Creating Sensations

John Morrell, Yale University

Workshop on Prototyping Haptic Actuators

Vancouver, BC

March 4, 2012

Actuators

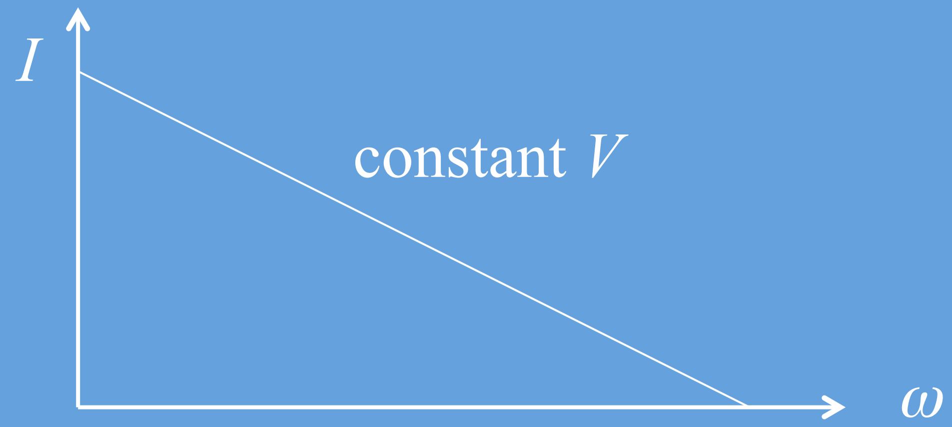
- DC motors
  - Eccentric masses (velocity)
  - Position (pressure)
  - Brushless
  - Brushed
  - Static, dynamic friction
- Tactors
- Maxon motors
- RC Servos
  - Analog, digital

DC permanent magnet motor

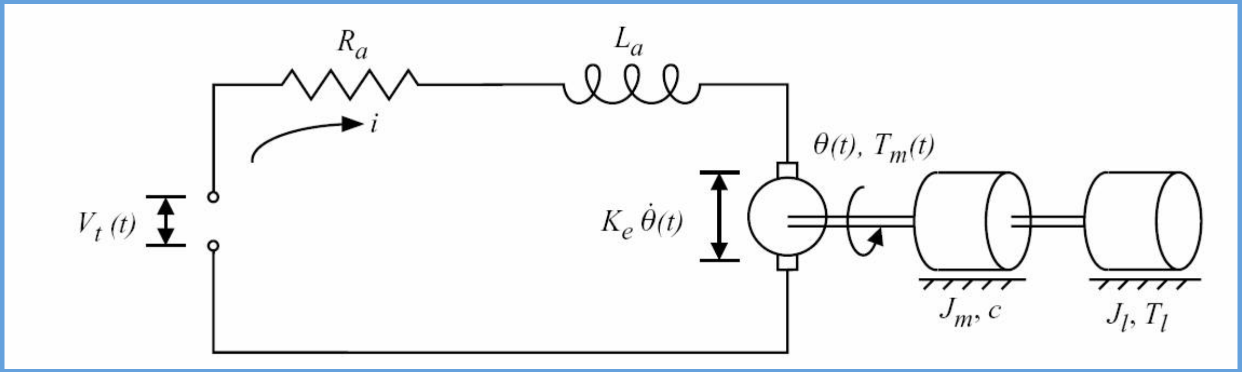
$$V = iR_a + K_e\omega + L_a \frac{di}{dt}$$

$$\tau = K_t i$$

$$K_e = K_t$$



(for a pm brushed motor when SI units are used).



DC permanent magnet motor

$$V = iR_a + K_e\omega$$

$$\tau_{shaft} = K_t i - \tau_{error} - b_{viscous}\omega$$

Friction Model:

$$\tau_{error} = \tau_{friction}$$

$$\tau_{friction} = \tau_{dynnamic} \qquad |\omega| > 0$$

$$\tau_{static} < \tau_{friction} < \tau_{static} \qquad \omega = 0$$

$$b_{viscous} = \text{viscous drag coefficient}$$

Cogging Model

$$\tau_{error} = \tau_{cog}\sin(n\theta)$$

$$n = \text{integer, a function of poles, magnets}$$

Inductance is usually much faster than our mechanical systems, so ignore it

Friction is always present so include it

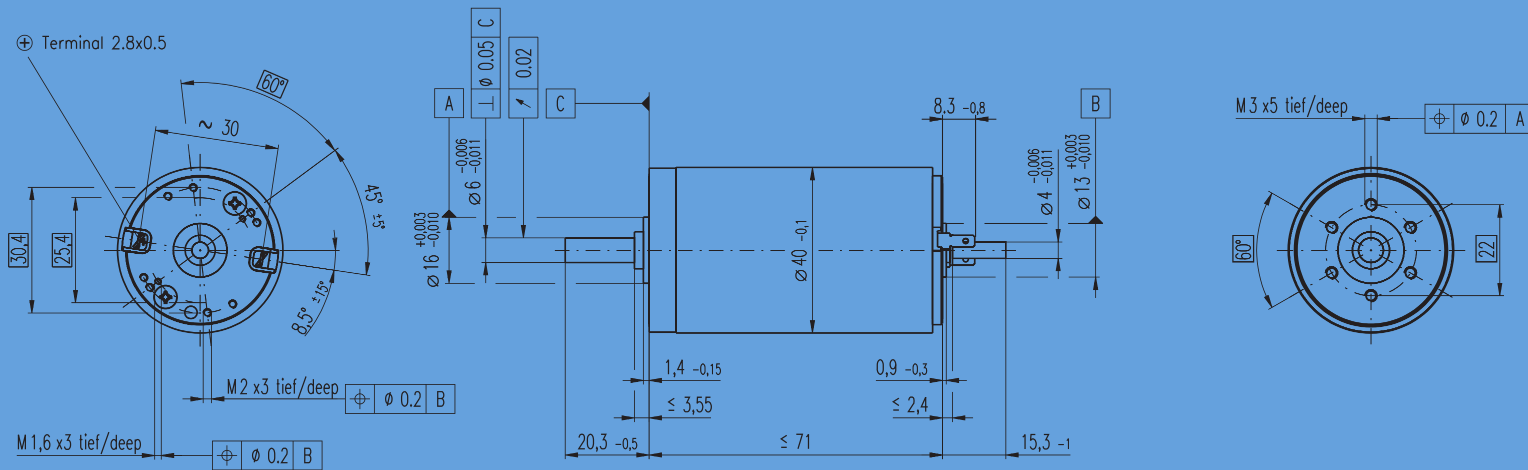
Cogging and brush friction both cause errors in static output torque

Other motor considerations

- Transient vs. Continuous
  - Heat dissipation drives performance
  - Fast: FETS in motor drive circuit (1-2secs)
  - Slow: melt insulation on windings (30-60secs)
  - Temperature sensors, temperature models
- Bearings, side loads
- Mechanical connection – smooth shaft, keyway, D-shaft

RE 40 ∅40 mm, Graphite Brushes, 150 Watt

Maxon is probably the best ($$$)



M 1:2

Stock program
Standard program
Special program (on request)

Order Number

			148866	148867	148877	218008	218009	218010	218011	218012	218013	218014	218015
	Industrial Version		263065	263066	263067	263068	263069	263070	263071	263072	263073	263074	263075
Motor Data													
	Values at nominal voltage												
1	Nominal voltage	V	12.0	24.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0
2	No load speed	rpm	6920	7580	7580	6420	5560	3330	2690	2130	1710	1420	987
3	No load current	mA	241	137	68.6	53.7	43.7	21.9	16.7	12.5	9.67	7.77	5.16
4	Nominal speed	rpm	6370	6930	7000	5810	4920	2700	2050	1500	1080	774	339
5	Nominal torque (max. continuous torque)	mNm	94.9	170	184	183	177	187	187	189	189	188	188
6	Nominal current (max. continuous current)	A	6.00	5.77	3.12	2.62	2.20	1.38	1.12	0.898	0.721	0.593	0.413
7	Stall torque	mNm	1680	2280	2500	1990	1580	995	796	641	512	415	289
8	Starting current	A	102	75.7	41.4	28.0	19.2	7.26	4.68	3.00	1.92	1.29	0.627
9	Max. efficiency	%	88	91	92	91	91	89	88	87	86	85	83
	Characteristics												
10	Terminal resistance	Ω	0.117	0.317	1.16	1.72	2.50	6.61	10.2	16.0	24.9	37.1	76.6
11	Terminal inductance	mH	0.0245	0.0823	0.329	0.460	0.612	1.70	2.62	4.14	6.40	9.31	19.2
12	Torque constant	mNm / A	16.4	30.2	60.3	71.3	82.2	137	170	214	266	321	461
13	Speed constant	rpm / V	581	317	158	134	116	69.7	56.2	44.7	35.9	29.8	20.7
14	Speed / torque gradient	rpm / mNm	4.15	3.33	3.04	3.23	3.53	3.36	3.39	3.35	3.37	3.44	3.45
15	Mechanical time constant	ms	6.03	4.81	4.39	4.36	4.35	4.31	4.31	4.31	4.31	4.32	4.33
16	Rotor inertia	gcm^2	139	138	138	129	118	123	121	123	122	120	120

Specifications

Thermal data

17	Thermal resistance housing-ambient	4.65 K / W
18	Thermal resistance winding-housing	1.93 K / W
19	Thermal time constant winding	41.6 s
20	Thermal time constant motor	1120 s
21	Ambient temperature	-20 ... +100°C
22	Max. permissible winding temperature	+155°C

Mechanical data (ball bearing)

23	Max. permissible speed	12000 rpm
24	Axial play	0.05 - 0.15 mm
25	Radial play	0.025 mm
26	Max. axial load (dynamic)	5.6 N
27	Max. force for press fits (static)	110 N
	(static, shaft supported)	1200 N
28	Max. radial loading, 5 mm from flange	28 N

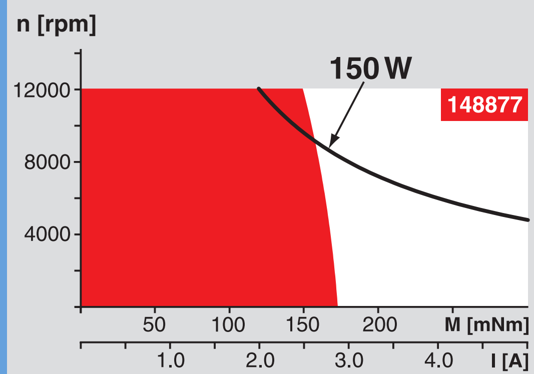
Other specifications

29	Number of pole pairs	1
30	Number of commutator segments	13
31	Weight of motor	480 g

Values listed in the table are nominal.
Explanation of the figures on page 49.

