq., 85% Eff, < 3000 RPM, Low J
- **Orbital**
  Vlow Bklsh, Med Stiffness, Smooth Otp Torq., 90% Eff, < 3000 RPM, Low J
- **Harmonic (Cycloidal)**
  Vlow Bklsh, Low Stiffness, Otp Torq. Ripple, 75% Eff, < 3000 RPM, High J
- **Spur / Helical**
  Med Bklsh, High Stiffness, Smooth Otp Torq., 98% Eff, < 5000 RPM, Low J
- **Differential**
  Med Bklsh, Med Stiffness, Smooth Otp Torq., 85% Eff, < 5000 RPM, High J
- **Plastic Gears**
  High Bklsh, Low Stiffness, Smooth Otp Torq., 50% Eff, < 5000 RPM, VLow J

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Slides and Guides

1 -> 4 in order of:
Lowest to Highest

Slide Type	Friction	Roller	Hydraulic	Aerostatic
Friction	4	3	2	1
Wear	4	3	2	

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				1
Stiction	**4**	**3**	**2**	
				1
Surface Finish	**1**	**2**	**-**	

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-

$ for Accuracy	**4**	**3**	**1**

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1

Stiffness **4** **3** **2**

1

Damping **4** **3** **2**

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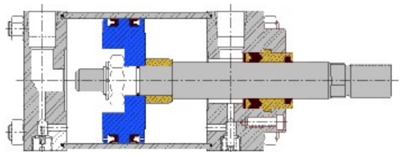
1

Hydraulics



- Noisy
- Expensive
- Liquid (mess)
- Hi Maintenance
- Safety Concerns
- Lots of Power
  > 2000 PSI

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Pneumatics

- ❑ **Air Purity**
- ❑ **Dry Air Requirement**
- ❑ **Not much Power**
  < 130 PSI
- ❑ **Compressible Medium**
- ❑ **Air Leaks Hard To Find**

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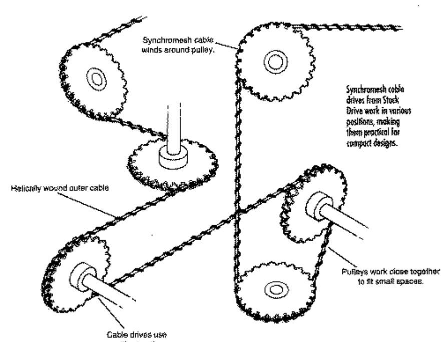
Cables & Pulleys

- ❑ **Many available Ratios**
- ❑ **Many Styles of Cables**
  Chain, Cable, etc.
- ❑ **Spongy**
- ❑ **Stretch Problems**
- ❑ **Guides May Be Required**
- ❑ **Can Be Mechanically Complex**
- ❑ **Can Simplify System Interconnection**



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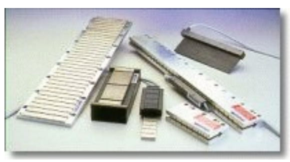
Magnetic's



- Dangerous around Computer Disks
- High Bandwidth
- Small Size
- Low to High Force Range
- Reasonably Quiet

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Voice Coil Motors

LINEAR AND ROTARY/LINEAR MOVING COIL ACTUATORS

Two Axis Moving Coil Actuator Designed for Pick, Orient and Place

- Semiconductor insertion
- Circuit board assembly
- Precision assembly with verification

Independent 2-axis control

Precision packaged, ready to mount

Low moving mass for high speed response

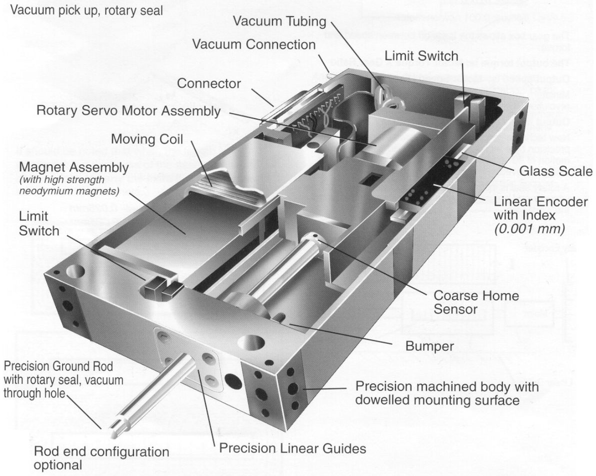
Vacuum pick up, rotary seal

Linear:

- Up to 100mm stroke, 0.5,1 or 5 micron resolution
- Programmable position, force, speed
- Vacuum pick-up

Rotary:

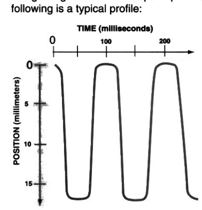
- Multi-turn servo motor, 0.07° to 0.007° resolution
- Low and zero backlash options



ASSEMBLY AUTOMATION REQUIREMENTS IN THE LATE 90's

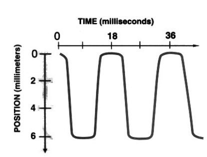
HIGH CYCLE SPEED

Circuit Board Assembly machines are aiming at higher speeds or on the fly programmable offset capability. Cams and ball screws no longer can do the job. Medium speed mounter machines are being designed to insert 10 parts per second. The following is a typical profile:



To achieve this level of performance, the actuator must be capable of generating an acceleration of about 6 times gravity (6 G).

For wire bonding applications, the cycle speeds being considered are much higher. The desired performance is 6 mm stroke in 6 milliseconds.



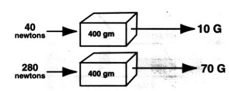
These profiles can be achieved using linear motors such as SMAC's moving coil actuators.

CONTROLLABLE FORCES

High Forces

Force (less weight, friction)= Moving Mass X Acceleration

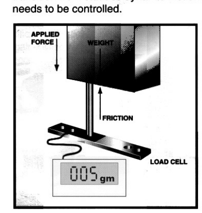
For high speed moves, the SMAC moving coil design uses a moving mass of 200 gms (typical), the moving mass of the end-effector is also kept to a minimum (e.g. 200 gms). At 10G, this would require an actuator capable of generating 40 newtons. At 70G, we are looking at 280 newtons.



Low Forces

NET FORCE = Applied Force less weight and friction

Friction represents the lower limit of the net forces applied to the part. Since dynamic friction is typically much less than static friction, the transition from static to dynamic friction also needs to be controlled.



SMAC Actuators can control forces to as low as 50 millinewtons

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10 Motion Building Blocks

- Define the Problem
- Define the Operating Specifications
- Develop the Machine Requirements
- Draft an Electrical/Mechanical Timing Diag.
- Determine the Real Time Needs
- Determine the Stability and Precision
- Determine the Mover
- Determine the Required Sensors
- Determine the Req. Interface (GUI:MMI)
- Look at the System from the Operators point of View

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Selecting the Mover

- ❑ **Requirement to go from Point A to Point B**
  Time, Speed, Trap, S, Vector Control, Index, etc.
- ❑ **Load Weight**
  Tons, Pounds, Liquid, etc.
- ❑ **Acceleration/Deceleration**
  'S', Trap, Special
- ❑ **Machine Stiffness**
  Loose, Tight, Resonant Freq.
- ❑ **Tools to be Used**
  Water Jet, Laser, Metal Cutter, etc.
- ❑ **Environment**
  Humidity, Dusty, Temp., Noise, Availability of Elect/Air/Hydraulics, etc.
- ❑ **Speed of Move**
  Low/High, Index, Top Speed, etc.
- ❑ **Top Speed of System**
  Ability of Machine to handle Speed and Acl Rates
- ❑ **Accuracy / Repeatability Requirement**
  Which is the Best?

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❑ Resolution Requirement

Frequency Restrictions, CE, etc.

3 Basic Types of Motion

- **Inline**
  Leadscrew
- **Tangential**
  Conveyor
- **Rotary**
  Circular Table

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Basic Types of Moves

- Velocity
  - Virtual
  - True

- Position
  - Point to Point
  - Multiple Axis Interpolation
  - Multiple Axis Coordination
  - Registration
  - Pick & Place
  - On-The-Fly
  - Gearing
  - Cam

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Velocity Move

- True VelMode
- Computer Controlled VelMode
- Position Can Be Maintained
- Stopping Point Optional
  - Can Stop After X Revs.
- % Regulation Depends on Control
  - Type of Mover, Need
- Can Control More than One Axis
  - at a Time

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Position

Point to Point

- ❑ **No Coordination Required**
- ❑ **Can Be PC, PLC, etc. Controlled**
- ❑ **Smart Drive Allowed**
- ❑ **Proportional Valve OK**
- ❑ **+/- Accuracy/Repeatability = $**
- ❑ **Formula is the same for All Movers**
- ❑ **Motion is a Gain Issue**
- ❑ **Tuning is not Necessarily Critical**
- ❑ **Profile Dependent on Job to Do**

