MEAM 520

More Robot Hardware

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General Robotics, Automation, Sensing, and Perception Lab (GRASP)

MEAM Department, SEAS, University of Pennsylvania

GRASP
LABORATORY

Lecture 19: November 7, 2013

Homework 6:
Velocity Kinematics and Jacobians

MEAM 520, University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

October 17, 2013

This paper-based assignment is due on **Sunday, October 27, by midnight (extended)** to the bin outside Professor Kuchenbecker's office, Towne 224. Late submissions will be accepted until Wednesday, October 30, by midnight (11:59:59 p.m.), but they will be penalized by 10% for each partial or full day late, up to 30%. After the late deadline, no further assignments may be submitted.

You may talk with other students about this assignment, ask the teaching team questions, use a calculator and other tools, and consult outside sources such as the Internet. To help you actually learn the material, what you write down must be your own work, not copied from any other individual or a solution manual. Any submissions suspected of violating Penn's Code of Academic Integrity will be reported to the Office of Student Conduct. If you get stuck, post a question on Piazza or go to office hours!

These problems are loosely based on problems that appear in the printed version of the textbook, *Robot Modeling and Control* by Spong, Hutchinson, and Vidyasagar (SHV); all of the needed instructions are included in this document. Write in pencil, show your work clearly, box your answers, and staple together all pages of your assignment. This assignment is worth a total of 20 points.

1. Skew-Symmetric Matrices *(6 points)*

a. We define $\hat{u} = [x \;\; y \;\; z]^T$ to be a unit vector. What is $S(\hat{u})$, the skew-symmetric matrix associated with this unit vector?

b. Now define $\vec{v} = [0 \;\; 10 \;\; 0]^T$ and calculate $S(\hat{u})\vec{v}$.

c. What is the geometric meaning of the result you obtained in the last step? Draw a sketch with an arbitrarily chosen unit vector $\hat{u}$ to explain. Think about both the magnitude and the direction of the result.

d. Show that $S^3(\hat{u}) = -S(\hat{u})$.

e. What is the geometric meaning of the equation $S^3(\hat{u}) = -S(\hat{u})$? Explain using words and a sketch.

f. $R_{\hat{u},\theta}$ is a rotation matrix representing rotation by the time-varying angle θ about the constant unit vector $\hat{u}$. By considering equation (2.43) in the book, one can show that $R_{\hat{u},\theta} = I + S(\hat{u})\sin\theta + S^2(\hat{u})\operatorname{vers}\theta$, where the versine $\operatorname{vers}\theta = 1 - \cos\theta$. Note that you do not need to show this equivalence. Instead, use this equivalence and the equation from the previous step to show that $\frac{dR_{\hat{u},\theta}}{d\theta} = S(\hat{u})R_{\hat{u},\theta}$.

g. What is the intuitive meaning of the equation $\frac{dR_{\hat{u},\theta}}{d\theta} = S(\hat{u})R_{\hat{u},\theta}$?

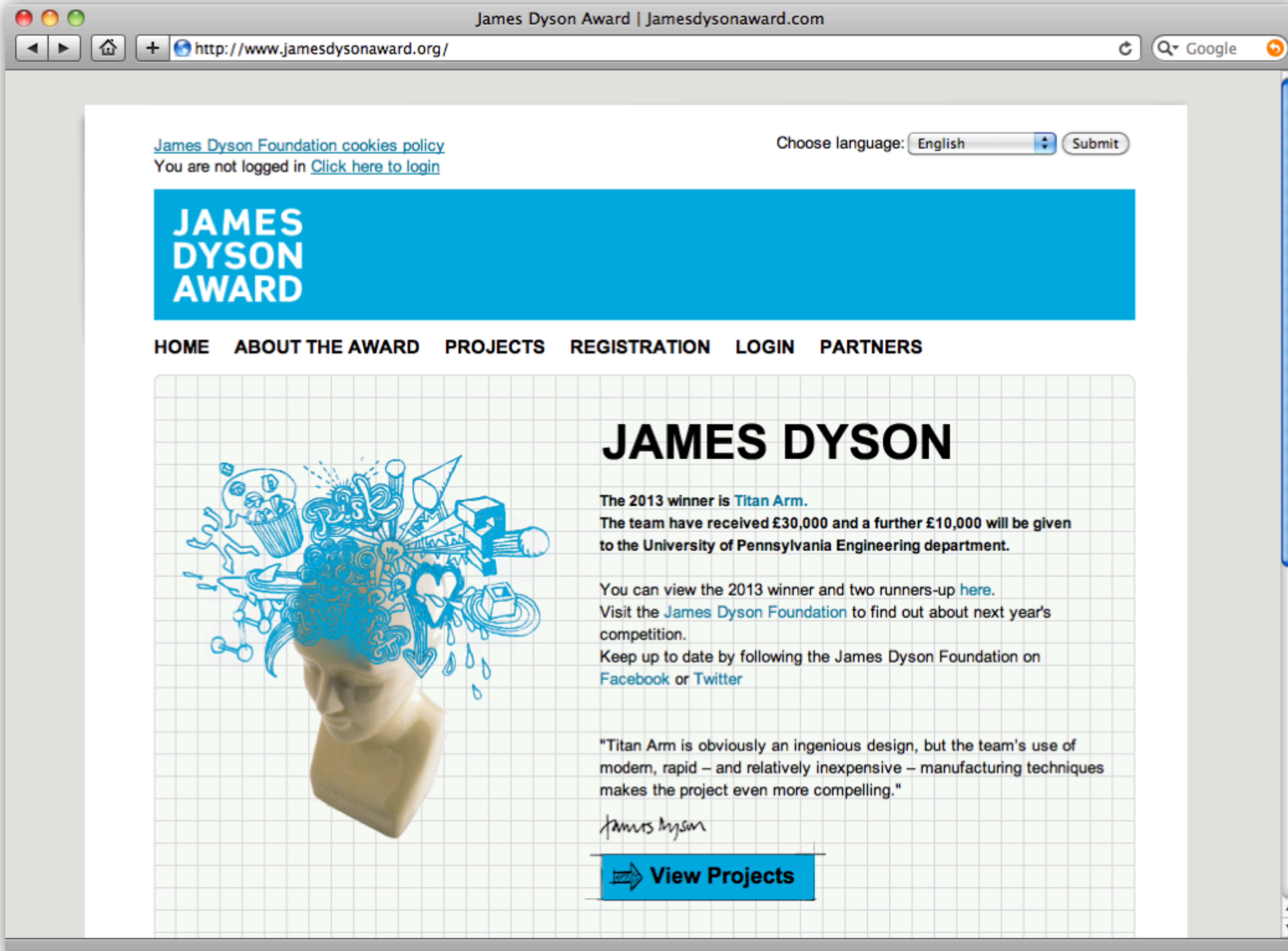
1

Homework 6 is graded

Pick yours up from Naomi

Thank you for taking the midterm on Tuesday.

One student has not yet taken the exam,
so we will not talk about it at all today.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JAMES DYSON AWARD
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JAMES DYSON
The 2013 winner is Titan Arm.
The team have received £30,000 and a further £10,000 will be given to the University of Pennsylvania Engineering department.
You can view the 2013 winner and two runners-up here.
Visit the James Dyson Foundation to find out about next year's competition.
Keep up to date by following the James Dyson Foundation on Facebook or Twitter
"Titan Arm is obviously an ingenious design, but the team's use of modern, rapid – and relatively inexpensive – manufacturing techniques makes the project even more compelling."
James Dyson
View Projects

TITAN ARM

Enhance strength

Low cost

Untethered

Data streaming

Long Battery Life

Onboard LiPo batteries run the suit for over 8 hours, take less than 30 minutes to recharge, & can be swapped in under a minute

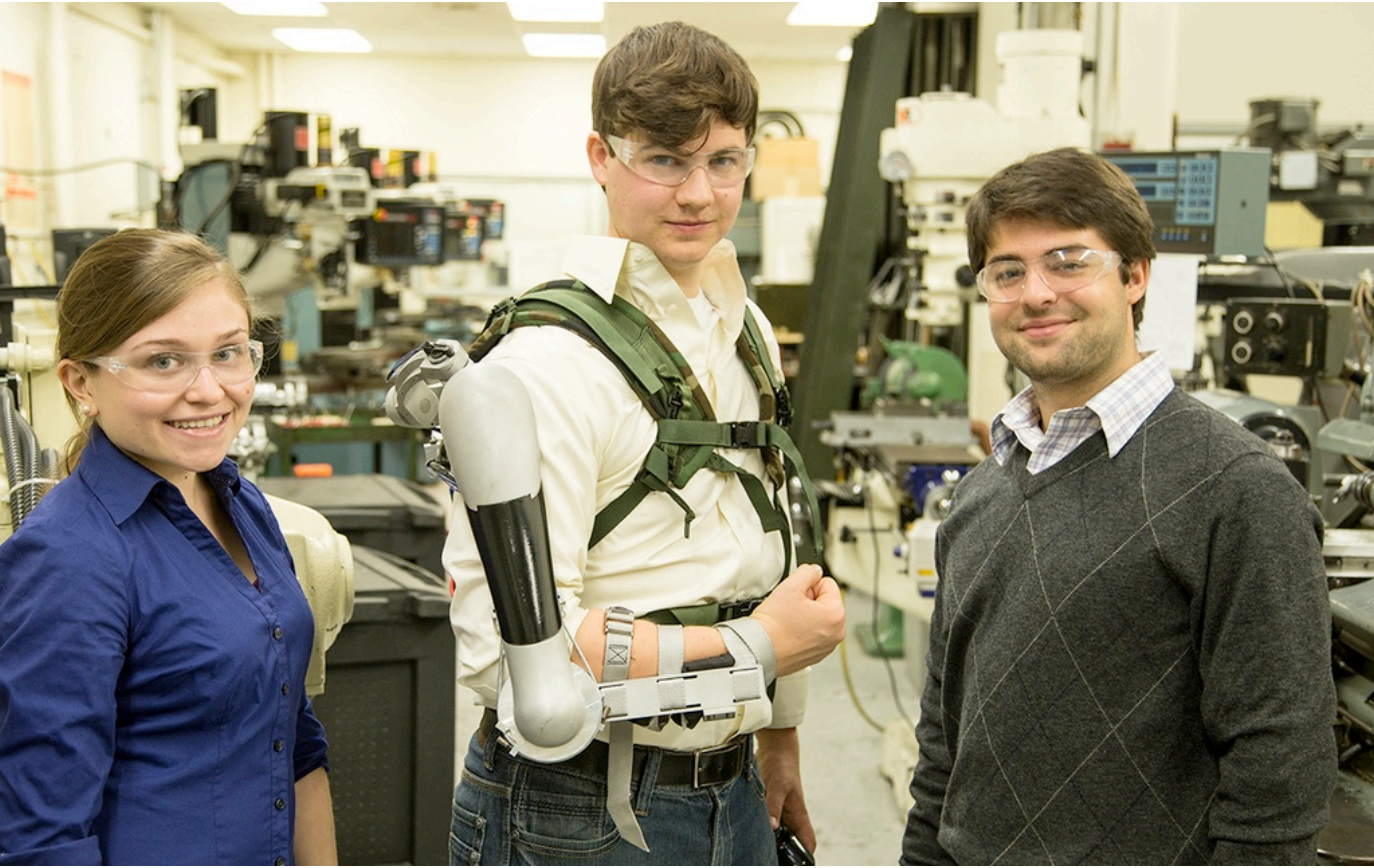
Versatile

The frame and straps adjust to fit anyone in the 15th-90th percentile of US adults by height

Light weight

The entire suit weighs under 9 kg, less than a typical school-bag load

TITAN ARM



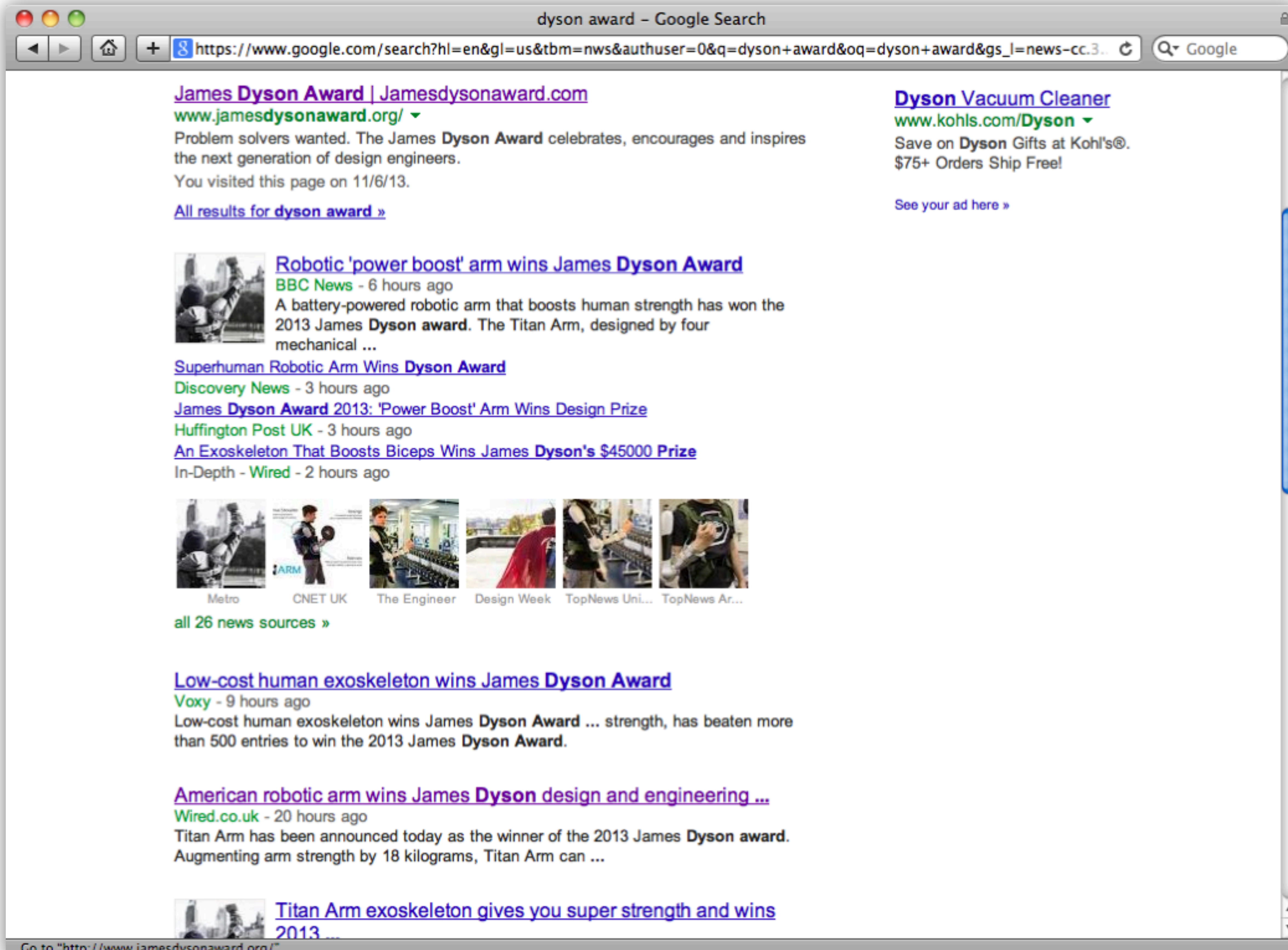
Congratulations to Penn Students

Elizabeth Beattie
Nick McGill
Nick Parrotta
and Niko Vladimirov
advised by Jonathan Fiene

for winning the

2013 James Dyson Award!

a $48,000 prize plus $16,000 for MEAM Department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Problem solvers wanted. The James Dyson Award celebrates, encourages and inspires the next generation of design engineers.
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American robotic arm wins James Dyson design and engineering ...
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Titan Arm has been announced today as the winner of the 2013 James Dyson award. Augmenting arm strength by 18 kilograms, Titan Arm can ...
Titan Arm exoskeleton gives you super strength and wins 2013 ...
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www.kohls.com/Dyson
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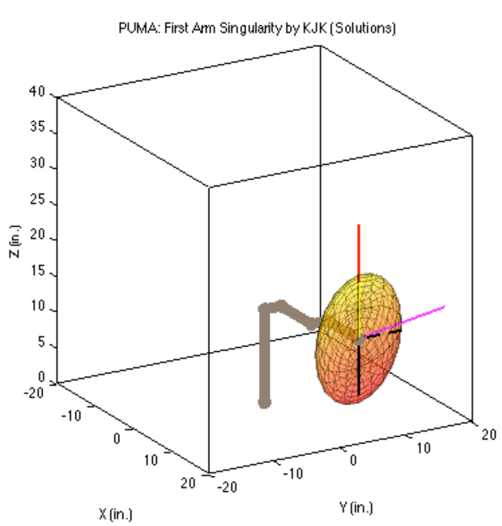
See your ad here »
Go to "http://www.jamesdysonaward.org/"