Option
Preloaded ball bearings Preload strength min. 2.4 N

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

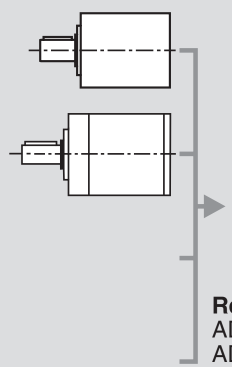
Assigned power rating

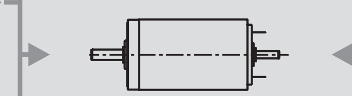
maxon Modular System

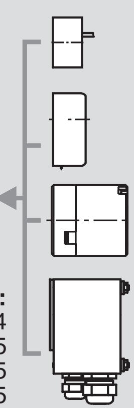
Overview on page 17 - 21

Planetary Gearhead
∅42 mm
3 - 15 Nm
Page 232

Planetary Gearhead
∅52 mm
4 - 30 Nm
Page 235







Recommended Electronics:

ADS 50/5	Page 264
ADS 50/10	265
ADS_E 50/5	265
ADS_E 50/10	265
EPOS 24/5	278
EPOS P 24/5	279
EPOS 70/10	279
MIP 50, MIP 100	281
Notes	**17**

Encoder MR
256 - 1024 CPT,
3 channels
Page 247

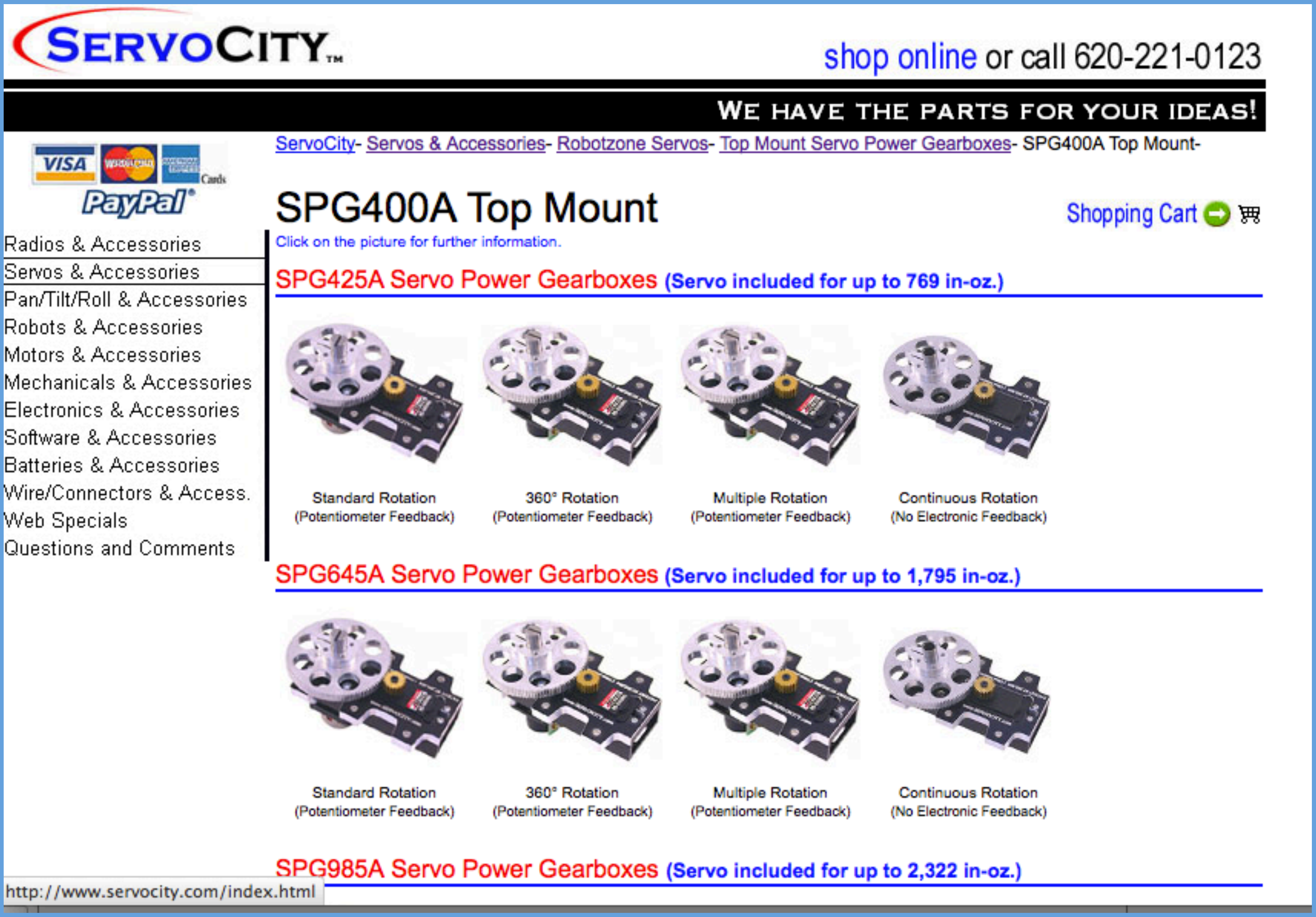
Encoder HED_ 5540
500 CPT,
3 channels
Page 250 / 252

Brake AB 40
∅40 mm,
24 VDC, 0.4 Nm
Page 289

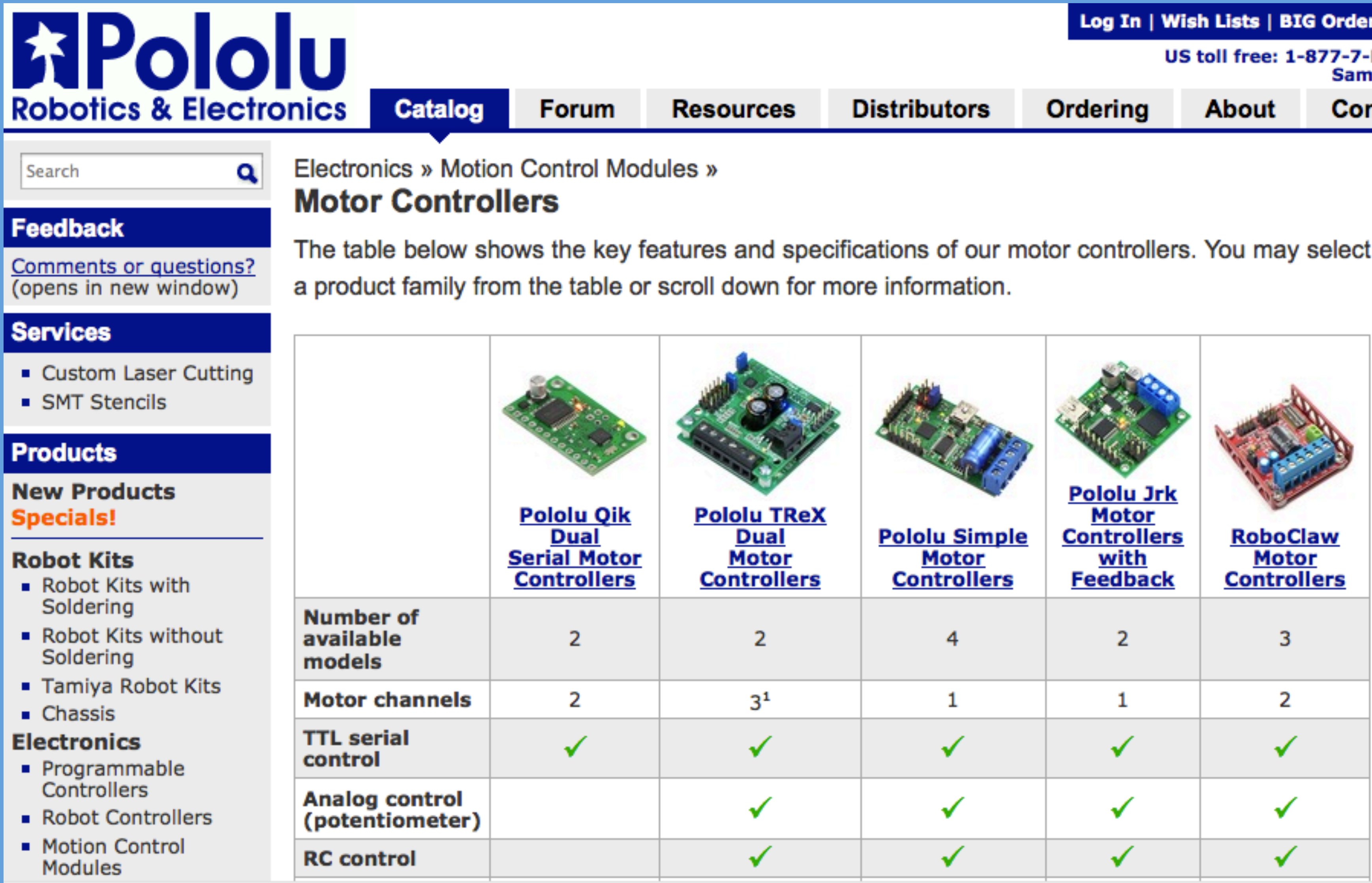
Industrial Version
Encoder HEDL 9140
Page 255

Brake AB 28
Page 288

Position control servos



$3-$40 w/o sensors



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- Programmable Controllers
- Robot Controllers
- Motion Control Modules

Electronics » Motion Control Modules »

Motor Controllers

The table below shows the key features and specifications of our motor controllers. You may select a product family from the table or scroll down for more information.

	Pololu Qik Dual Serial Motor Controllers	Pololu TReX Dual Motor Controllers	Pololu Simple Motor Controllers	Pololu Jrk Motor Controllers with Feedback	RoboClaw Motor Controllers
Number of available models	2	2	4	2	3
Motor channels	2	3[1]	1	1	2
TTL serial control	✓	✓	✓	✓	✓
Analog control (potentiometer)		✓	✓	✓	✓
RC control		✓	✓	✓	✓