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Position

Multiple Axis Interpolation

- Simultaneous Axis Motion
- All Start/Stop Together +/-
- No Special Algorithms Needed
- +/- Accuracy/Repeatability = $
- Formula is the same for All Movers
- Motion is a Gain Issue
- Tuning is not Necessarily Critical
- Profile Dependent on Job to Do

Position

Multiple Axis Coordination

Circles

- Chordal Error Sets Ang. of Rotation
- Accel. Control Reduces Chordal Errors
- Ensure BW is Good for the Job

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Position

Multiple Axis Coordination

Splines

- ❑ **Chordal Error Sets Ang. Of Rotation**
- ❑ **Accel. Control Reduces Chordal Errors**
- ❑ **Splining Reduces Data   Req. by Control**

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Position

Registration

- Maintaining Relative Positions in Space
- Master Slave Coordination
- Types of Applications:
  Packaging, Labeling, Marking

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Position

Pick & Place

- ❑ **Part Assembly**
- ❑ **Packaging**
- ❑ **Speed - Voice Coil Motor?**
- ❑ **Stability**
- ❑ **Accuracy / Repeatability**

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Position

On-The-Fly

- ❑ **Match Speed**
- ❑ **Return Home**
- ❑ **Registration**
- ❑ **General Length Cuts**
- ❑ **Following Error OK**
- ❑ **Acceleration Profiling**

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Position

Gearing

- Master Slave
- Resolution is of Concern
  - Master Slave 5:1
- Slave Accel > Master Accel
- Slave Speed > Master Speed

Master/Slave Relationship is Critical

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Position

Cam

- BW is Critical
- Brushless is Best
- Current Mode Amplifier
- How can we do It?

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The Motion Formula's

- Torsional Deflection
- Inertia of Squares & Rectangles
- Inertia of Solid and Hollow Cylinders
- Parallel Axis Theorem
- RMS Calculations

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Torsional Deflection

(Twist)

$$Td = \frac{584 * T * L}{D^4 * G} \quad \text{Degrees}$$

Where:

T = Twisting Moment (Torque in InLbs)
L = Shaft Length (In)
D = Shaft Diameter (In)
G = Torsional Modulus of Elasticity
(11,500,000 Lbs/in^2 for Steel)

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Torsional Example

How much HP will it take to twist a shaft 7.625 inches in diameter and 16 feet long .25 degrees?

D = (16384 / 360) = 45.5 cnts / deg
= 16 / 45.5 = 0.355 degrees
L = 16 feet * 12 = 192 inches
r = 7.625 / 2 = 3.8125 inches

Then:

T = (0.355 * 3.8125^4 *11,500,000) / (192 * 584)
T = 7692 InLbs = 641 FtLb

Generated Motor HP = RPM * T (FtLb) / 5252
= 1710 * 641 / 5252
= 208 HP

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Inertia of Square Area and Rectangular Solids

- **Volume (v) = l * w * h**
- **Weight (w) = v * Density**
- **Mass (m) = w / g**
  where: g = 32.16 ft/sec^2
- **Inertia (Jzz) = m / 12 * (h^2 + w^2)**

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Inertia of Solid Cylinders

- **Area (a) = PI * r^2**
- **Volume (v) = a * h**
- **Weight (w) = v * Density**
- **Mass (m) = w/g**
  where: g = 32.16 ft/sec^2
- **Inertia (Jzz) = ½ * m *r^2**
  = ½ (PI * r^2 * h * w / g) * r^2
- **Inertia (Jxx) =**
  PI * R^2 * h * w / g) * h^2 / 3 + r^2 / 4)

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Hollow Cylinder Inertia Calc's

- **Area (a) = PI / 4 * (Do^2 - Di^2)**
- **Volume (v) = a * h**
- **Weight (w) = v * Density (d)**
- **Mass (m) = w / g**
  where: g = 32.16 ft/sec^2
- **Jzz = ½ m [(Do/2)^2 - (Di/2^2]**

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Parallel Axis Theorem

J1 = J1 + (S1^2) * M1

J2 = J2 + (S2^2) * M2

Jtotal = J1 + J2 InLbSec^2

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RMS Torque Calc's

Where:

T = Torque Values
t = Time Values

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