Solutions to Homework 7
PUMA 260 Singularities and Manipulability

MEAM 520
Introduction to Robotics
University of Pennsylvania
Professor Kuchenbecker
Fall 2013



Solutions to Homework 7 are on reserve in the Engineering Library

Untitled2

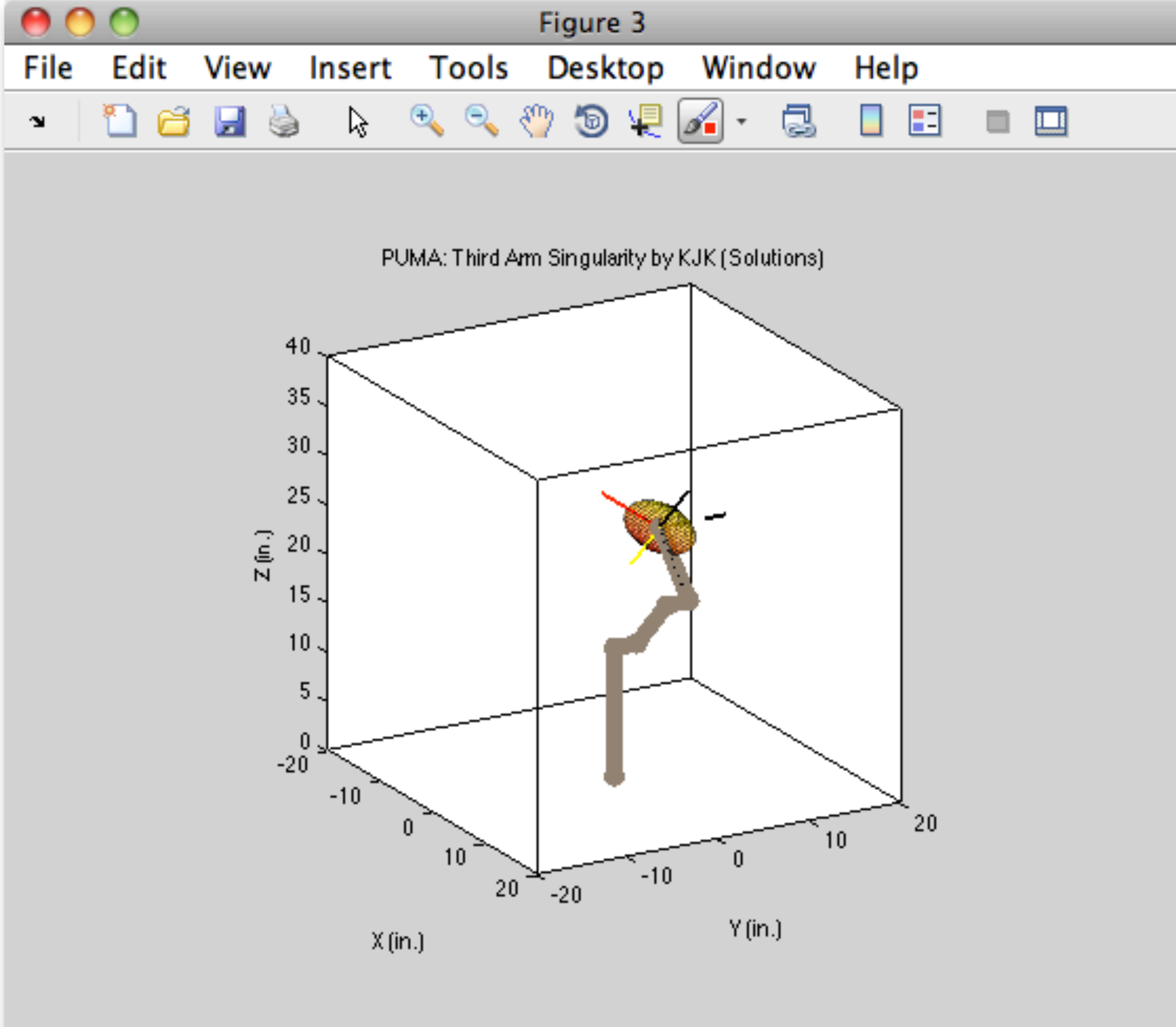
Editor – /Users/kuchenbe/Documents/teaching/meam 520/assignments/07 manipulability/matlab/analyze_puma_kuchenbe.m

EDITOR PUBLISH VIEW

analyze_puma_kuchenbe.m plot_puma_kuchenbe.m

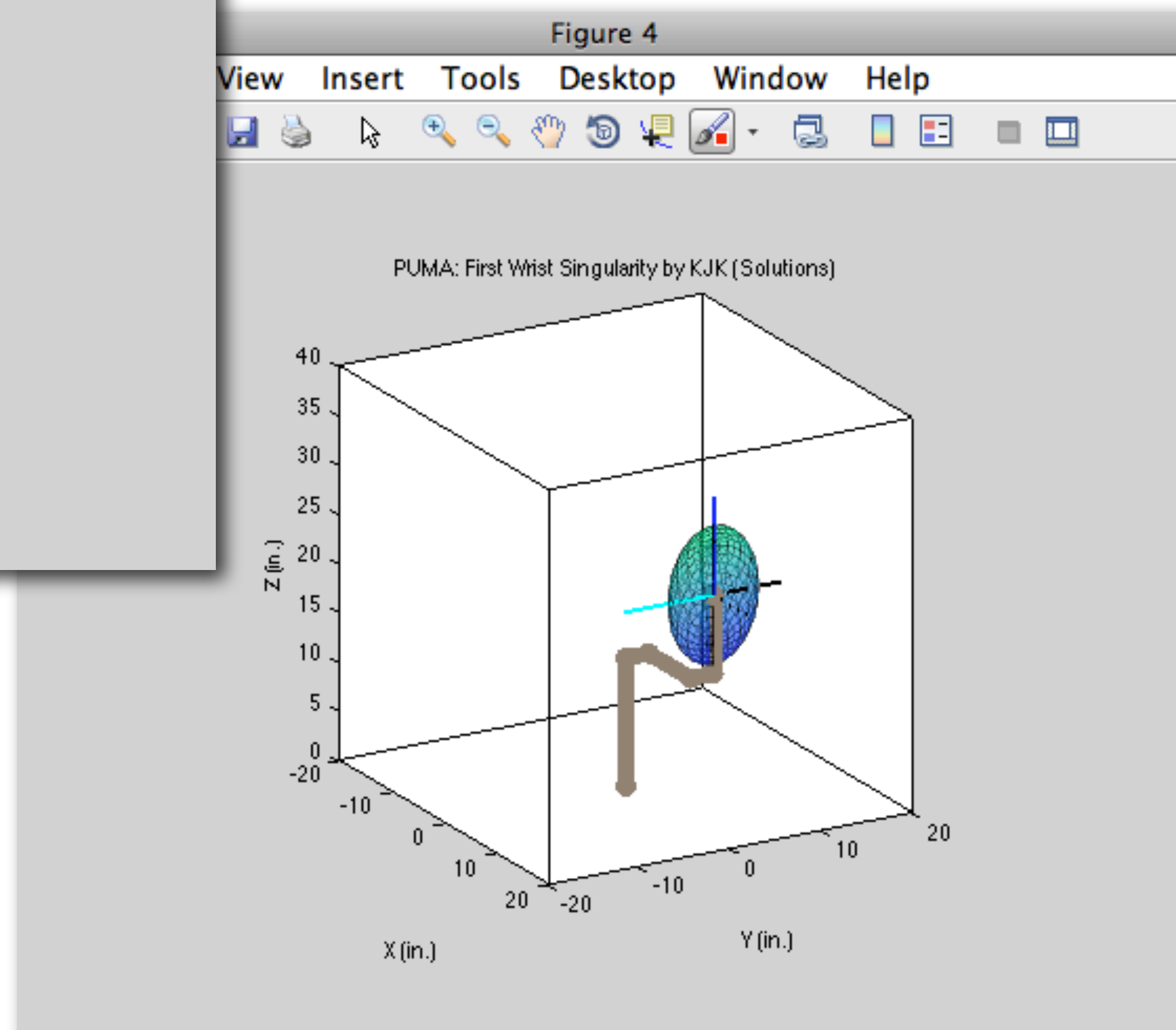
```matlab
%% analyze_puma_kuchenbe.m
%
% This Matlab script is part of the solutions for Homework 7 in MEAM 520 at
% the University of Pennsylvania in Fall of 2013.
% Written by Professor Katherine J. Kuchenbecker.


%% SETUP

% Clear all variables from the workspace.
clear all

% Home the console, so we can more easily find any errors that may occur.
home

% Set student names.
studentNames = 'KJK (Solutions)';


%% CALCULATE THE ARM'S SYMBOLIC LINEAR VELOCITY JACOBIAN

% Define real-valued symbolic variables for all six joint angles, all of
% the link lengths and link offsets, and pi.
syms theta1 theta2 theta3 theta4 theta5 theta6 a b c d e real

% Calculate the six A matrices using the provided DH function.  These are
% all symbolic entities now.
A1 = dh_kuchenbe(0,  pi/2,   a, theta1);
A2 = dh_kuchenbe(c,     0,  -b, theta2);
A3 = dh_kuchenbe(0, -pi/2,  -d, theta3);
A4 = dh_kuchenbe(0,  pi/2,   e, theta4);
A5 = dh_kuchenbe(0, -pi/2,   0, theta5);
A6 = dh_kuchenbe(0,     0,   0, theta6); % <-- Use zero instead of f to put o6 at wrist center.

% Calculate the transformation matrix from frame 0 to frame 6, which moves
% with the end-effector and is at the center of the wrist.
T06 = A1*A2*A3*A4*A5*A6;

% Pull out the position of the wrist center, then pull out its components.
d06 = T06(1:3,4);
x = d06(1);
y = d06(2);
z = d06(3);
```

script Ln 33 Col 43



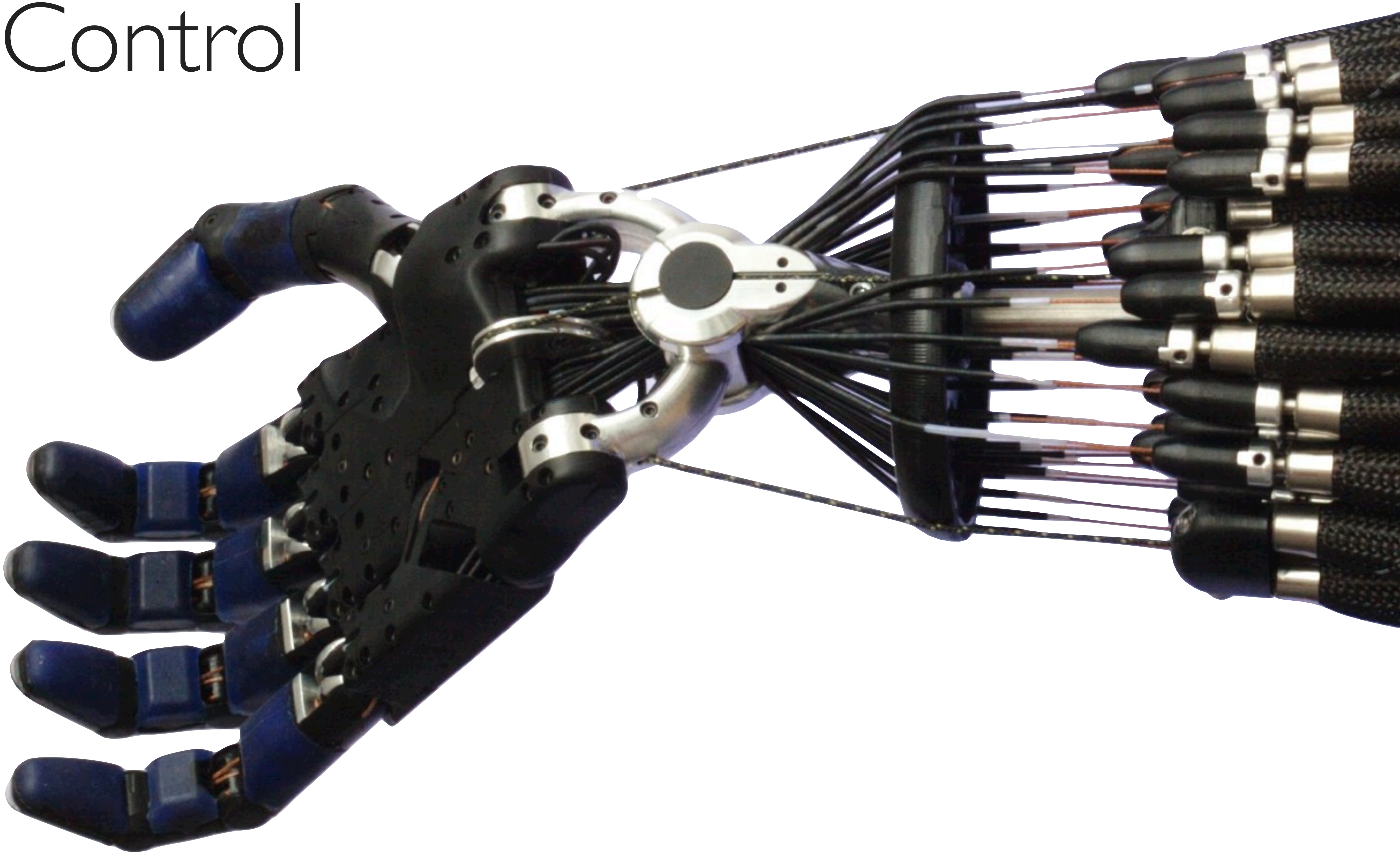

```
detJv =

c*e*cos(theta3)*(e*sin(theta2 + theta3) - c*cos(theta2))
```

```
detJw =

-sin(theta5)
```



What questions do you have?