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Robotzone Gearmotors
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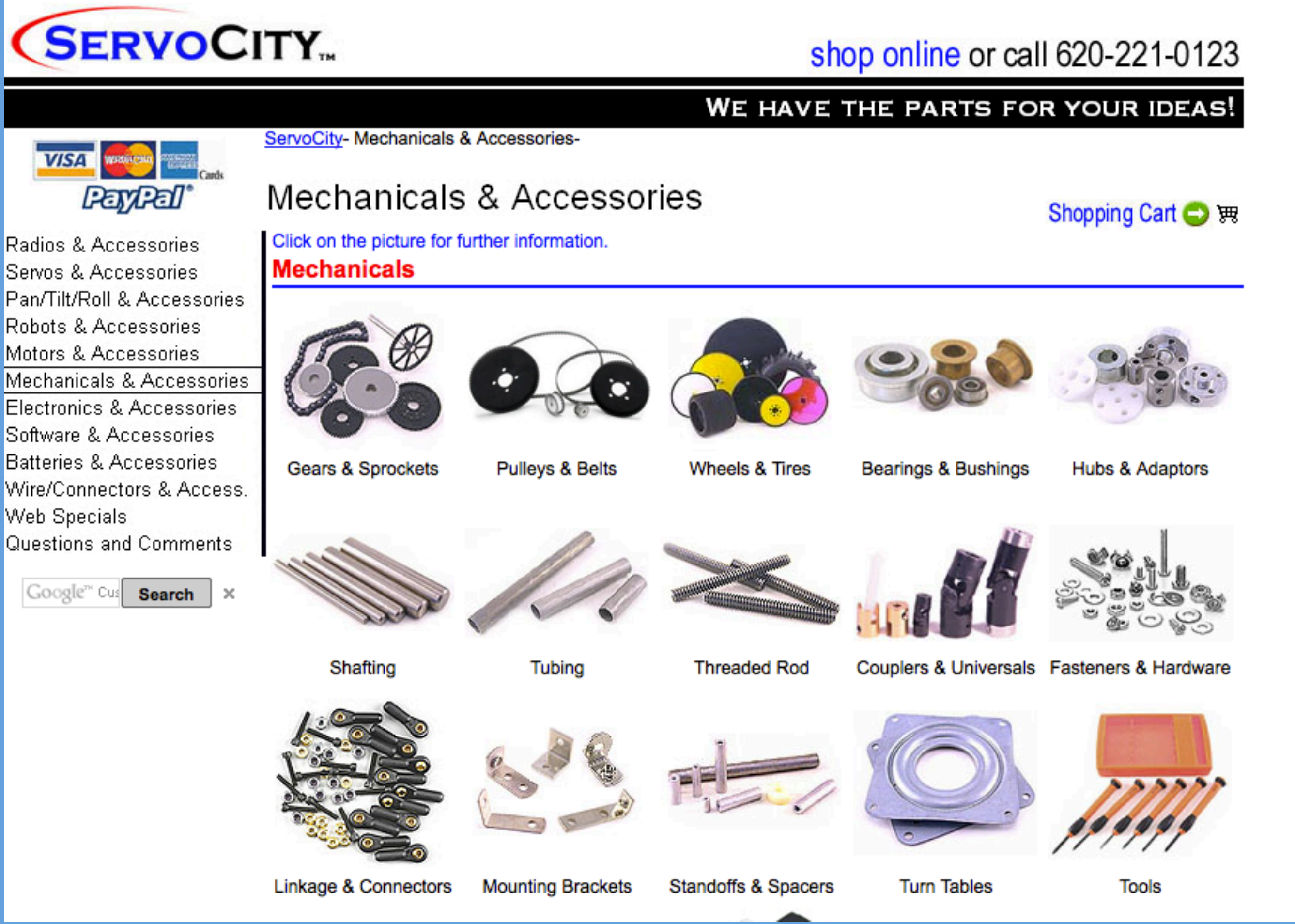
12-24V Gearmotors
6-12VDC Gearmotors
Precision
Belt Drive Pan Systems
Worm Drive Gearbox
Vertical Shaft
BRAND NEW!
Tamiya Gearmotors

Small mechanicals



C-2 TACTOR

The C-2 Tactor† is a miniature vibrotactile transducer that has been optimized to create a strong, localized sensation on the body. Using a body-referenced arrangement of Tactors activated individually, sequentially or in groups, C-2 Tactors can provide intuitive "tactile" instruction to a user. EAI's C-2 Tactor represents a state-of-the-art, wearable vibrotactile transducer, suitable for a wide variety of military, biomedical and commercial applications.

C-2 Tactor, actual size

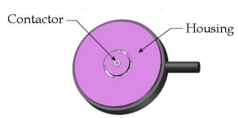
†patent pending

SPECIFICATIONS: C-2 TACTOR

Physical Description:	1.2" diameter by 0.31" high
Weight:	17 grams
Exposed Material:	anodized aluminum, polyurethane
Electrical Wiring:	Flexible, insulated, #24 AWG.
Skin Contactor:	0.3" diameter, pre-loaded on skin.
Electrical Characteristics:	7.0 ohms nominal.
Insulation Resistance:	50 megohm minimum at 25 Vdc, leads to housing.
Response Time:	33 ms max
Transducer Linearity:	+/- 1 dB from sensory threshold to 0.04" peak displacement.
Recommended Drive:	Sine wave tone bursts 250Hz at 0.25A rms nominal, 0.5 A rms max for short durations.
Recommended Driver:	Bipolar, linear or switching amplifier, 1 W max, 0.5 W typical.

DETAILS OF OPERATION

The C-2 Tactor is a linear actuator that has been optimized for use against the skin. The C-2 Tactor incorporates a moving "contactor" that is lightly preloaded against the skin. When an electrical signal is applied, the "contactor" oscillates perpendicular to the skin, while the surrounding skin area is "shielded" with a passive housing. Thus, unlike most vibrational transducers (such as common eccentric mass motors that simply shake the entire device), the C-2 provides a strong, point-like sensation that is easily felt and localized.



For optimum vibrotactile efficiency, the C-2 is designed with a primary resonance in the 200-300 Hz range that coincides with peak sensitivity of the Pacinian corpuscle, the skin's mechanoreceptors that sense vibration. The C-2's high force and displacement level allow the vibration to be easily felt at all locations on the body, even through layers of clothing.

EAI's offers Tactors in various configurations for different applications – please contact us for details. EAI also offers multi-channel controller/interface boards and complete turnkey vibrotactile systems.

INFORMATION through the sense of TOUCH

From left: C-2 Tactor with Silicone Gel "snap-in" mounting pad; C-2 Tactor with integral polyurethane flange for sewing into a garment; ruggedized C2-A Tactor with internal moisture/sand seal and highly flexible "tinsel" wire with Kevlar strength member.

ENGINEERING ACOUSTICS, INC.

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email: sales@eaiinfocom; www.eaiinfo.com
phone: 407 645-5444; fax: 407 645-4910

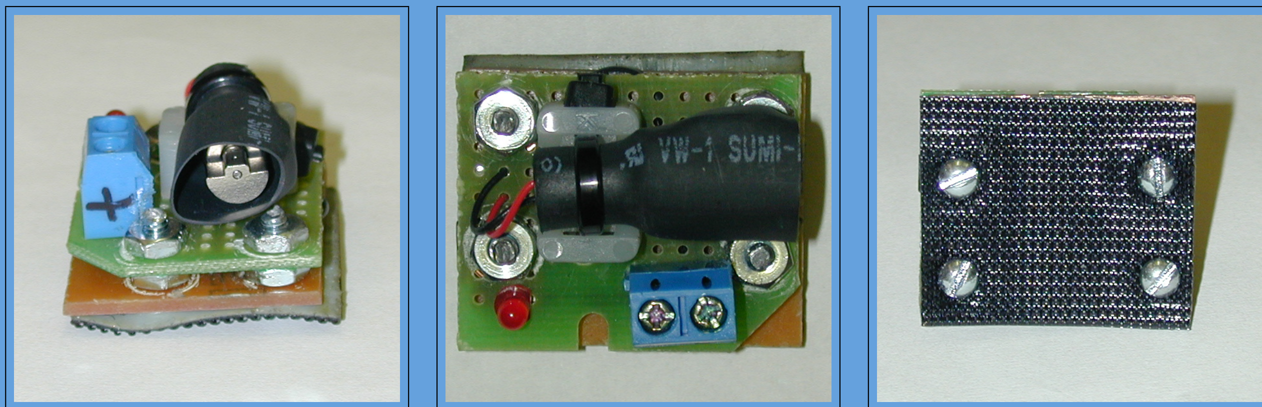
Vibrating actuators (I)

- ERM (eccentric rotating mass) actuators or pager motors. These can be bought from surplus sites, a Google search would give plenty of places to buy from (e.g.
  - http://www.precisionmicrodrives.com/haptics-haptic-feedback-vibration-alerting,
  - http://evilmadscience.com/productsmenu/partsmenu/131-pagermotor,
  - http://www.hobbyengineering.com/H1202.html)
  - These motors are driven a constant voltage and usually take a few 10s of milliseconds to reach peak speed and to stop completely after voltage is removed. Good for a buzz effect, e.g. alerts.
- LRA (linear resonant actuator) is an actuator that resonates at a specific frequency with a high Q. A nice description of the actuator can be found and they can also be bought a
  - http://www.precisionmicrodrives.com/vibrating-vibrator-vibration-motors/linear-resonant-actuator-lra-vibration-motors. This is a low end actuator because of it size (10mm diameter X 3.6mm) and power consumption.
  - Also popular: http://www.eaiinfo.com/Tactor%20Products.htm.
  - They fabricate "high" end actuators that resonate at 250Hz (most popular) 100Hz, and 124Hz. The 205Hz resonant actuator has dimensions of 1.2" diameter by 0.31" thickness. These actuators need to be driven with a bidirectional sine wave, usually an audio amp would be enough. The haptic-vibration effects that can be created with this actuator are of higher quality (e.g. button click)

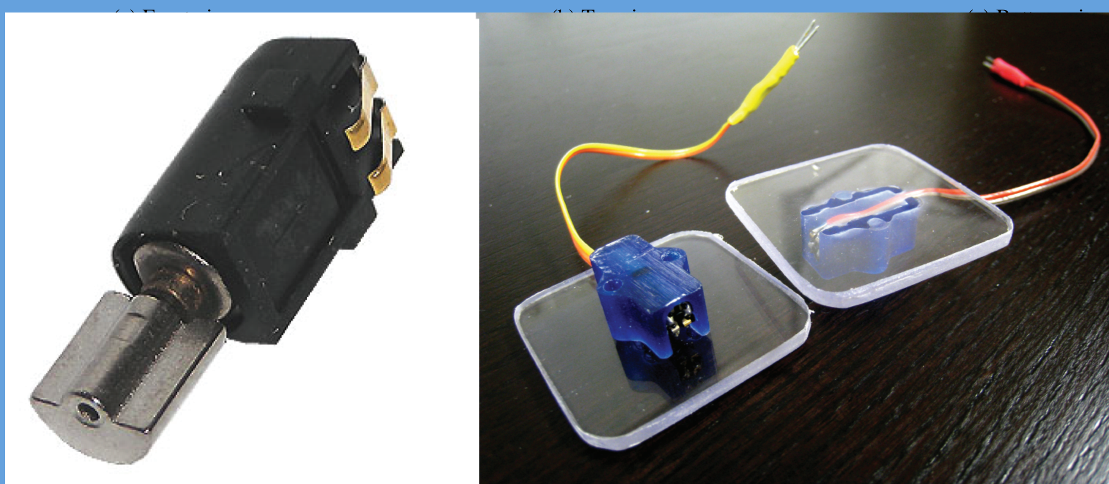
Vibrating actuators (II)

- Electroactive polymer actuators. Commercialized now by Artificial Muscle Inc. under the brand name of ViviTouch, this is a resonant actuator made from EAP films that shake a mass to create a resonant actuator with higher fidelity because of the wide band (low Q) and relatively large dynamic range. The following video describes the how this actuator is built and used:
  - http://www.vivitouch.com/technology.php,
  - Note the difference with pager motors. The actuator might not be for sale, but they sell a "jacket" for the iPhone that has the ViviTouch actuator.
- Piezoelectric actuators configured in a resonant mode (this is shaking a mass)
  - http://www.pbinterfaces.com/documents/Tactile_Feedback_Solutions.pdf)
  - Has the similar bandwidth as the EAP actuators and generates similar vibration effects. IT has been commercialized now by Immersion, there is a product released recently by Pantech that uses a piezo actuator, first device with high fidelity vibrations http://www.pantechusa.com/phones/element/
- There are also the surface haptics (vibrations) that have been created in the past but that require a more sophisticated actuator:
  - Vibration using Electrostatic forces (two plates attracting each other)
    - http://www.pacinian.com/
  - Electrostatic forces between the surface and the finger
    - http://www.disneyresearch.com/research/projects/hci_teslatouch_drp.htm,
    - http://senseg.com/
  - Mechanical vibration using a lateral displacement piezo actuator (see attached reference paper ICCE 2010)
  - Ultrasonic vibration to reduce friction basically a piezo attached to a touch sensitive surface vibrates at ultrasound frequencies creating air pockets under the finger and the user perceived this as friction reduction of the surface (see Giraud and Winfield attached here).