Manipulator Hardware and Control



SHV Chapter 6 plus extra material

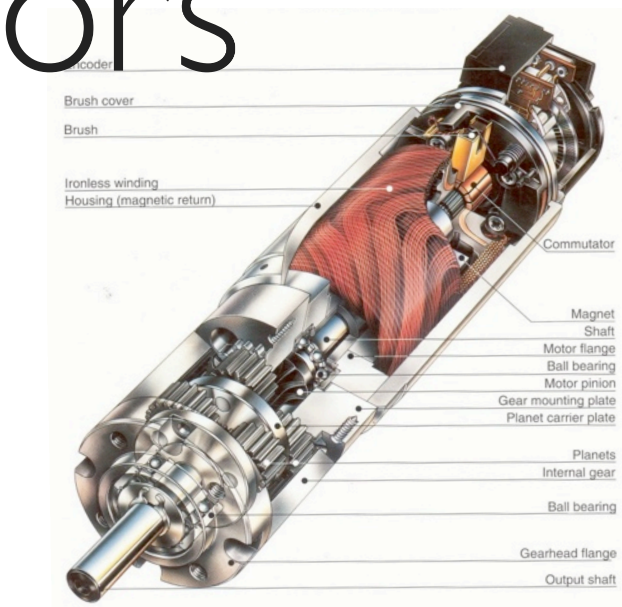
Brushed DC Motors

DC Brushed

Coil Rotor

Magnetic Stator

Brushes carry current to the rotor

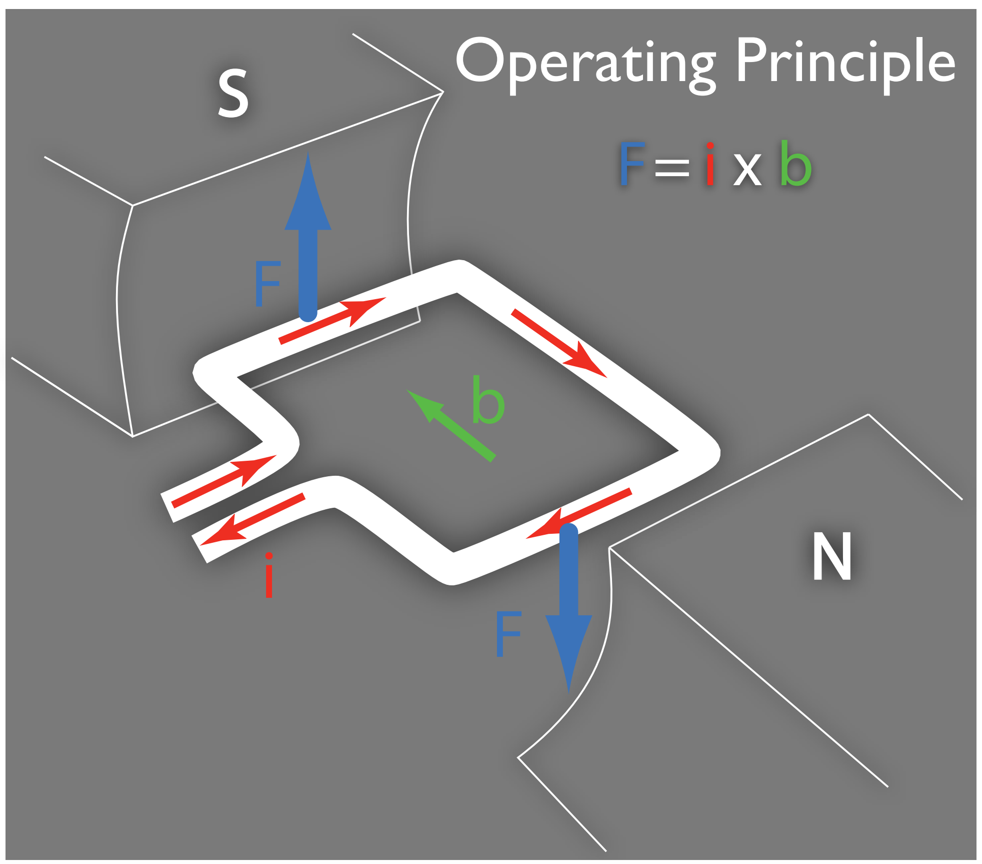


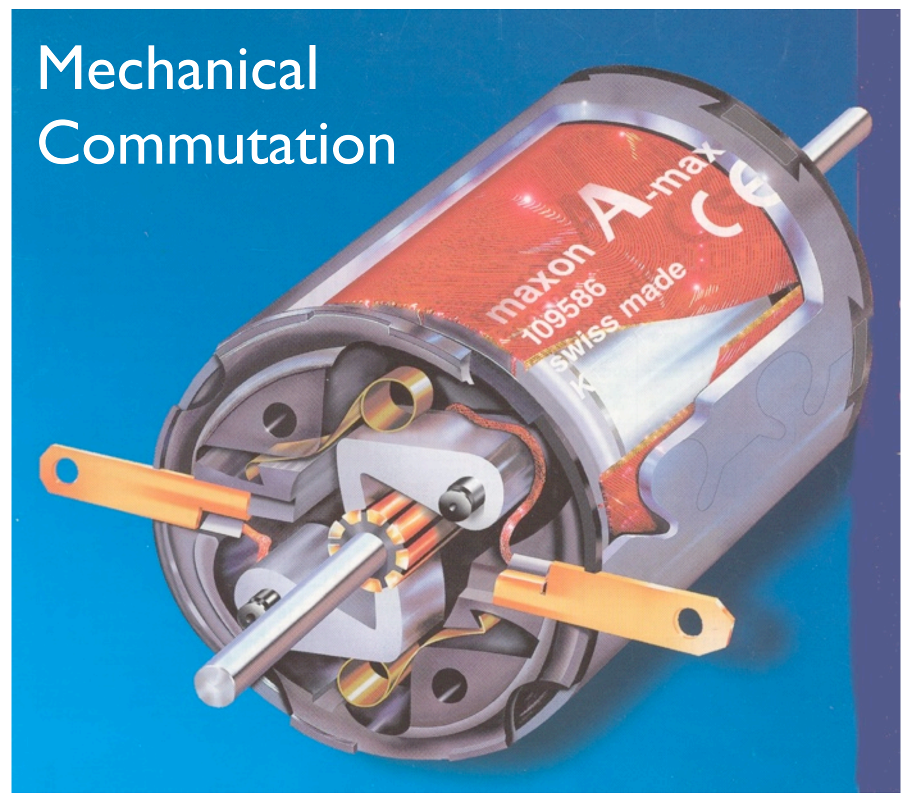
torque constant (N•m/A)

$$\tau_m = k_t \, i_a$$

generated torque (N•m)

armature current (A)



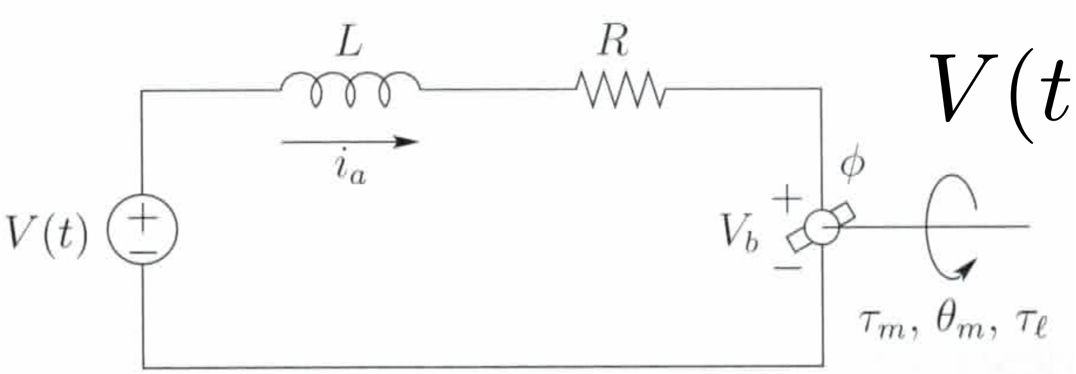


back emf (V)

back-emf constant (V•s)

$$V_b = k_v \, \omega_m$$

motor velocity (rad/s)

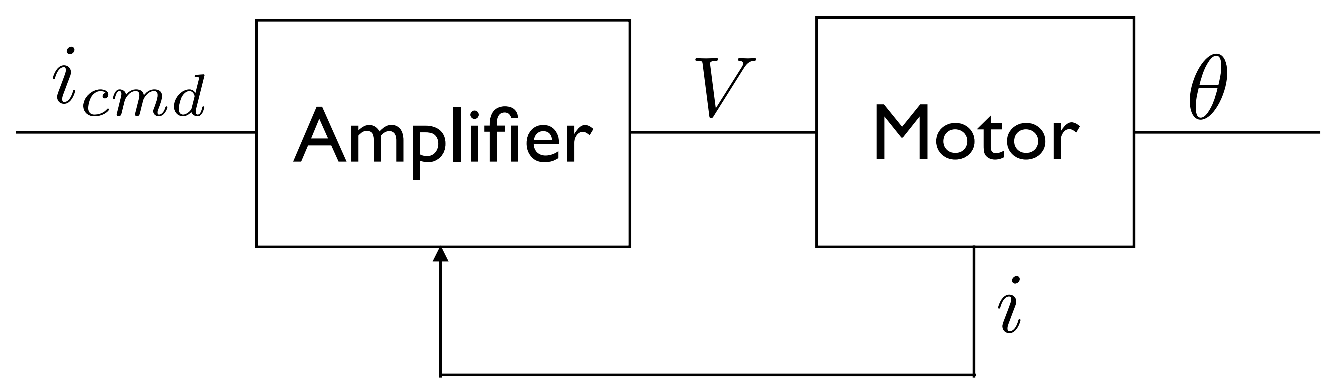


$$V(t) = L\frac{di_a}{d_t} + R\, i_a + k_v \, \omega_m$$

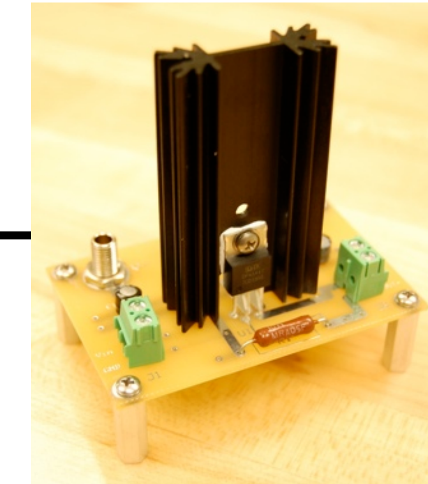
$$i_a \approx \frac{V(t)}{R}$$

$$k_t = k_v$$

if using meters, kilograms and seconds


i_{cmd}
Amplifier
V
Motor
θ
i

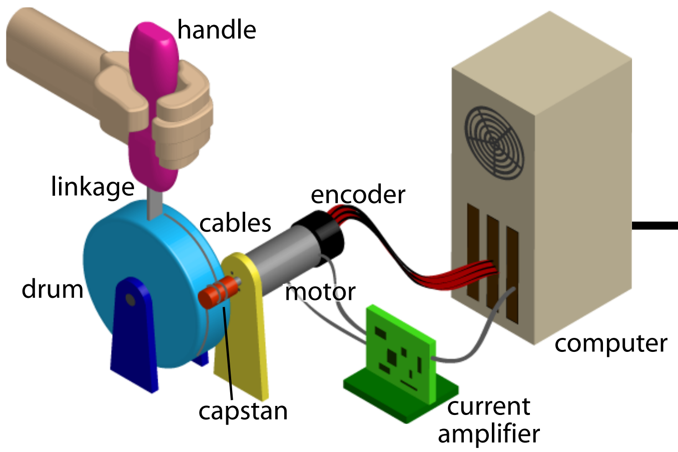
Current Amplifier



$$\tau_m = k_t \, i_a$$

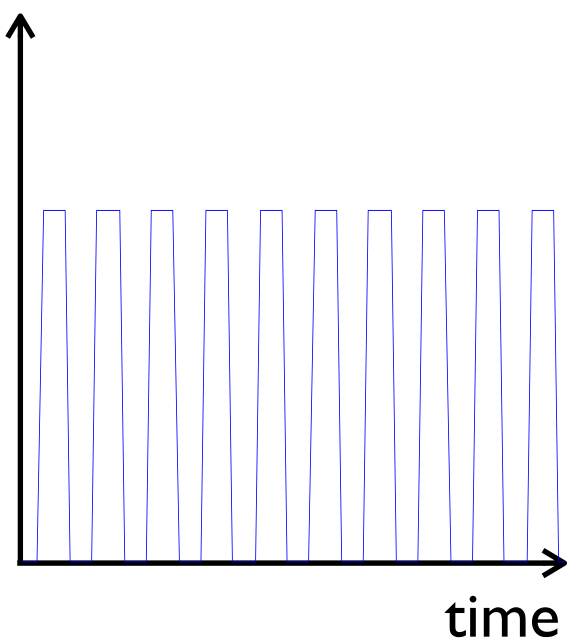
- Takes an information signal (usually an analog voltage) from the computer and drives the requested amount of current through the actuator.
- Note that this is a *current drive* scenario, not a voltage drive. Motor torque is proportional to current, regardless of speed, so we can essentially ignore the motor's electrical dynamics (inductance, back-emf).
- Two common types are Pulse Width Modulation (PWM) and Linear. Linear amplifiers often have higher bandwidth and cause less electrical noise.