Homemade tactors



UPenn,
Bloomfield, Badler



Yale HMI Lab
Morrell, Myelle, Wasileweski,

Actuator Resources

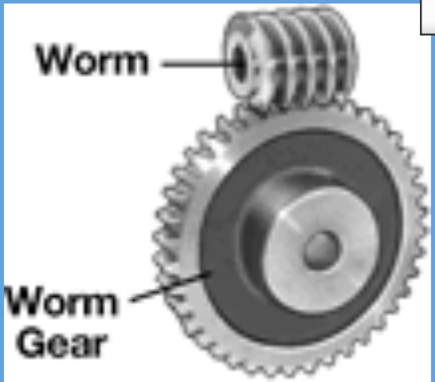
- Pololu http://www.pololu.com/
- Servo City http://www.servocity.com/
- DC motor models

Transmissions

- Direct
- Rigid Drive Elements: Gears, Gearheads
  – Friction, hysteresis, inertia, efficiency
- Flexible Elements: Belts, Cables
  – Static friction, compliance, wear, packaging volume
- Bearings
  – Rotating vs. linear

Gears

- Spur
- Helical
- Bevel
- Worm

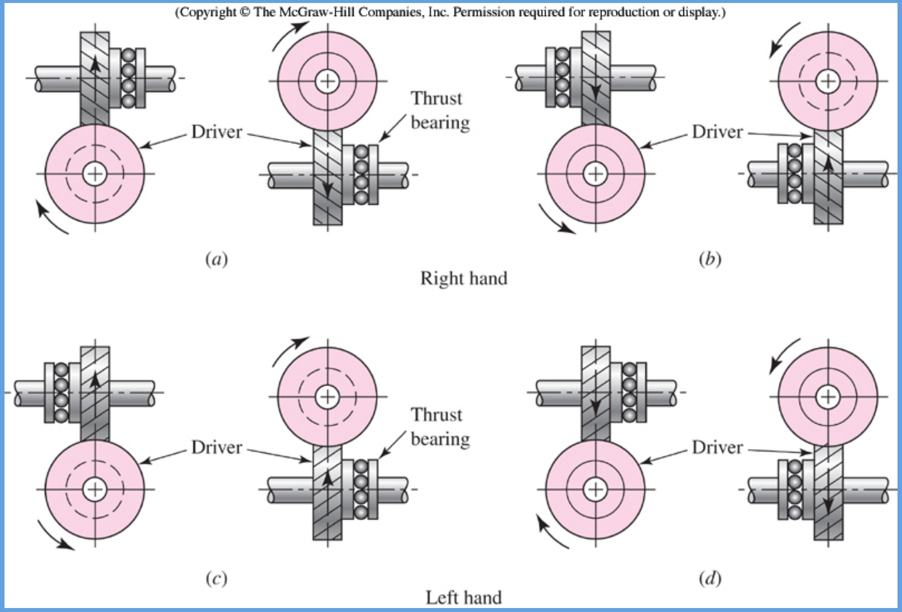


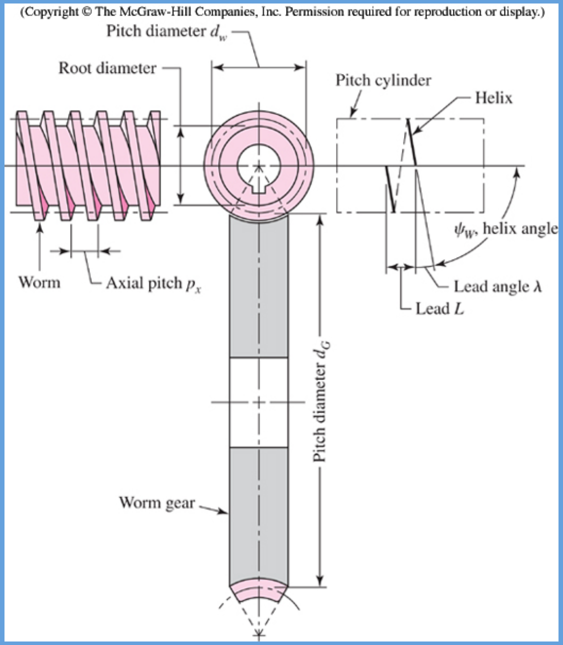
Gear Basics

- Constant angular velocity is given by an involute profile – no sliding contact – only rolling contact.
- Gear failure is caused by:
  - Bending stresses
  - Contact stresses
- Gear failure can result in a locked shaft
- The majority of applications are looking at high-ish speeds which is a poor fit with haptics applications
- Specs will be hard to interpret (efficiency in particular)

Worm Gears

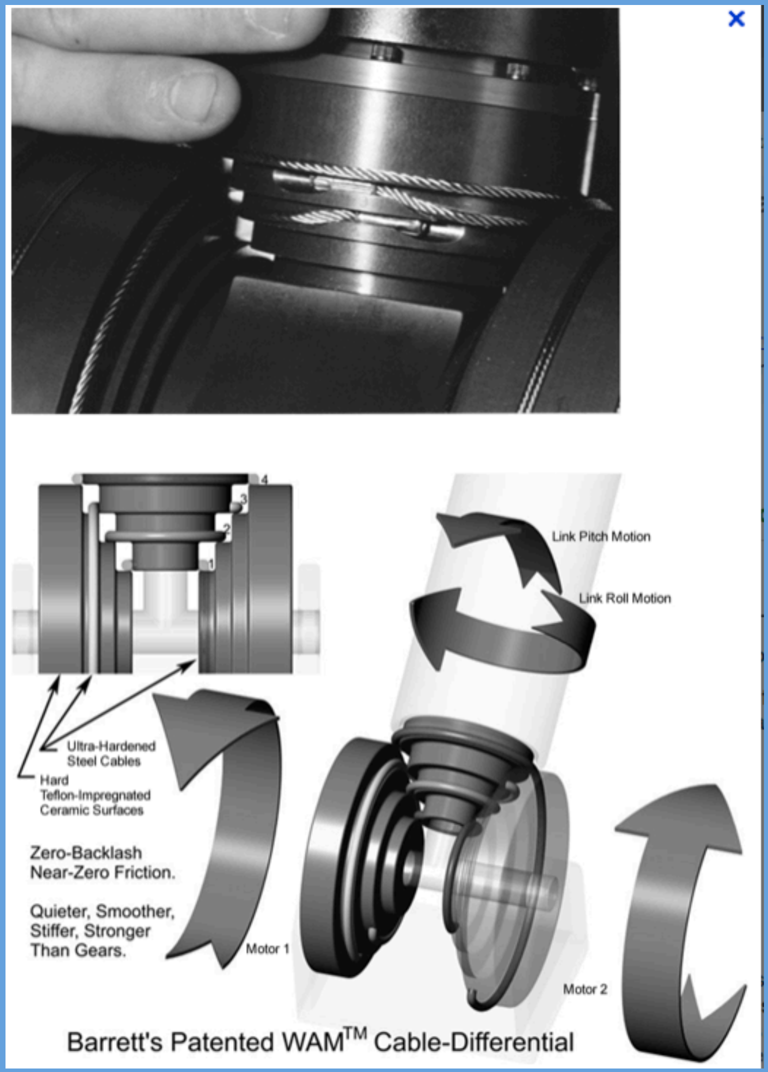
- Forward and Backward dynamics are different
  - →helix angle
  - →friction

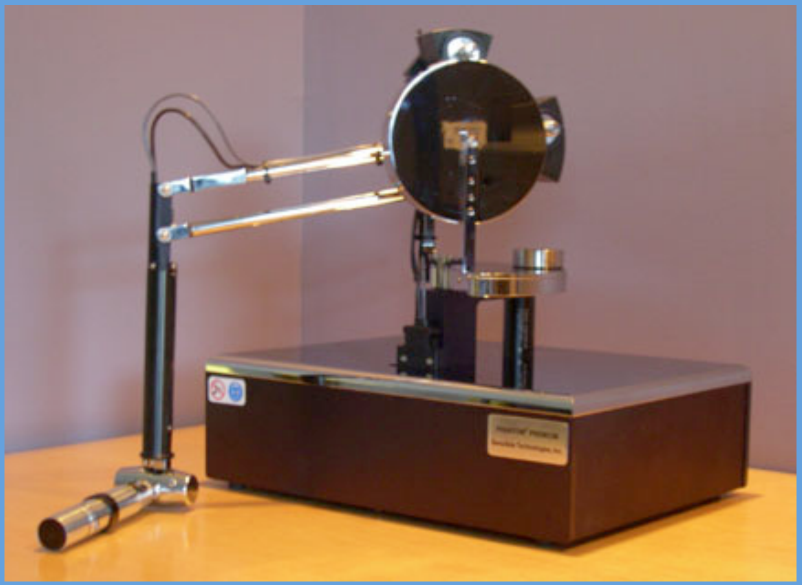


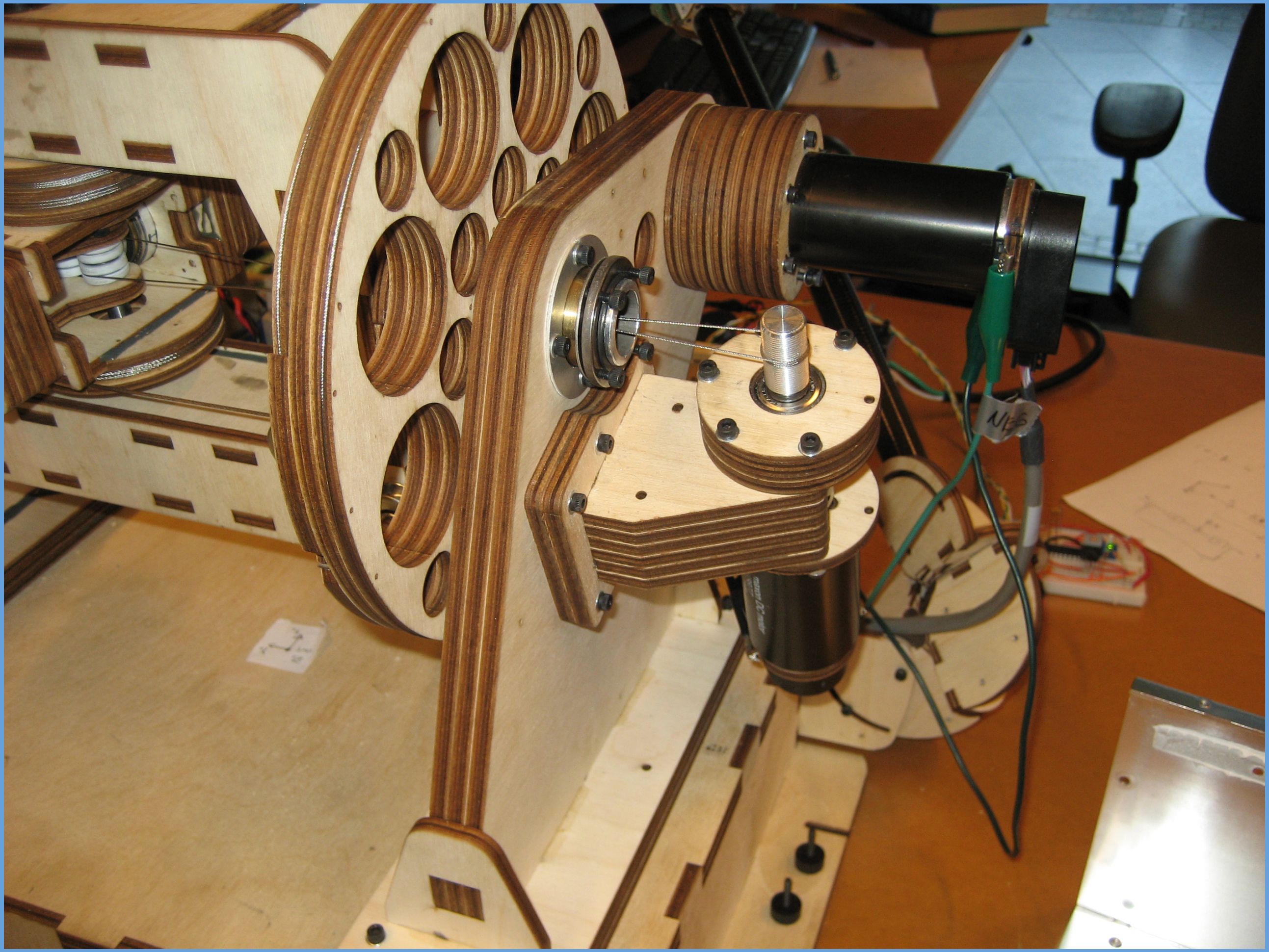


Cables

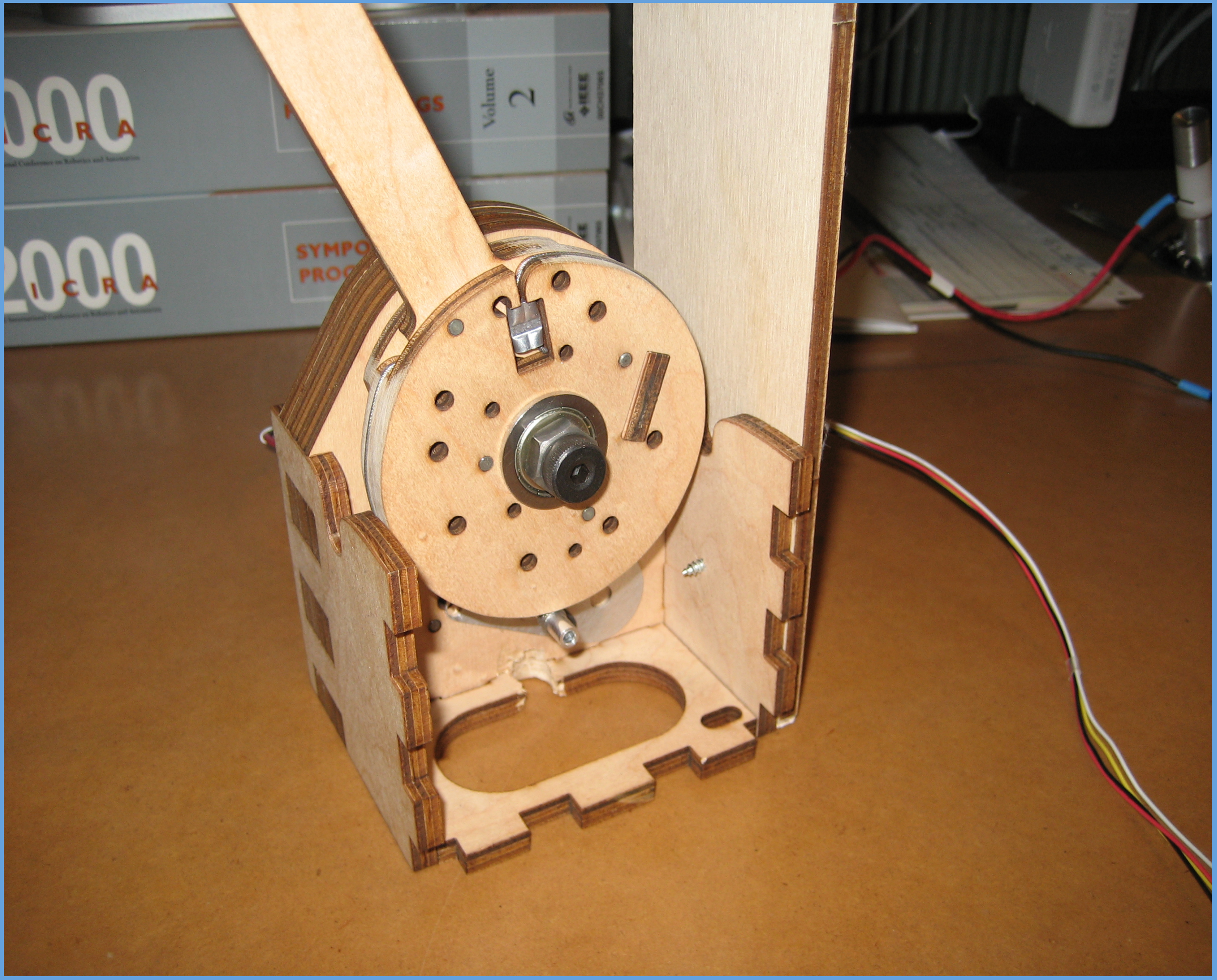
- The state of the art for transmission efficiency, linearity
  - Backdriveable
  - Low friction
  - Zero backlash
- Harder to maintain
- Many design paradigms to copy
  - WAM
  - Phantom
  - Omni


Link Pitch Motion
Link Roll Motion
Ultra-Hardened Steel Cables
Hard Teflon-Impregnated Ceramic Surfaces
Zero-Backlash Near-Zero Friction.
Quieter, Smoother, Stiffer, Stronger Than Gears.
Motor 1
Motor 2
Barrett's Patented WAMTM Cable-Differential





Stanford Robotics Laboratory, Ken Salisbury



Stanford Robotics Laboratory, Ken Salisbury

Repairing a PHANTOM Omni

The PHANTOM Omni is a commercially available, six degree-of-freedom haptic device. In our lab, we use these devices for research and instruction, and have found that the cable drive of devices is susceptible to failure. This page describes how to disassemble the Omni and fix the cable drive.

Diagnosing a Cable Drive Failure

In our experience, the cable drive to the distal link of the Omni is a likely failure point. The link may move more freely than the other joints and you may hear a rattle inside the device (which is the pin that has come free). To confirm that the cable drive is disconnected, run the "PHANTOM test" program, move the stylus, and monitor the encoders. If all but the distal link encoder show activity, then the cable drive is probably broken.

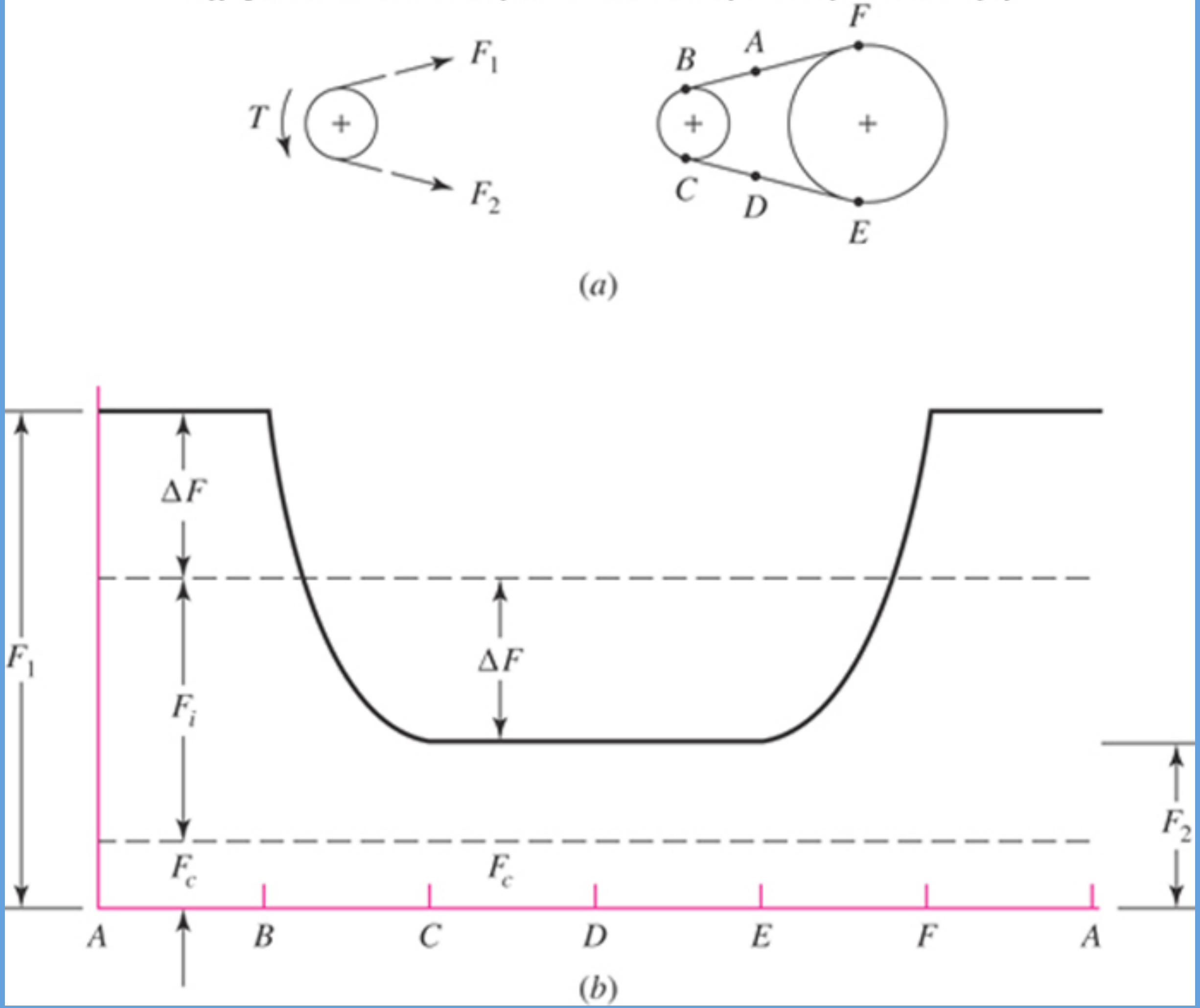
A second failure mode, which we have seen on a recently purchased omni, is slippage between the motor shaft and the capstan drive under load. Slippage may be exacerbated when motor heat is conducted through the motor output shaft to the capstan drive. The videos below show the motor for the proximal link slipping at high torques. The two parts may be connected by some adhesive, but once overcome, the capstan has a sliding fit on the motor shaft. We have installed a set screw on the capstan to fix the slippage.