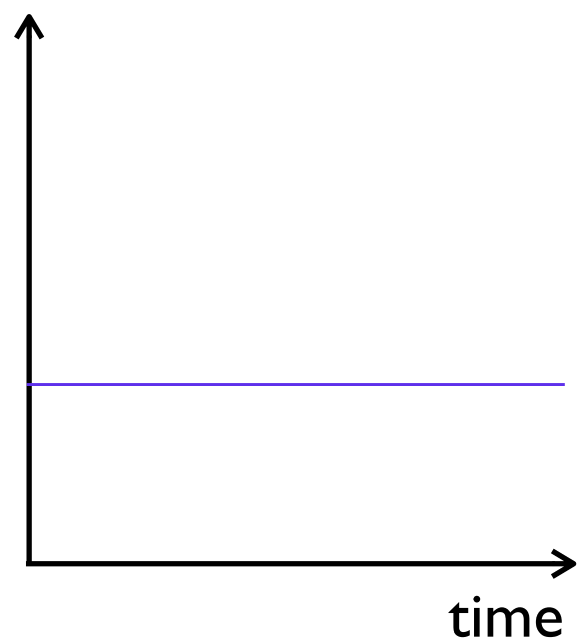
PWM Amplifier

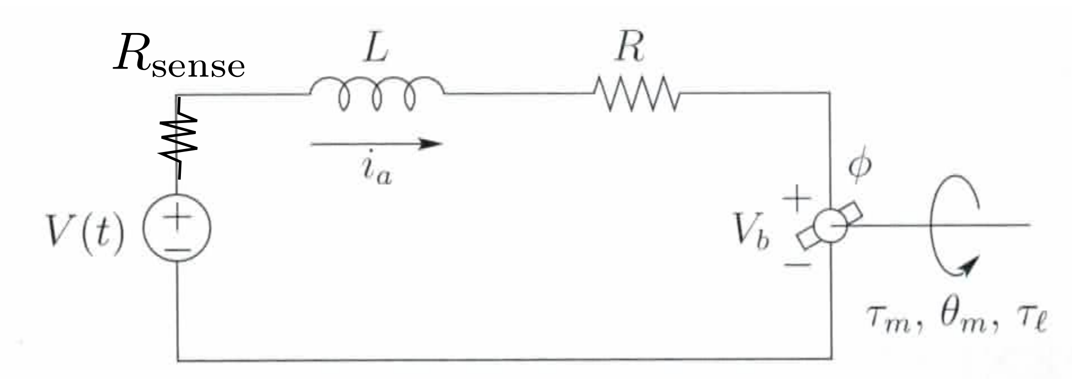


Applied Voltage | **Equivalent Voltage**

50%
Duty Cycle

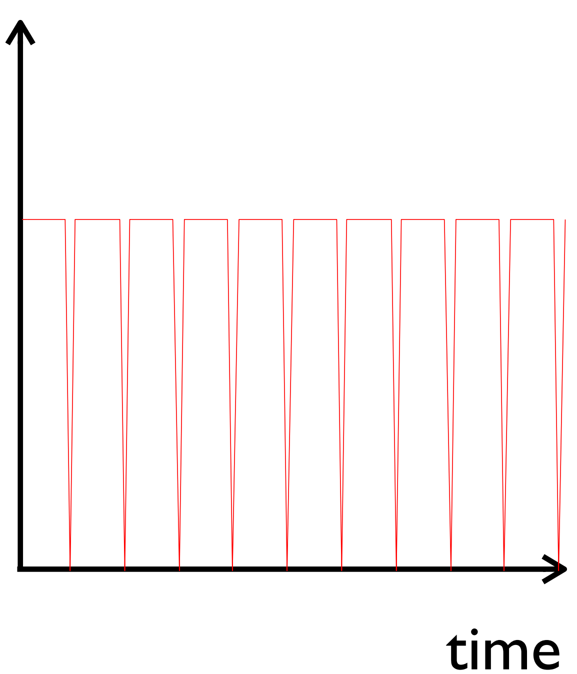


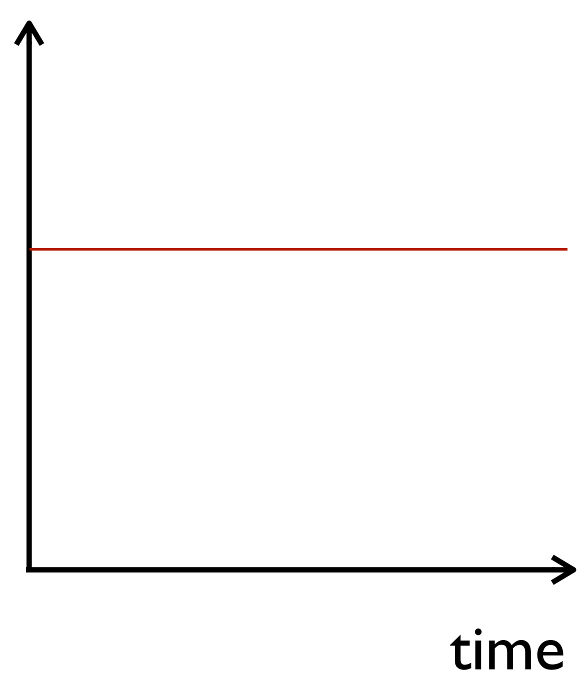




$$V(t) = L\frac{di_a}{d_t} + R\,i_a + k_v\,\omega_m$$

90%
Duty Cycle

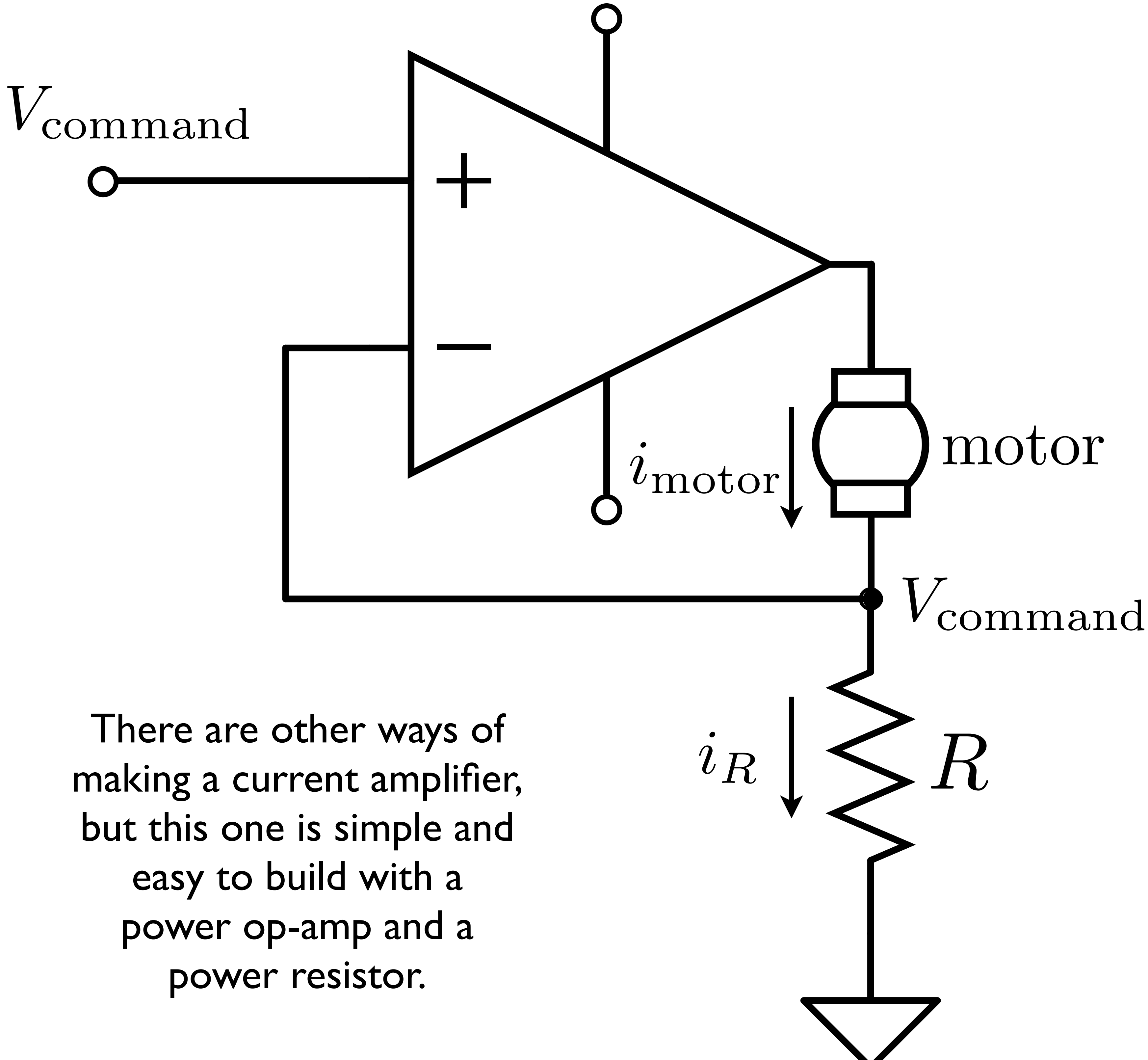




Uses a current-sense resistor in series with the motor for feedback.

Some material adapted from slides by A. Okamura and W. Provancher

Current Amplifier Circuit



Operational amplifier in negative feedback, so it follows the two golden rules of op-amps:

No current enters or leaves the inverting or non-inverting inputs.

The voltages at the inverting and non-inverting inputs are equal.

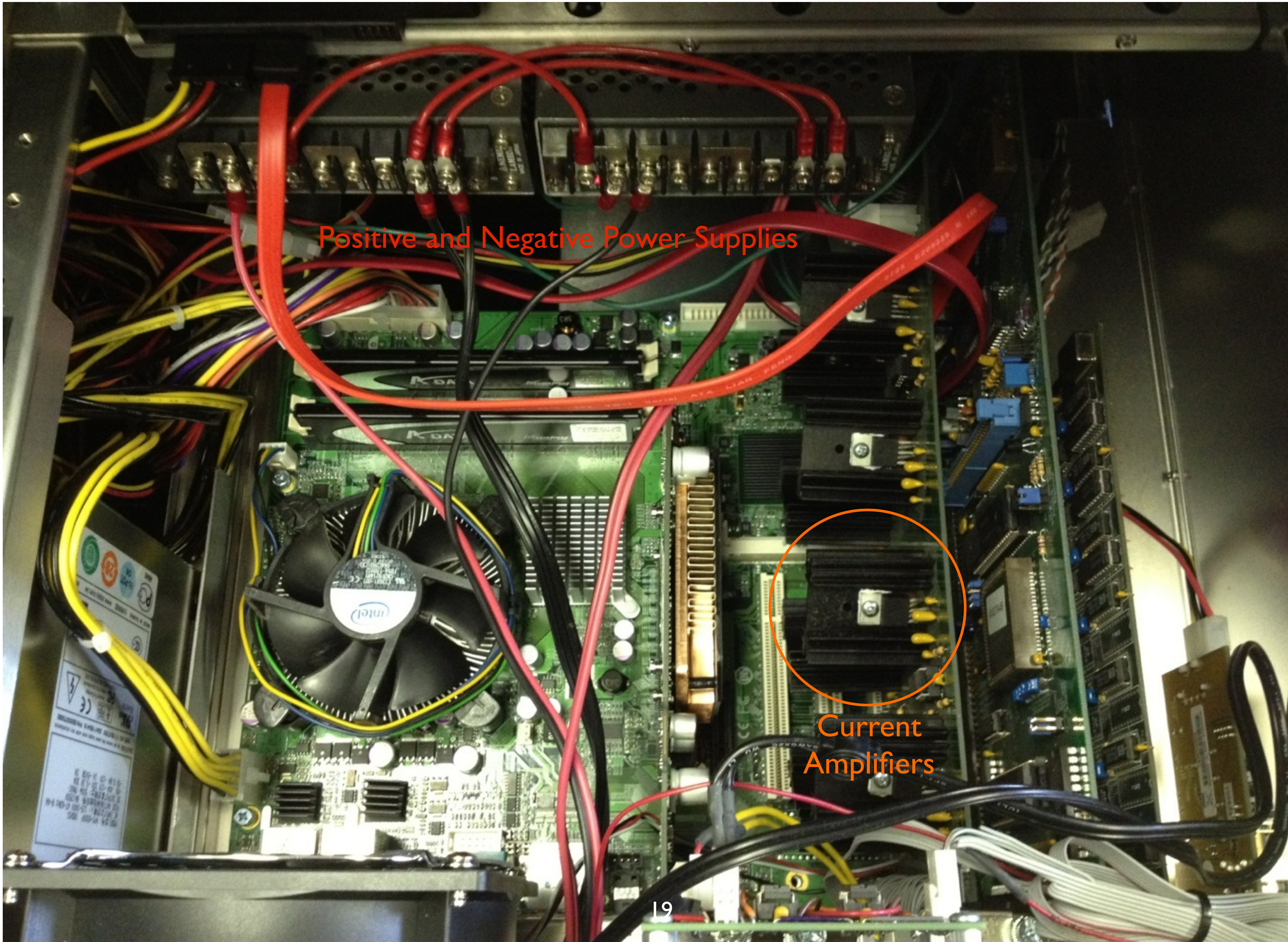
$$i_{\mathrm{motor}} = i_R$$

$$i_R = \frac{V_{\mathrm{command}}}{R}$$

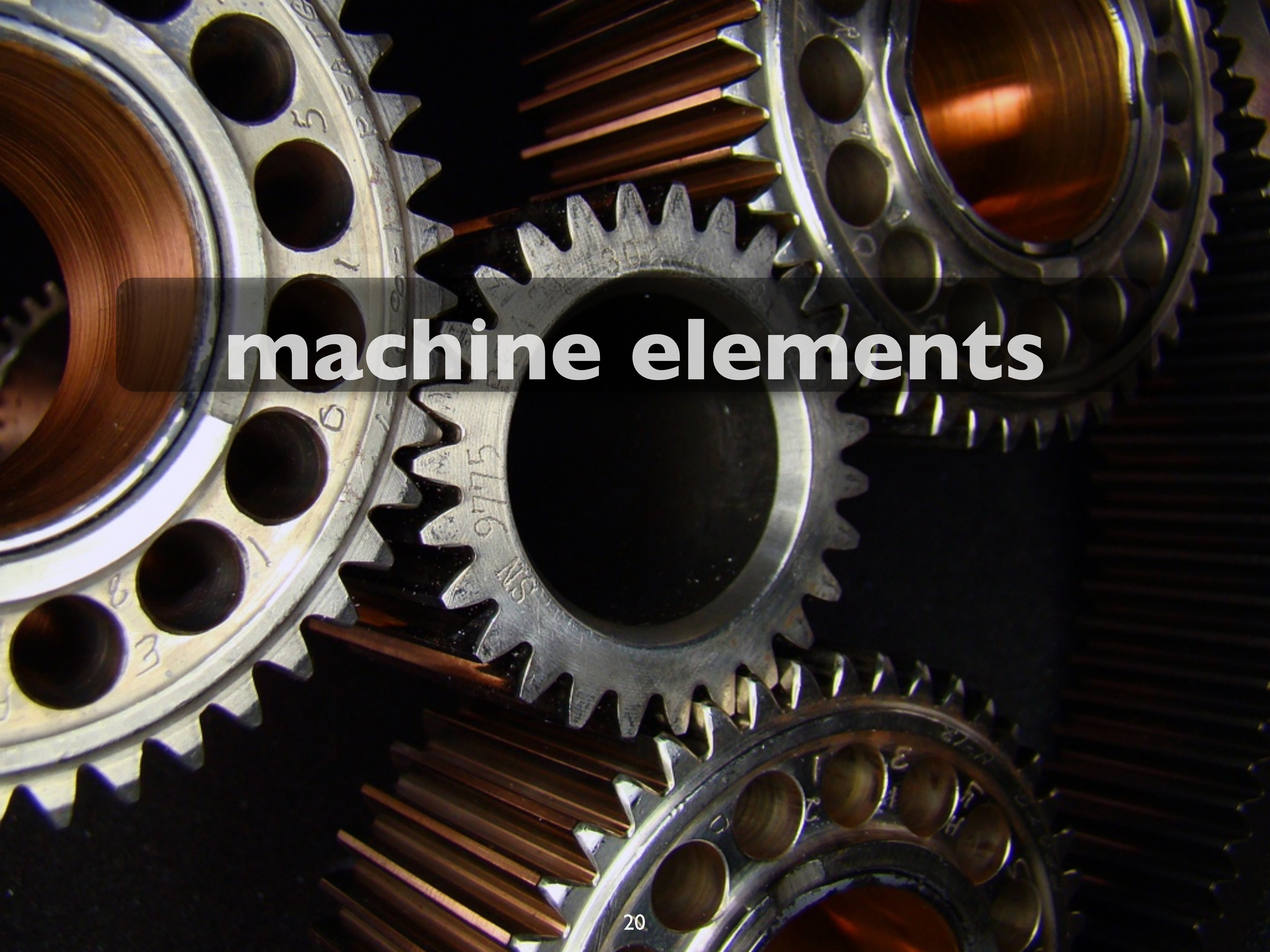
$$i_{\mathrm{motor}} = \frac{V_{\mathrm{command}}}{R}$$