http://haptics.lcsr.jhu.edu/Repairing_a_PHANTOM_Omni, From website: Haptics Laboratory, Johns Hopkins

Belts

- Good for long distances
- Can accommodate changes in shaft center distances
- Slippage occurs (except timing belts)
- Failure is generally to a no torque condition
- Slippage can be used as “mechanical fuse”
- Life/Reliability is driven by bending fatigue

Tension in a Flexible Drive System



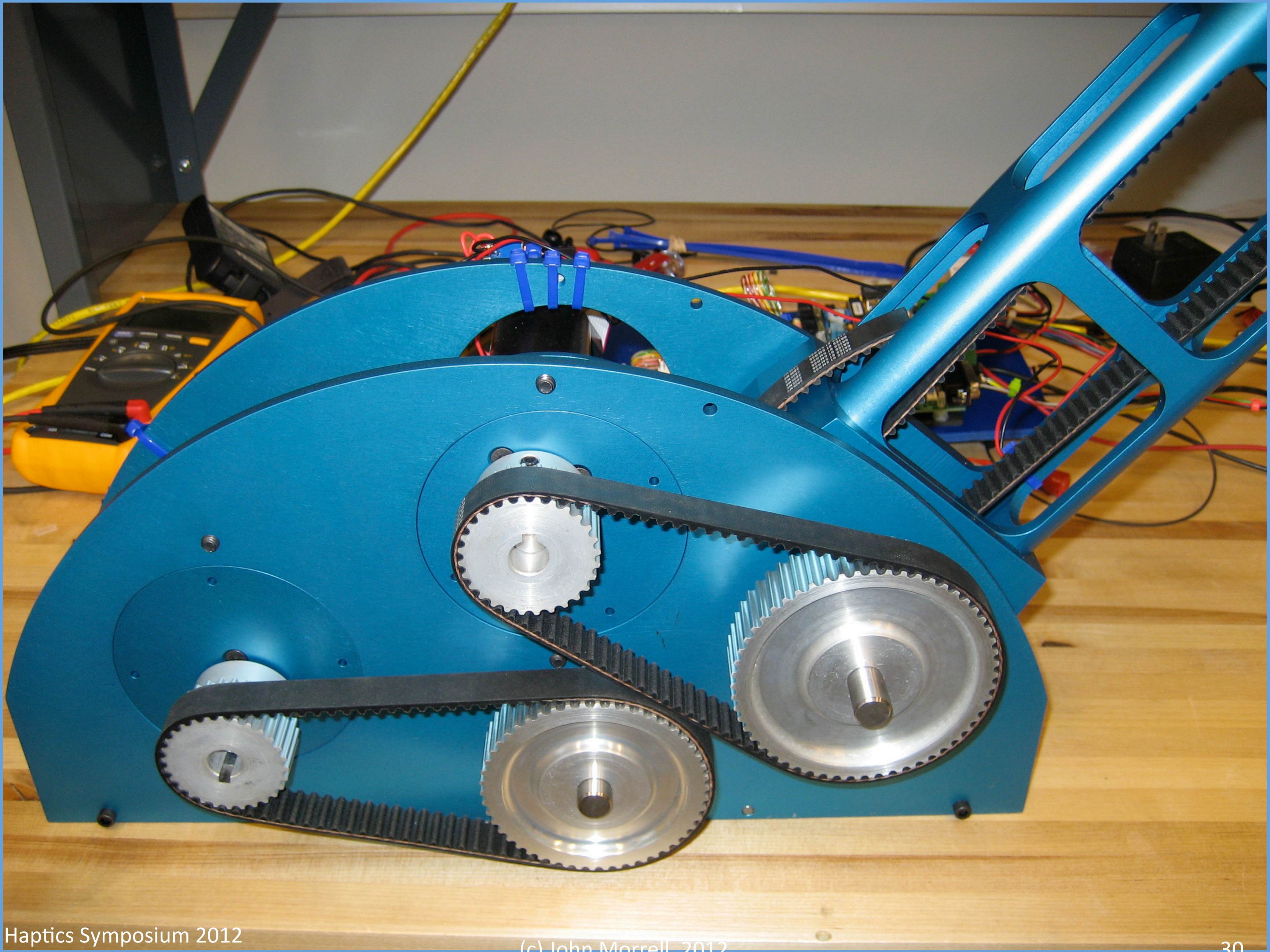
Belt Design

- Load, Speed, Reliability, Life
- Ratio
- Center Distance

- Belt Thickness
- Belt Width
- Pulley Diameters
- Tensioning Scheme

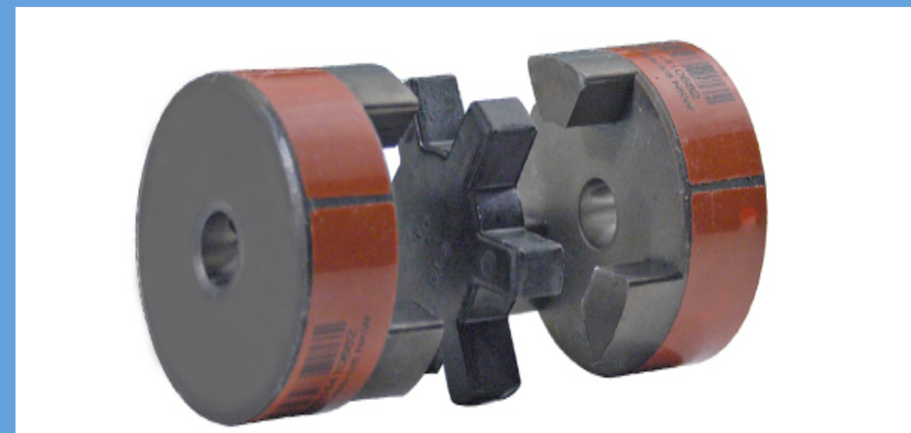
- Example Design Handbook: Gates

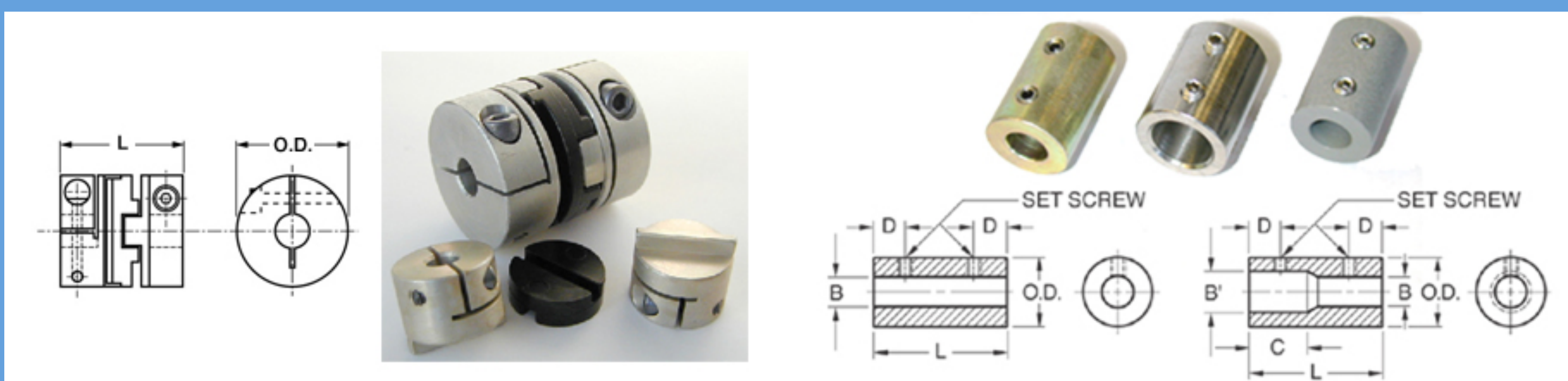
- Like gears, the applications are high-ish speeds. Low speed numbers are not typically available.



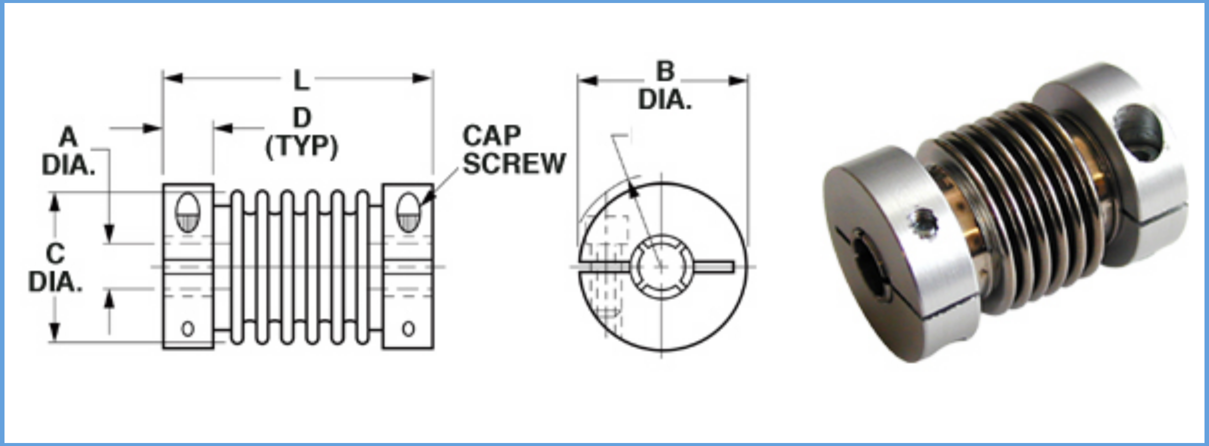
Couplings

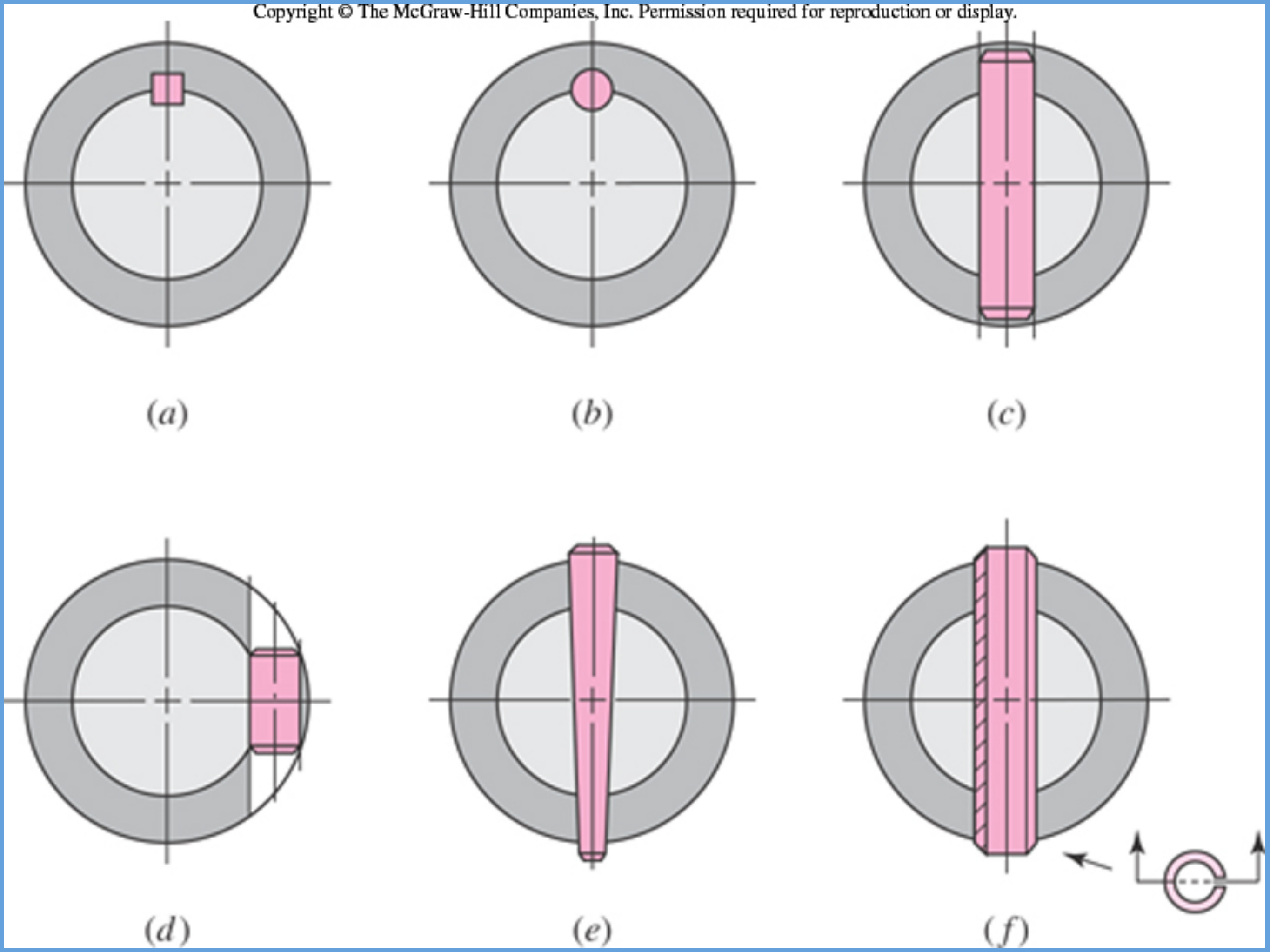
- Torque capability
- Displacement misalignment
- Angular misalignment
- Stiffness / Hysteresis





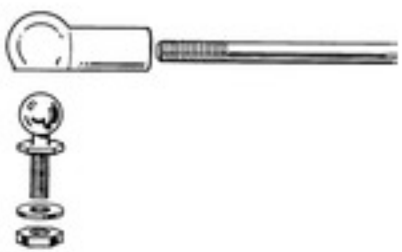
Couplings





The ubiquitous set screw is probably the poorest way possible of transferring torque

RC off-the-shelf parts



2-56 Threaded Ball Link (QTY/PKG: 1)

USD$ 1.94

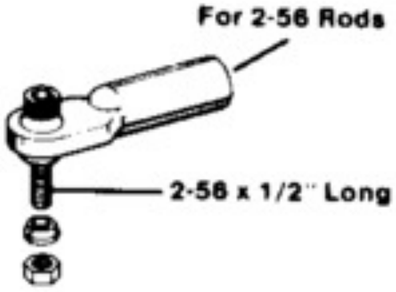
Item is available.

VIEW DETAILS

Blind Nuts 2-56 (QTY/PKG: 4)

USD$ 0.99

Item is available.



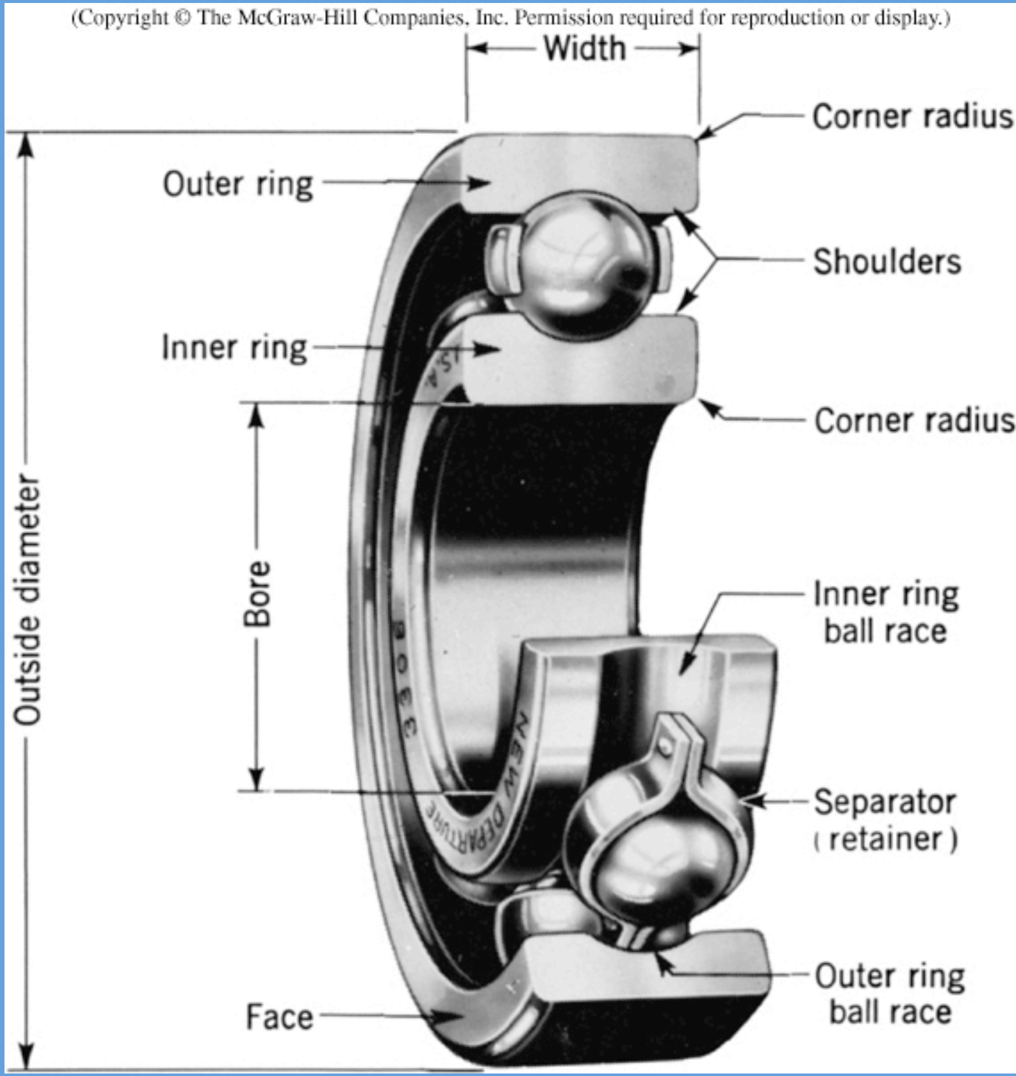
2-56 x 1/2 Swivel Ball Links Without Hardware (2/ pkg)