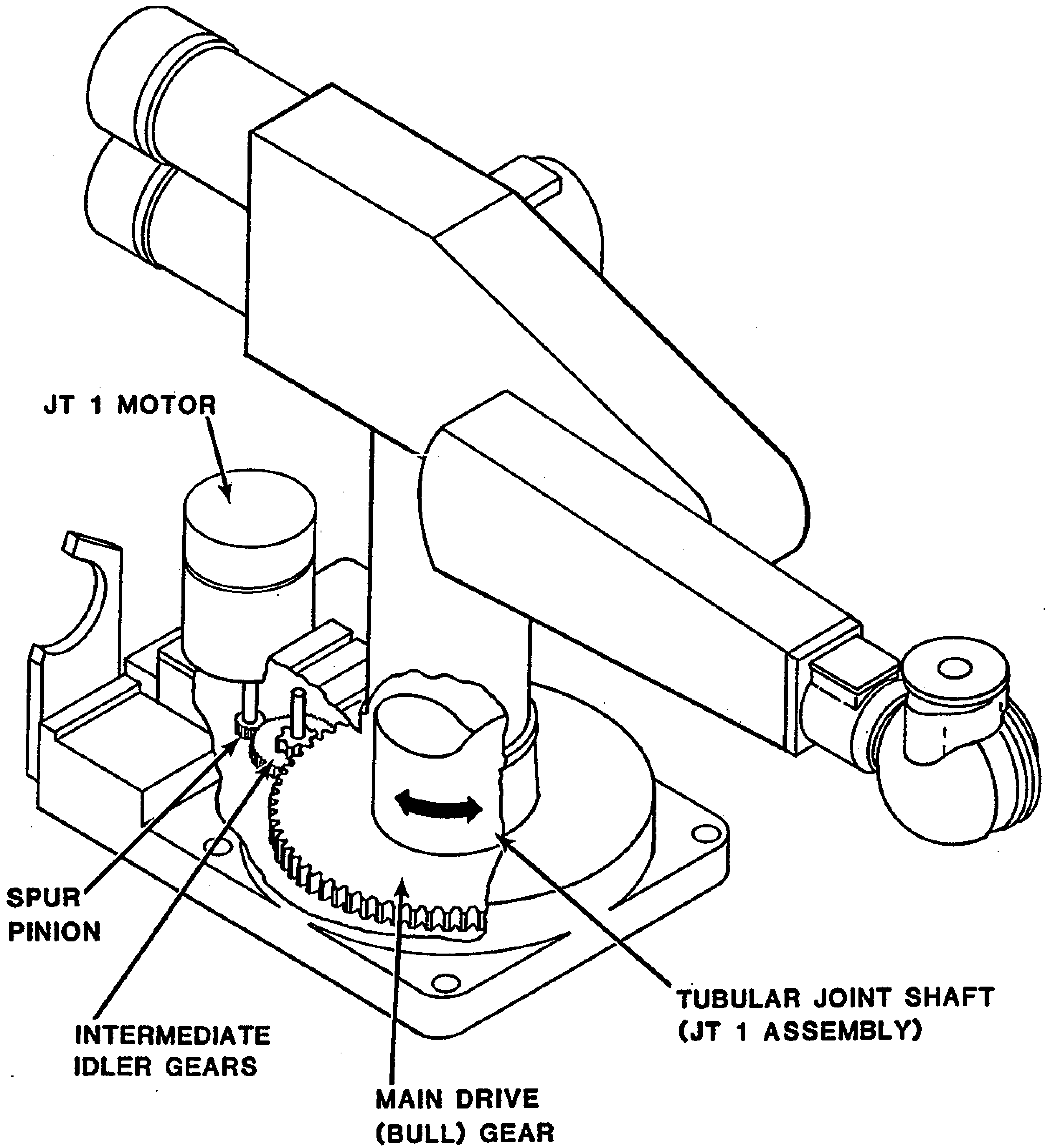
There are other ways of making a current amplifier, but this one is simple and easy to build with a power op-amp and a power resistor.

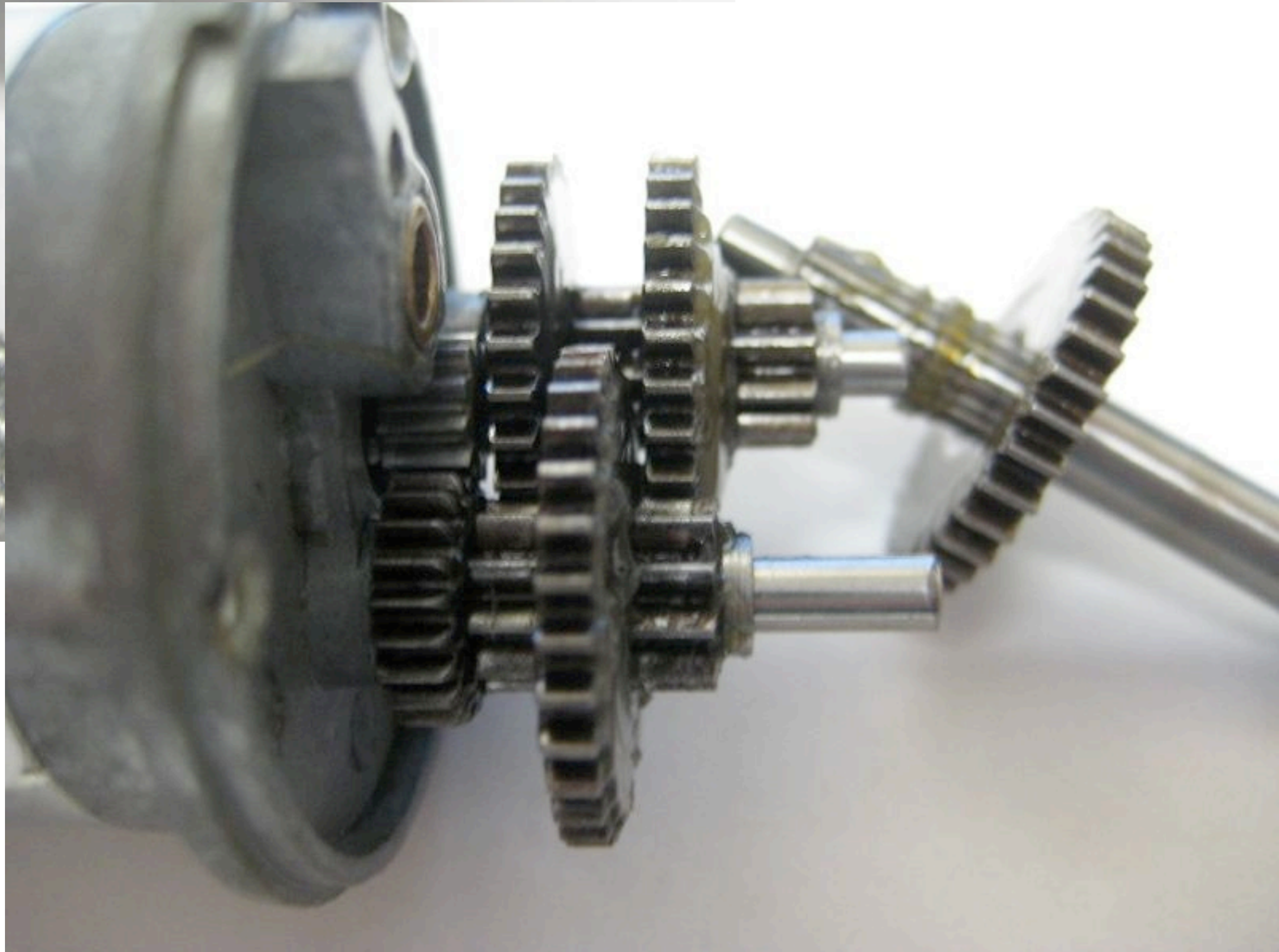
inside the PUMA 260 controller



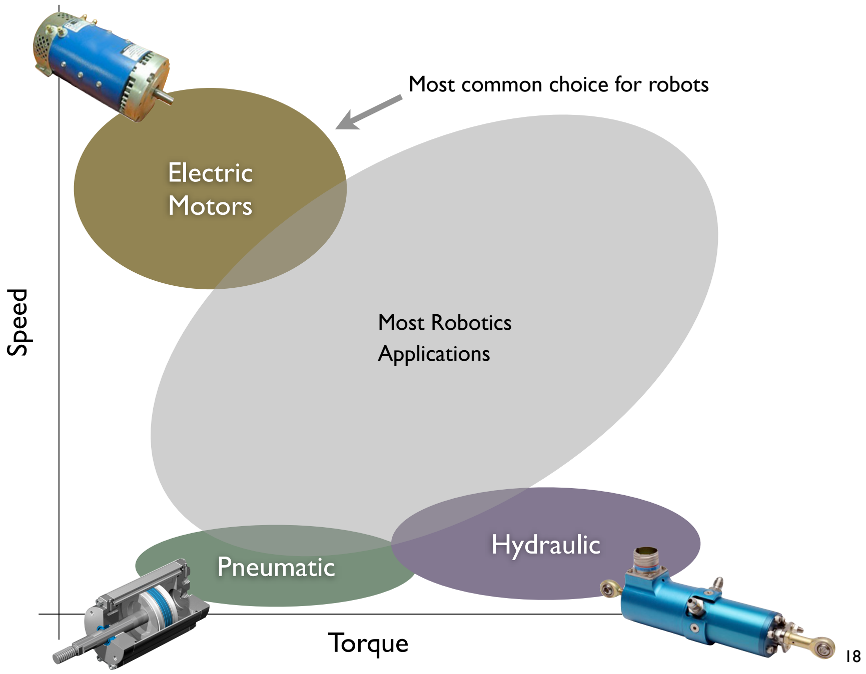
machine elements

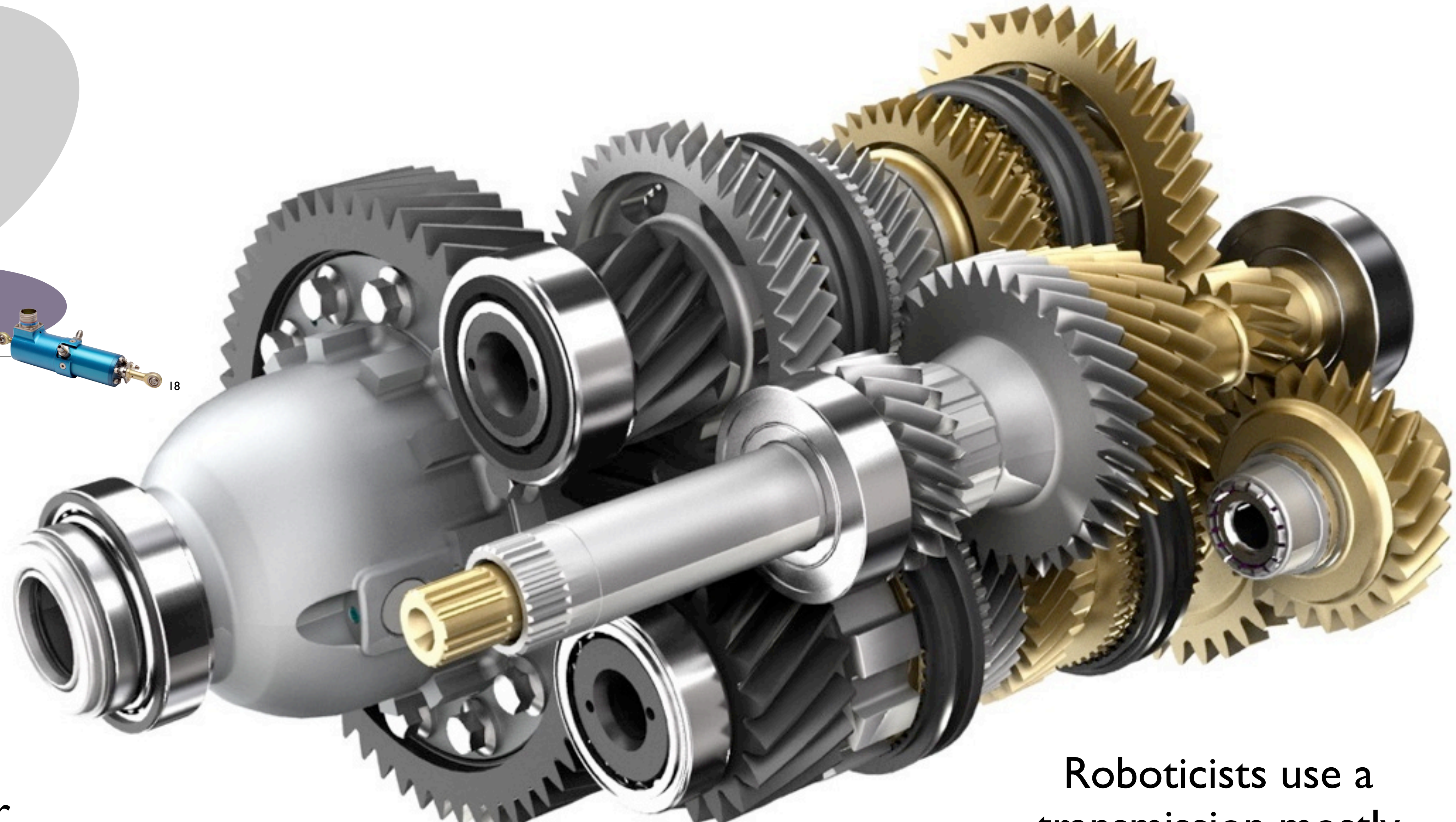


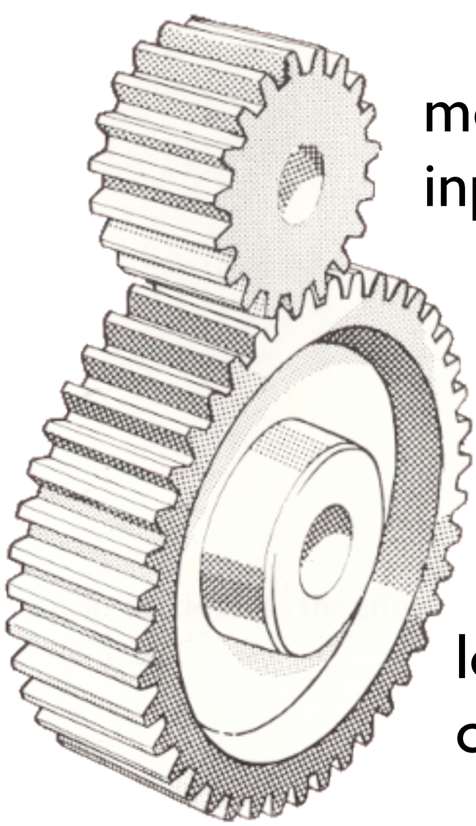

JT 1 MOTOR
SPUR PINION
INTERMEDIATE IDLER GEARS
MAIN DRIVE (BULL) GEAR
TUBULAR JOINT SHAFT (JT 1 ASSEMBLY)



Inside the gearhead
of a DC motor







motor input

load output

Roboticists use a transmission mostly to increase torque output!

gear ratio

$$N = \frac{\omega_{\text{in}}}{\omega_{\text{out}}} = \frac{\tau_{\text{out}}}{\tau_{\text{in}}} = \frac{n_{\text{out}}}{n_{\text{in}}} = \frac{r_{\text{out}}}{r_{\text{in}}}$$

Speed Torque Teeth Radius

Same equations apply for belts, pulleys, and friction drive

$$N = \frac{r_{out}}{r_{in}}$$

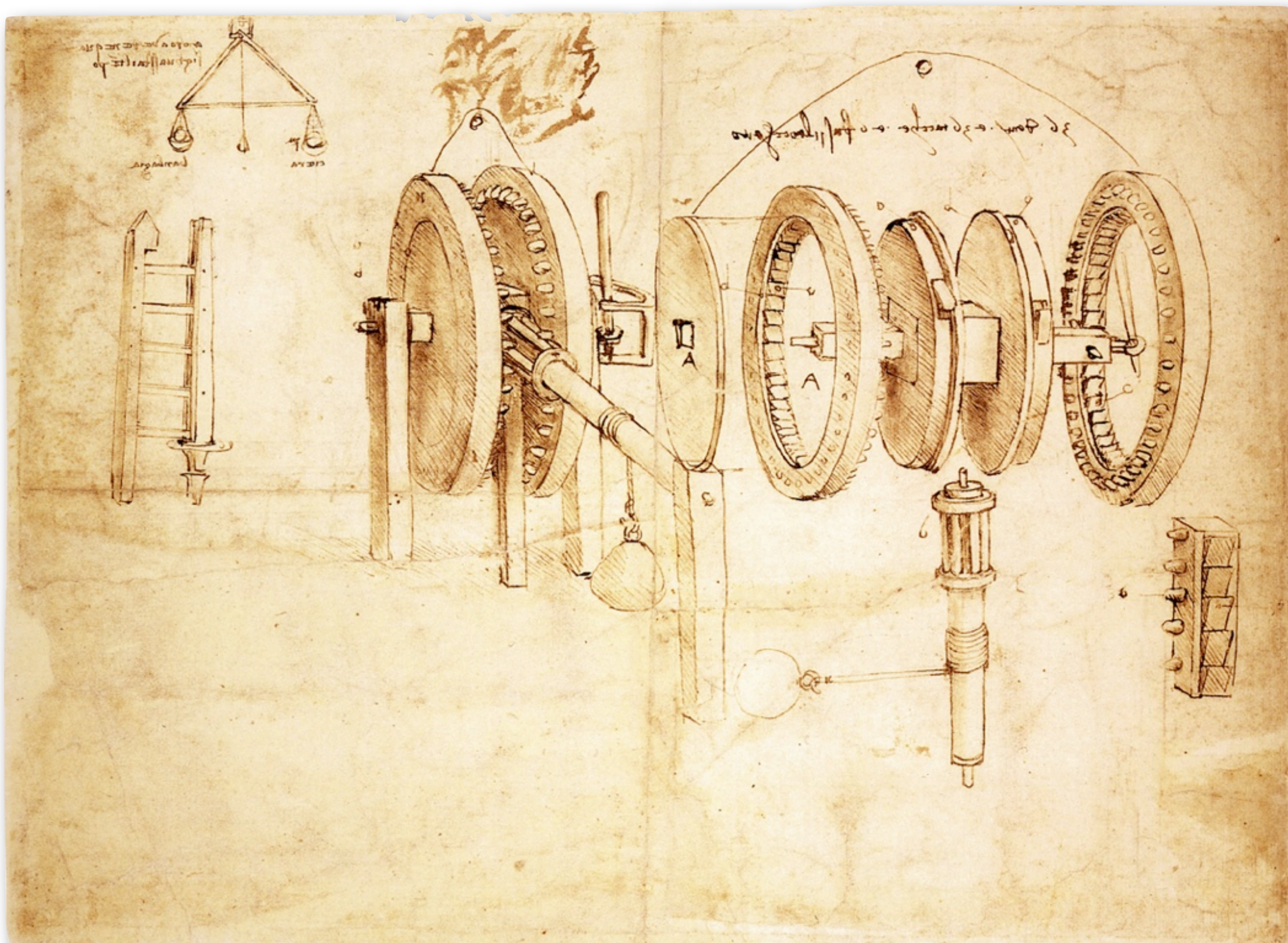
$$N = \frac{3.125\,\text{in.}}{0.625\,\text{in.}}$$

$$N = 5 : 1$$

$$r_{out} = 3.125\,\text{in.}$$

$$d_{in} = 1.25\,\text{in.}$$

$$r_{in} = 0.625\,\text{in.}$$

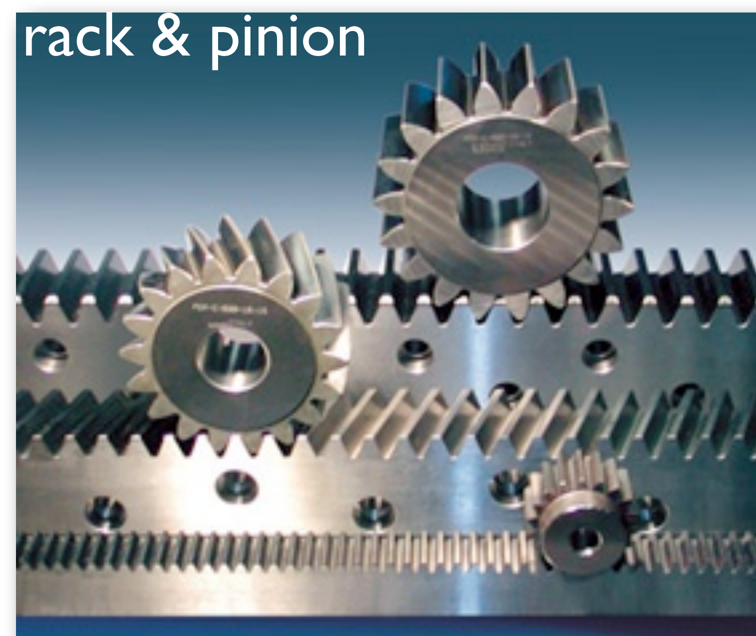



spur


helical


crossed
helical
MORSE

FIGURE 6.14 Hypoid gears. (Courtesy of Gleason Works.)

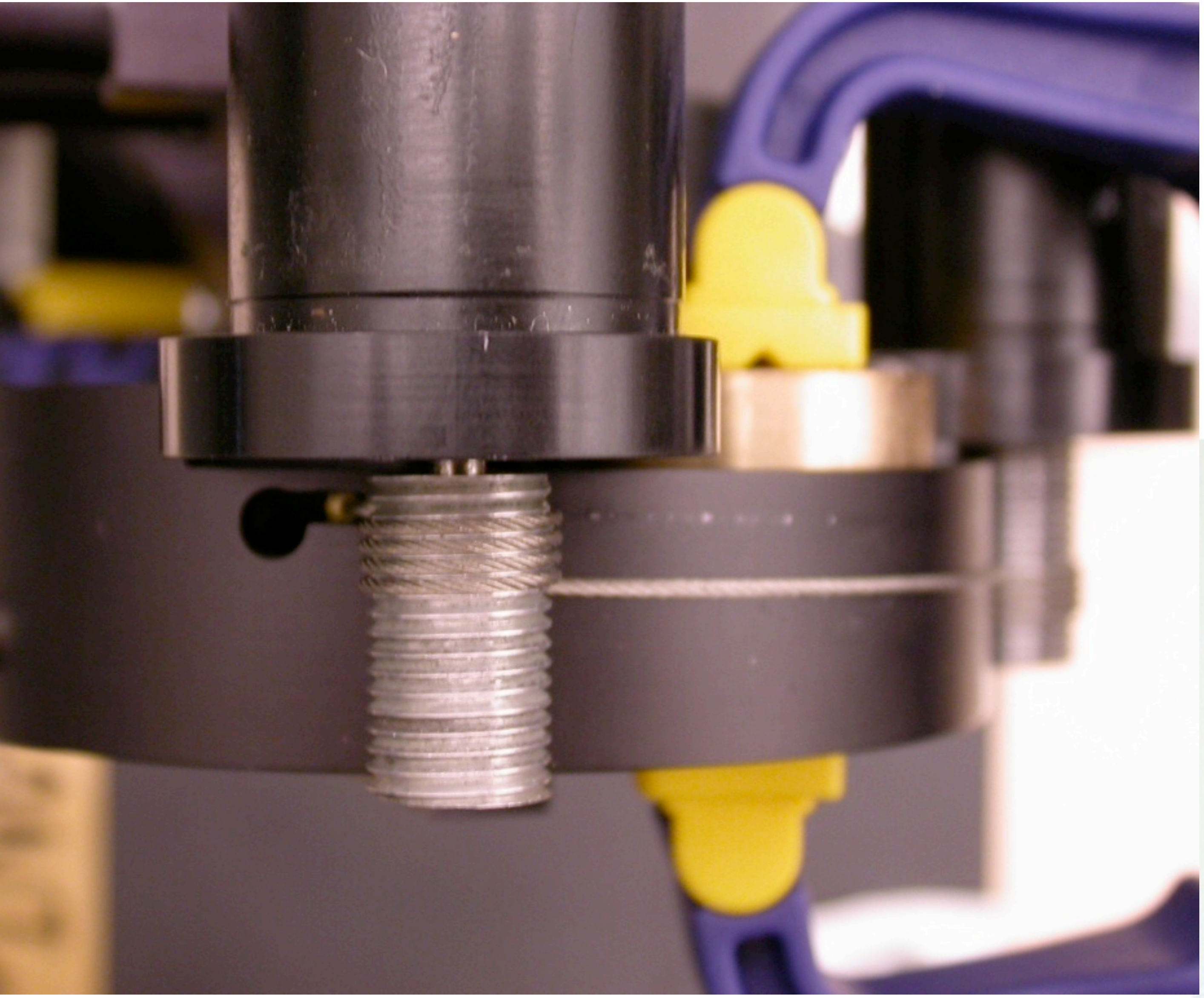


Capstan Drive

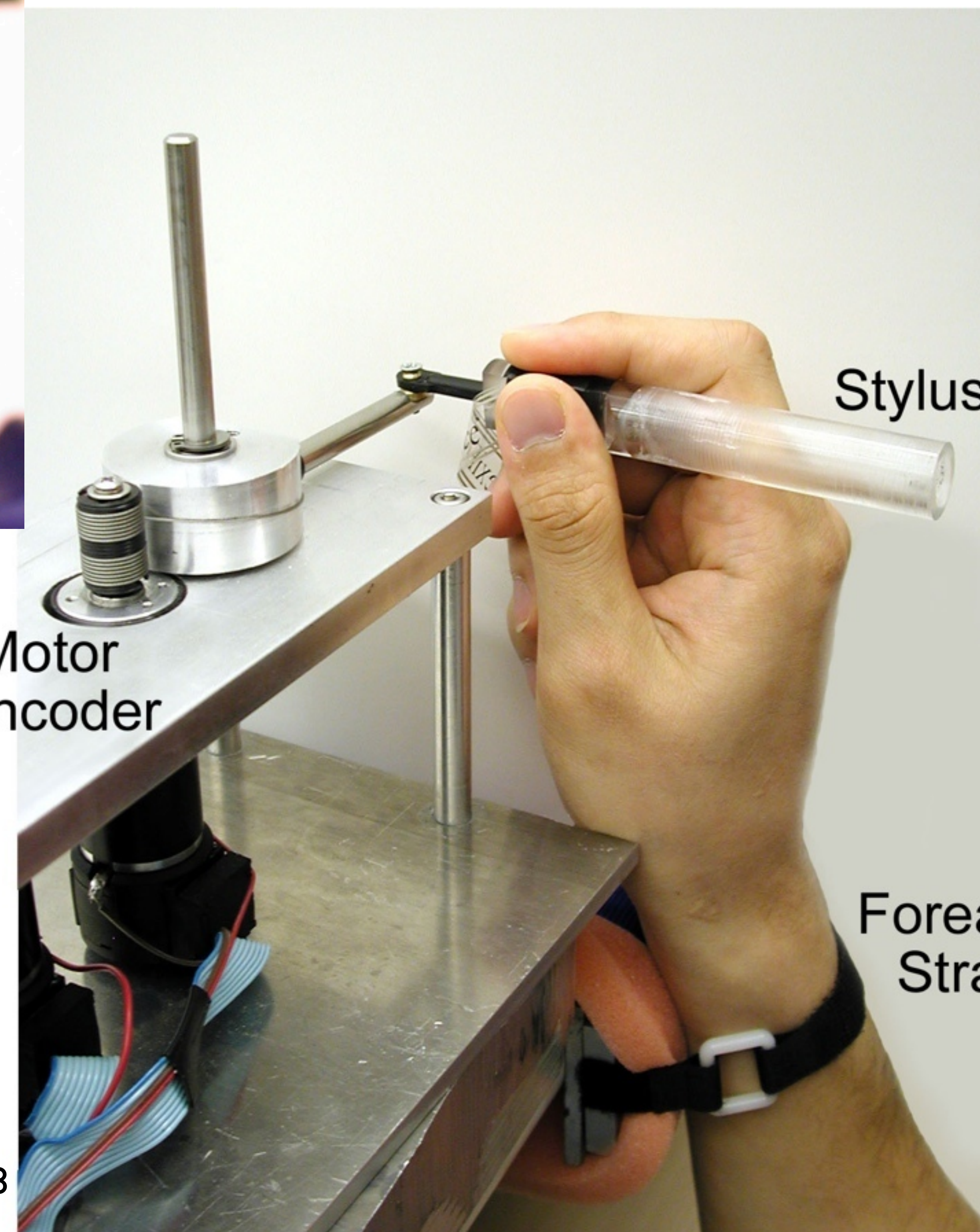
Many high-performance robots and most haptic interfaces use a capstan drive, with thin stranded cables from a company like Sava Industries.

- The rotation of the motor shaft is coupled to the rotation of a larger drum or the motion of a linear stage by wrapping cables around a capstan.
- When pre-tensioned, cables provide a very stiff connection with zero backlash.
- We don't use belts or gears because we need motion to be smooth and efficient. Users dislike vibration.