USD$ 1.85

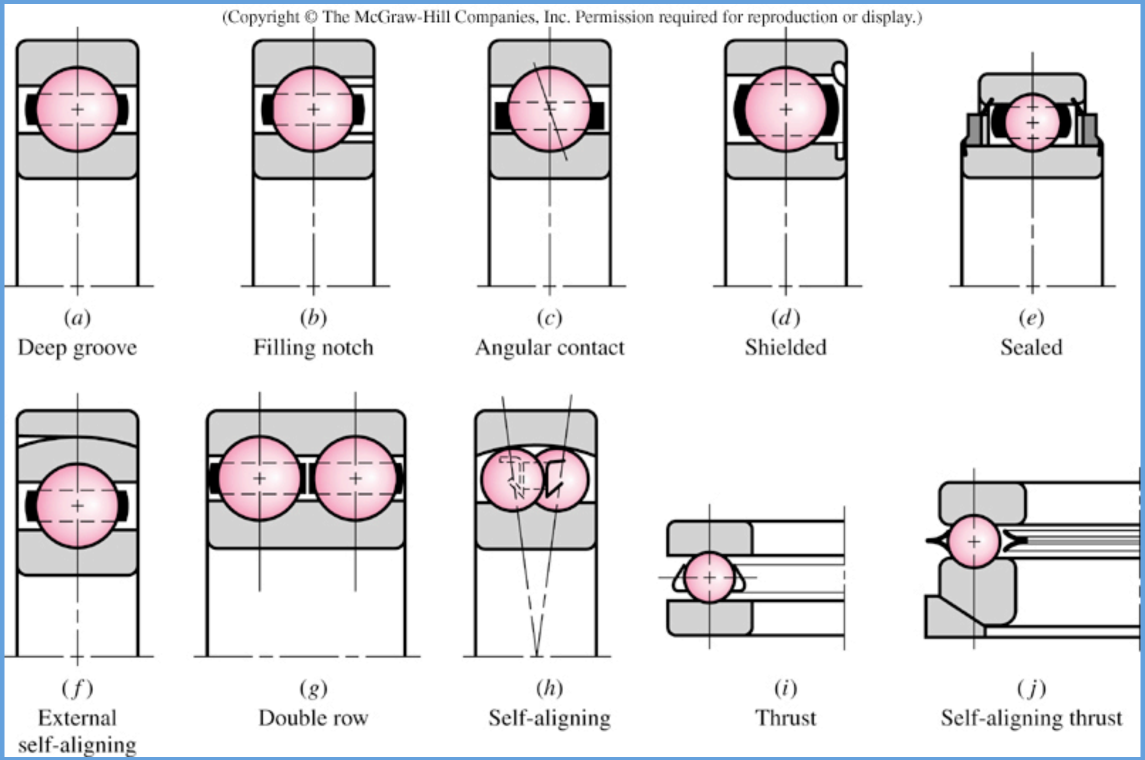
www.dubro.com

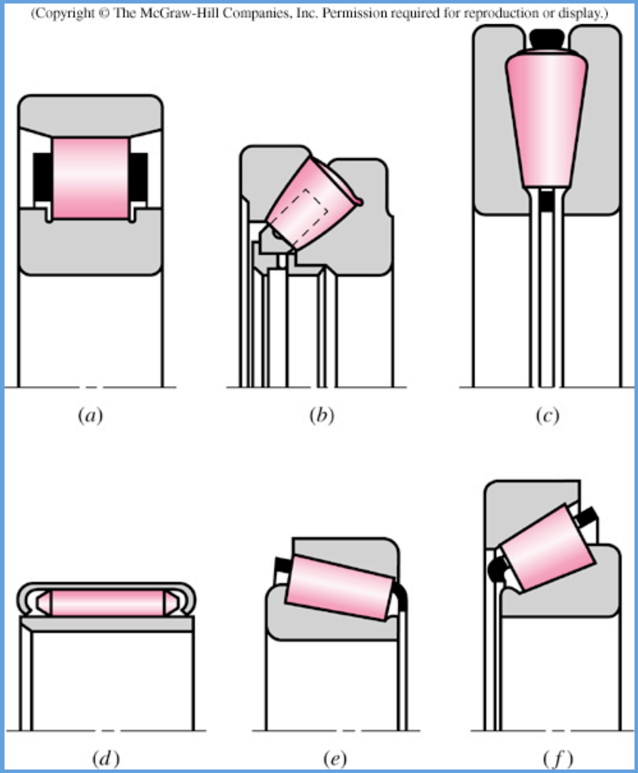
Rolling Contact Bearings

- Bearings have become highly specialized
- Check manufacturer's data books



A few common configurations





Main Selection Criteria

- Reliability at imposed load
- Expected life at imposed load
- Housing/Seals (environmental exposure)
- Mounting Scheme
- Tolerance/accuracy
- Radial vs. Thrust loading

➢ Most academic devices don't get near wear or fatigue failures – overload, dirt and friction are the main enemies

Control of Contact Force

- MIT Force Control Family Tree
  - Whitney, Salisbury, Pratt, Seering, Asada, Hogan
    - Eppinger (colocation of sensor/actuator)
    - Townsend (cable drives)
    - Morrell (parallel coupled, macro/micro)
    - Williamson (series elastic acuators)
    - Madhani (high DOF cable drive)
    - Robinson (more SEA)
    - Zinn (more parallel micro/micro)
- Hollerbach, Jacobsen, Khosla, Kazerooni

➢ Hardly complete but a reasonable place to start.

Power

- DC power from a wall is straight-forward
- Batteries
  - Sealed Lead Acid – heavy, tough, cheap
  - NiCad – not green, prone to memory effects. Must be maintained
  - NiMH – the most perishable, must be maintained continuously
  - LiPo – prone to fire
  - LiFE – the safest, lightest option
- Batteries are like muscles
  - They don't like extreme hot or cold
  - They don't like to be run down really low
  - They like regular use (not total rest, not overuse)

Charging Batteries

- Use a charger that is designed for the chemistry you have
- Set up a rotation scheme (like watering plants)
- Assign serial numbers, use in sets
- Charge LiPo cells in a ceramic dish with fireproof bag
- Fire is most likely when charging several cells in series.

Control

- Stationary
  - Labview
  - Matlab
- Mobile
  - Arduino
  - PIC
  - Phones
  - RC electronics
  - 626 boards
  - Gumstix
  - Etc.

Labview and Matlab

"I'm a mac … and I'm a PC" - Different views of the world

- Matlab started as a control & signal processors application
- NI started as a test & measurement tool, selling data acquisition hardware
- Both have attempted to produce hardware for real-time control
- NI suffered from reliance on Windows – not real time
- Matlab suffered from not being a hardware company – boutique hardware producers catered to big customers
- Much less difference now.
  - Matlab compiles for arduino, PC104 stacks with real-time workshop
  - NI makes realtime embedded FPGA systems (RIO)
  - Both require a lot more hardware and processing power than a custom system (i.e. weight & volume)

Small micros

- Arduino
- PIC
- Gumstix
- RC hobby hardware (speed controls, robot servos)

Model 2426 | Ethernet Multi-Function Interface

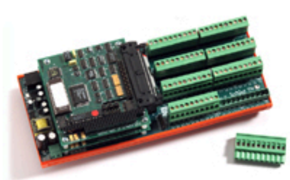
Features

- Controls/monitors real world signals over Ethernet
- 24 digital I/O, 6 analog in, analog out, serial comm, incremental encoder in
- PWM and debounce on digital I/Os
- Integral support for safety interlocks
- Embedded HTTP and Telnet servers
- Open source API
- Low cost, low power & compact size

Model 2518/2519TDIN | Ethernet A/D Interface

Features

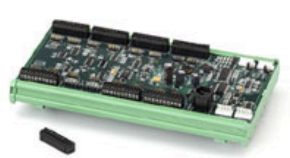
- 8 or 16 differential thermocouples, RTD's, strain gauges, thermistors, resistance, 4-20 ma, or voltage inputs
- Includes screw terminals for field wiring
- 10-Base-T Ethernet server with embedded TCP/IP stack
- Includes interface DLL
- Single supply operation
- Each channel is software programmable for sensor type, gain, low-pass filtering, scan rate
- Optional NEMA Enclosure



Model 2608 Series | Analog I/O via Ethernet

Features

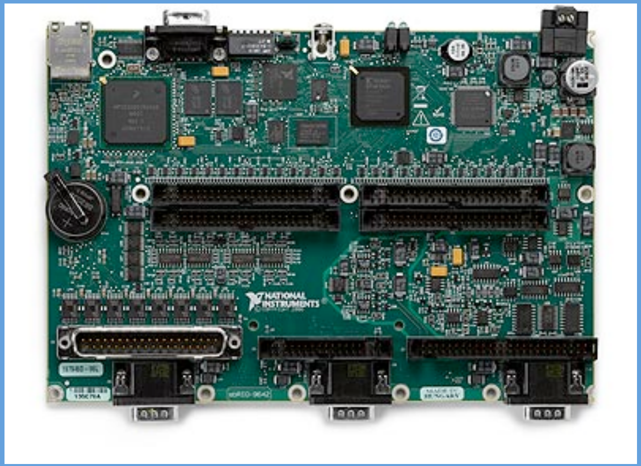
- 16 inputs of voltage, thermocouple, or 4-20 mA16-bit A/D, 15 -bit D/A
- Up to 8 analog outputs with remote sensing
- Auto standardization
- Selectable input gain
- All differential inputs
- Watchdog Timer
- Compatible with Linux and Windows
- Use our design assistant to configure a system and calculate pricing



Sensoray
Ethernet based I/O modules

http://www.sensoray.com/

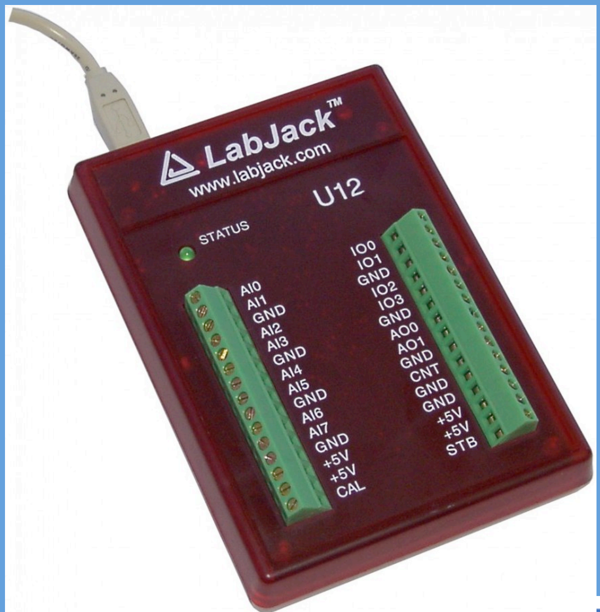
Larger Systems

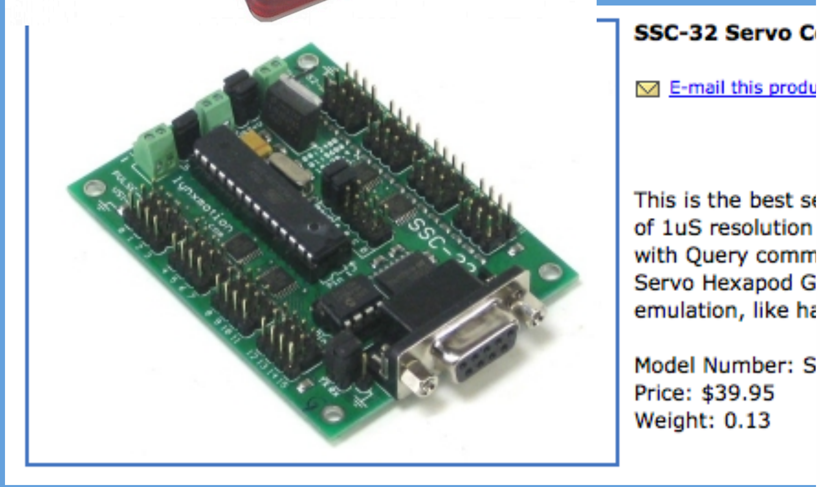


National Instruments RIO and C-RIO

http://www.ni.com/compactrio/
http://www.ni.com/singleboard/

Use a PC


LabJack™
www.labjack.com
U12
STATUS
AI0
AI1
GND
AI2
AI3
GND
AI4
AI5
GND
AI6
AI7
GND
+5V
+5V
CAL
IO0
IO1
GND
IO2
IO3
GND
AO0
AO1
GND
CNT
GND
GND
+5V
+5V
STB


SSC-32 Servo C
E-mail this produ
This is the best se
of 1uS resolution
with Query comm
Servo Hexapod G
emulation, like ha
Model Number: S
Price: $39.95
Weight: 0.13


NATIONAL INSTRUMENTS
NI USB-6008
8 inputs, 12-bit, 10 kS/s Multifunction I/O
Analog
Digital

Control Algorithms

- Proportional - Derivative position control
  - Derivative drives performance of the loop (damping)
  - Resolution of position sensor drives quality of velocity estimate
  - PD is "Spring-Damper" control – damper absorbs energy
  - Hard to achieve high stiffness with conventional position sensing
- Endless other possibilities
  - Passivity formulation (Hannaford)
  - Force control and it's many variants
- The best systems do not rely on control algorithms to address nonlinearities.

Other Resources

- Micro Mark – hobbyist tools
- Jewelry Tools