Some material adapted from slides by A. Okamura and W. Provancher




PHANToM


Stylus
DC Motor
with Encoder
Forearm
Strap

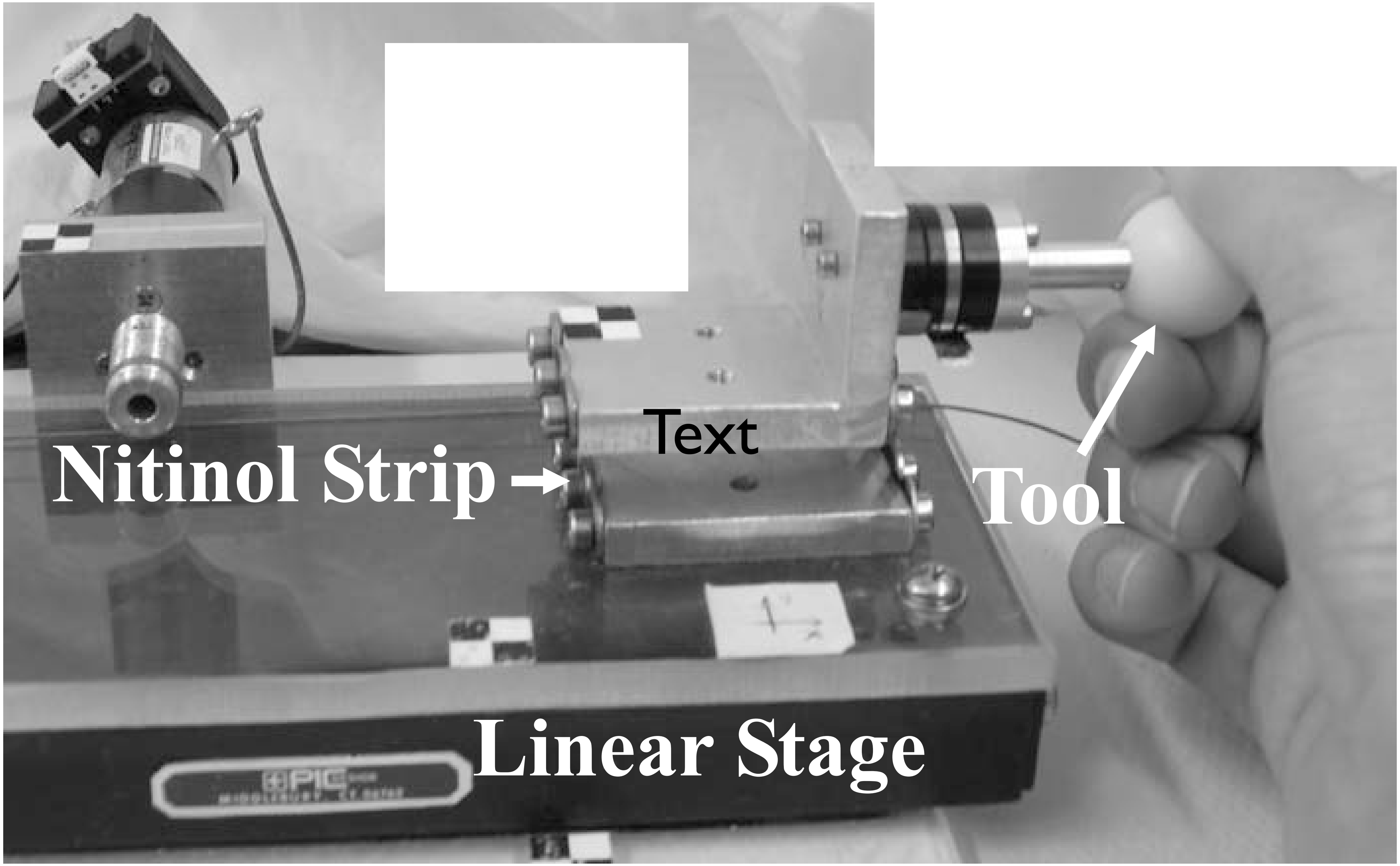
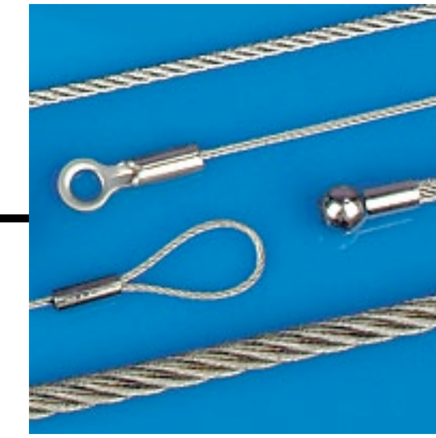


Image from Marayong, Na, and Okamura (ICRA 2007)

Capstan Drive



- The gear ratio is the ratio of the diameters (or equivalently the ratio of the radii).

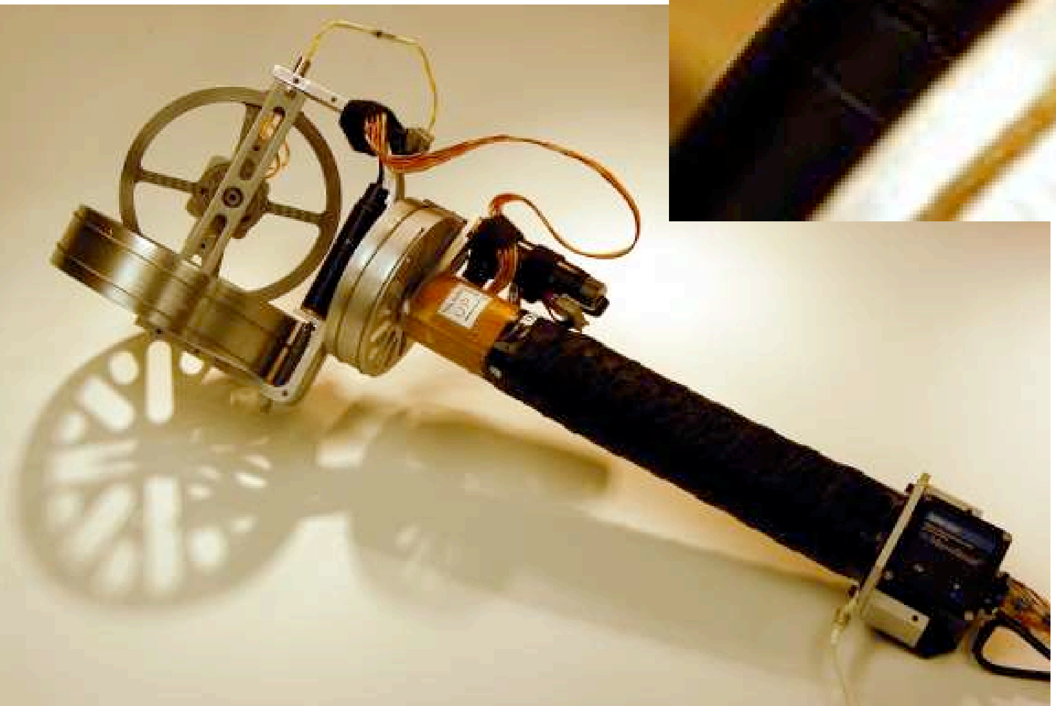
$$\rho = \frac{d_d}{d_c}$$

- The drum is almost always larger than the capstan, so rho is greater than one.

$$\tau_d = \rho\, \tau_m \qquad \omega_m = \rho\, \omega_d$$

- The drum torque is greater than the motor torque.
- The motor speed is greater than the drum speed.
- A drawback - the user feels amplified versions of the motor's inertia and friction, goes with gear ratio squared.

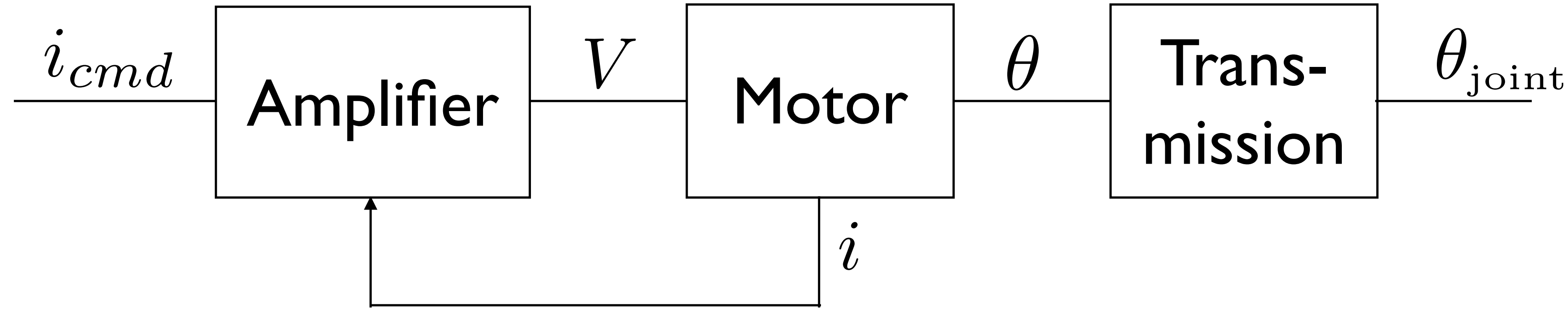
Some material adapted from slides by A. Okamura and W. Provancher



Images from the Masters thesis of Kyle Winfree,
"An Ungrounded Haptic Torque Feedback Device: The iTorqU"

Also need good bearings!

Rolling resistance is much lower than sliding friction.



i_{cmd}
Amplifier
V
Motor
θ
Trans-
mission
θ_{joint}
i

object's mass
(kg)

$$\sum \vec{F} = m\vec{a}$$

sum of external
forces on an object
(N)

object's
linear acceleration
(m/s²)

$$a = \ddot{x}$$

object's mass
moment of inertia
(kg m²)

$$J = I_g$$

$$\sum \tau_g = I_g \alpha$$

sum of external
torques on an object
around an axis that
goes through center
of mass
(N m)

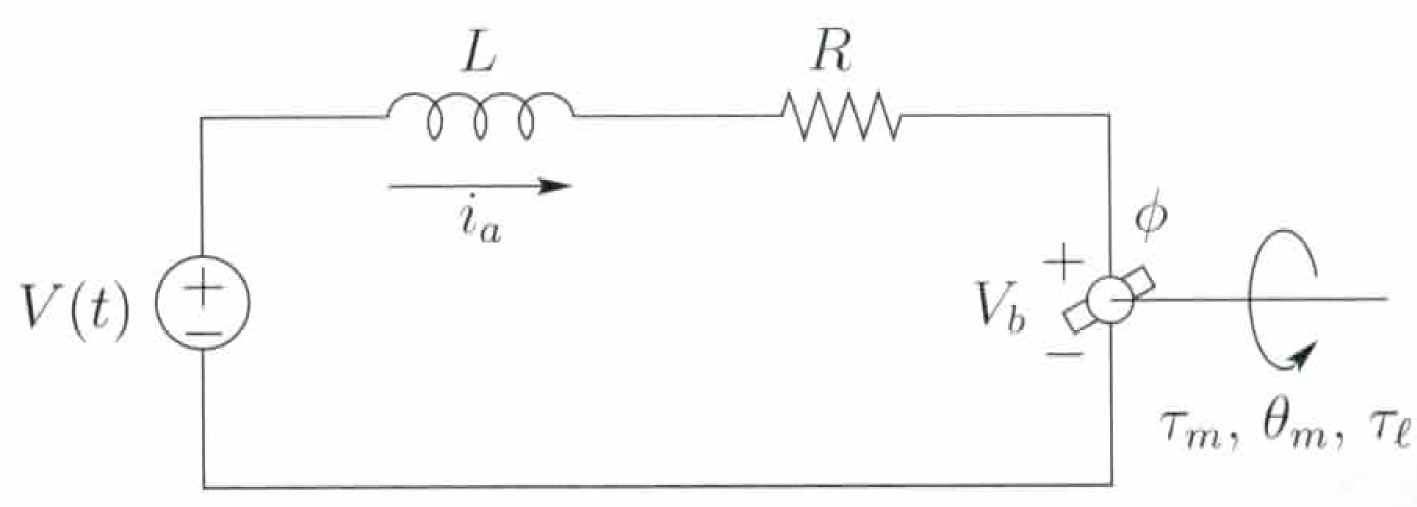
object's
angular acceleration
(rad/s²)

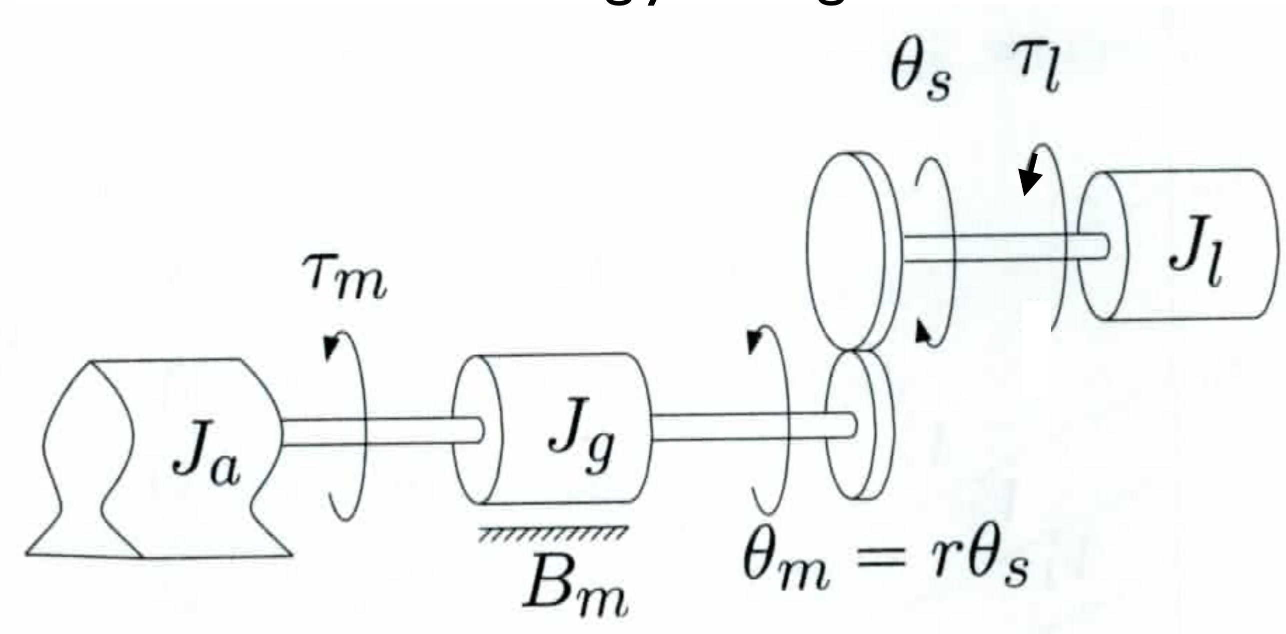
$$\alpha = \ddot{\theta}$$

Joint Dynamics (SHV 6.2)

Linear Model of Electrical and Mechanical Dynamics

SHV shows the load torque in the wrong direction and confusingly calls gear ratio "r"





$$V(t) = L\frac{di_a}{d_t} + R\,i_a + k_v\,\omega_m$$

$$\tau_m = k_t\,i_a$$

gearhead inertia

$$\sum \tau \text{ on motor} = \tau_m - \tau_l/r - B_m\dot{\theta}_m = (J_a + J_g)\ddot{\theta}_m$$

motor output torque | load torque over g.r. | viscous motor friction | motor inertia | motor angular acceleration

This system of differential equations describes the motor's response.

Other effects can matter too, especially backlash and static friction.

Typically, roboticists treat each joint independently, as a single-input/single-output (SISO) model.

This is adequate for applications that don’t involve very fast motions, especially if the transmission has a large gear reduction, which helps decouple the links from one another.

This is what we do on the PUMA.

A Biological Inspiration

Mechanical Structure

Bones	Frame / Links
Joints	Joints

Actuators

Muscles	Electric Motors
	Hydraulics
	Pneumatics
	SMA, etc.

Sensors

Kinesthetic	Encoders
Tactile	Load Cells
Vision	Vision
Vestibular	Accelerometers

Controller

Brain	Computer
Spinal Cord Reflex	Local feedback

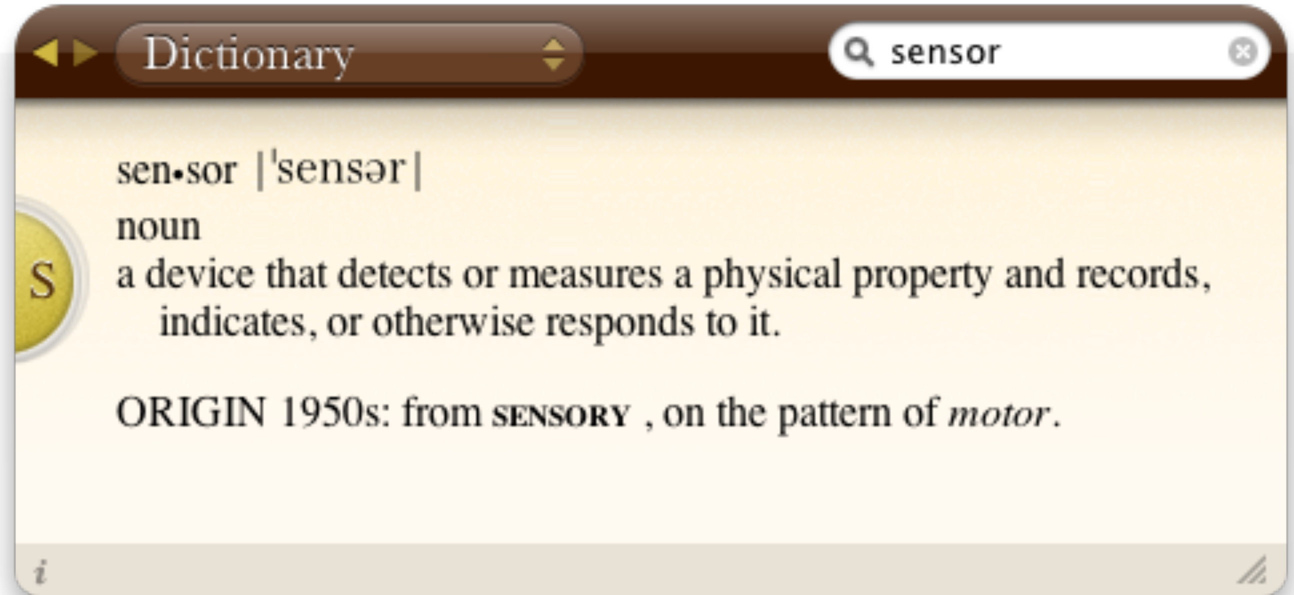
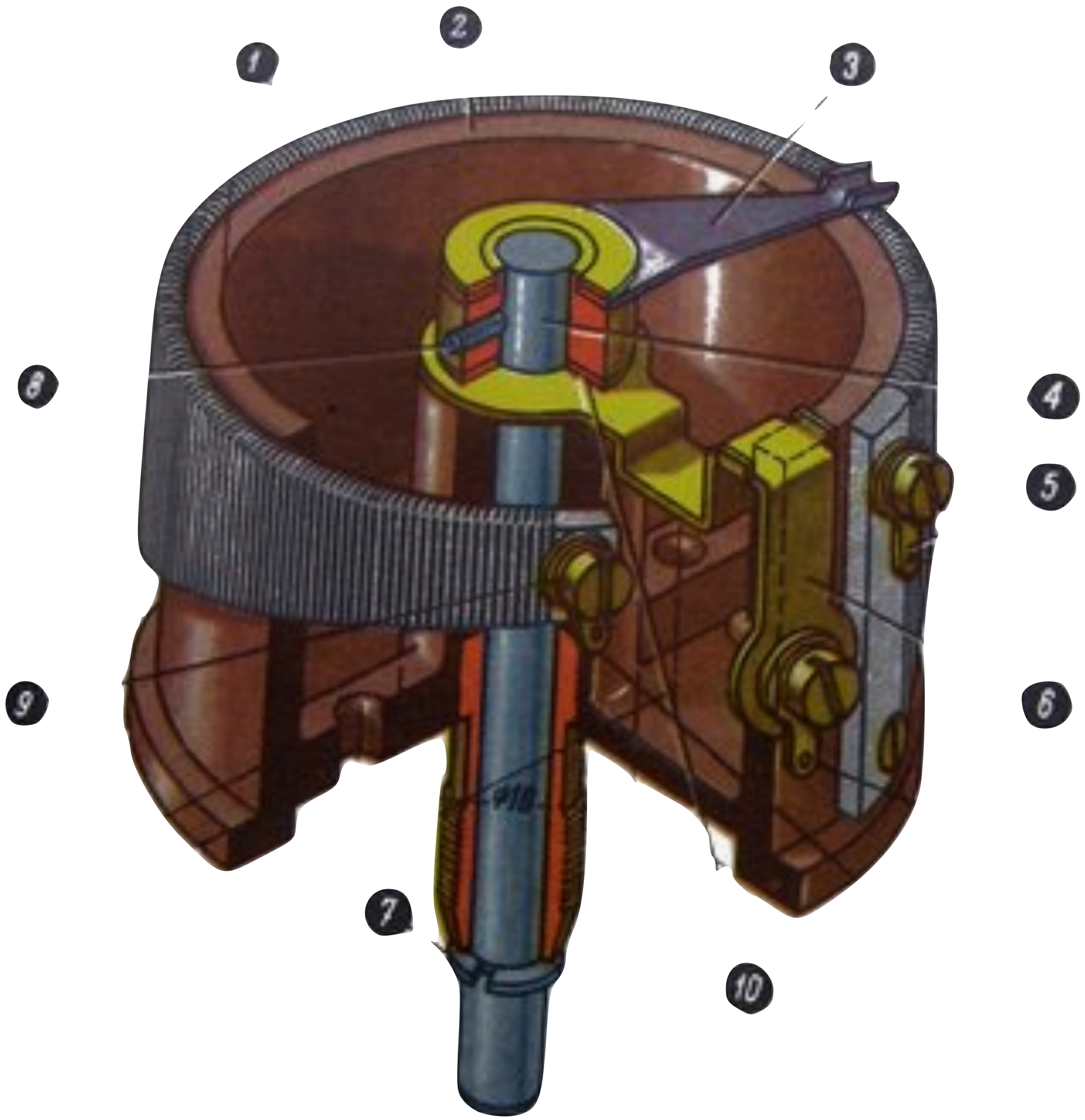
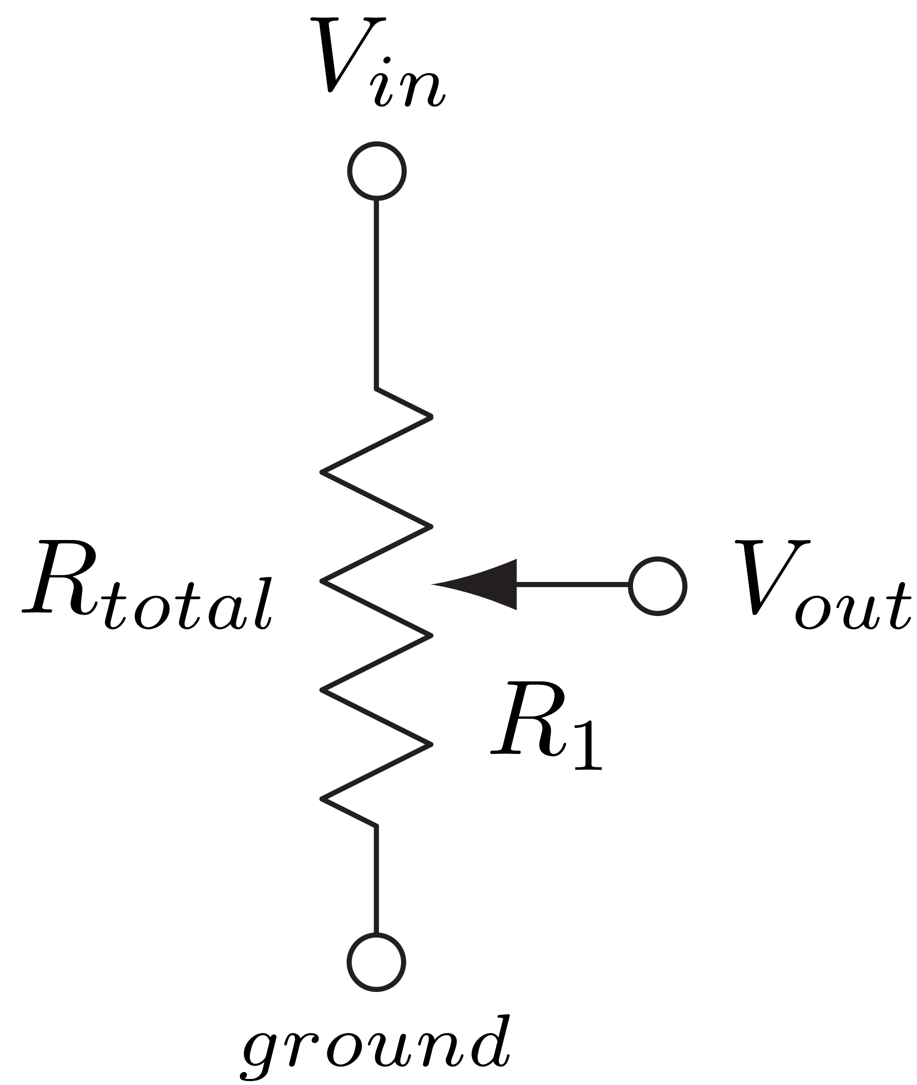


Photo © Immersion Corp.

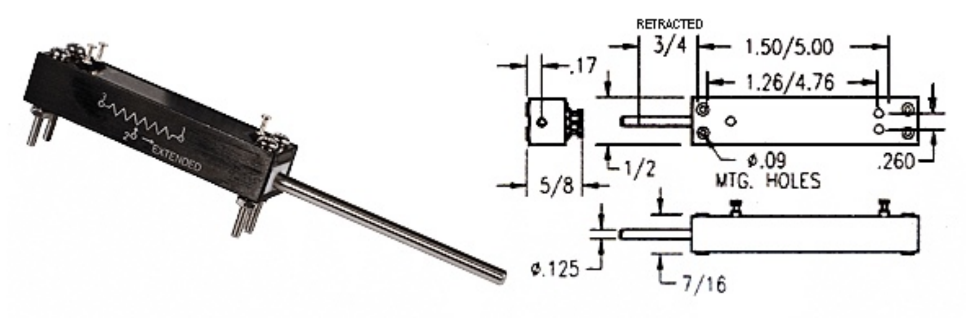
potentiometers

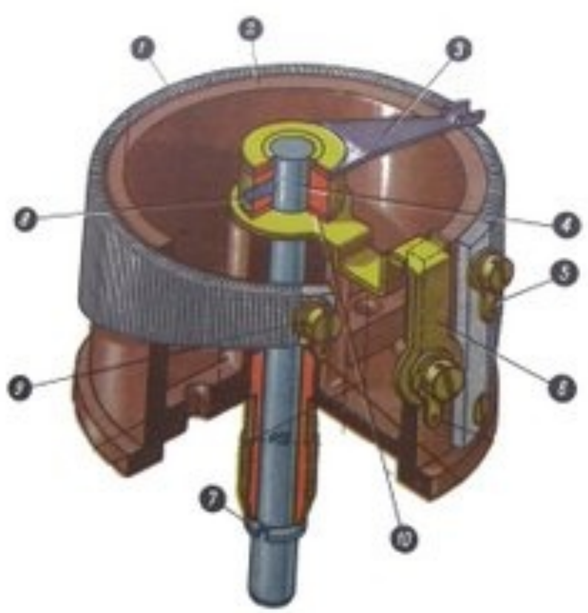




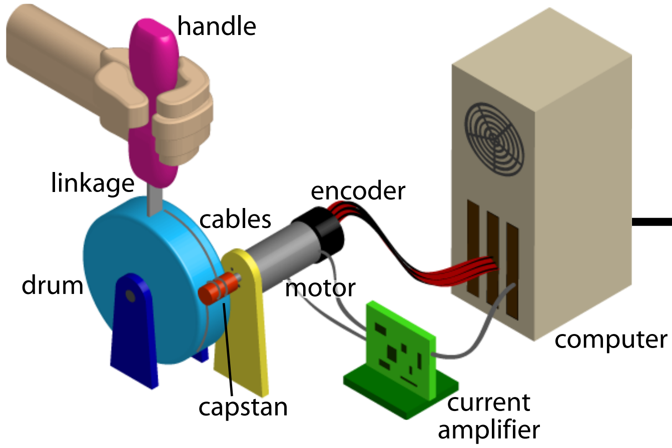
$$V_{out} = \frac{R_1}{R_{total}} V_{in}$$

Potentiometers

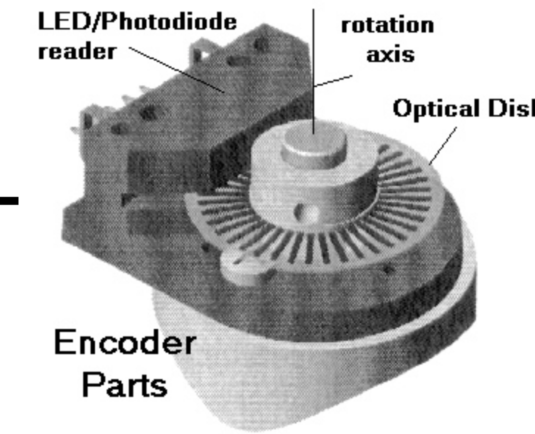




- Typically rotary, but linear exist.
- Cheap and easy.
- Moving parts means it can wear out.
- Hard to waterproof or dustproof.
- Susceptible to electrical noise from other system elements.
- Has non-negligible friction.



Encoder

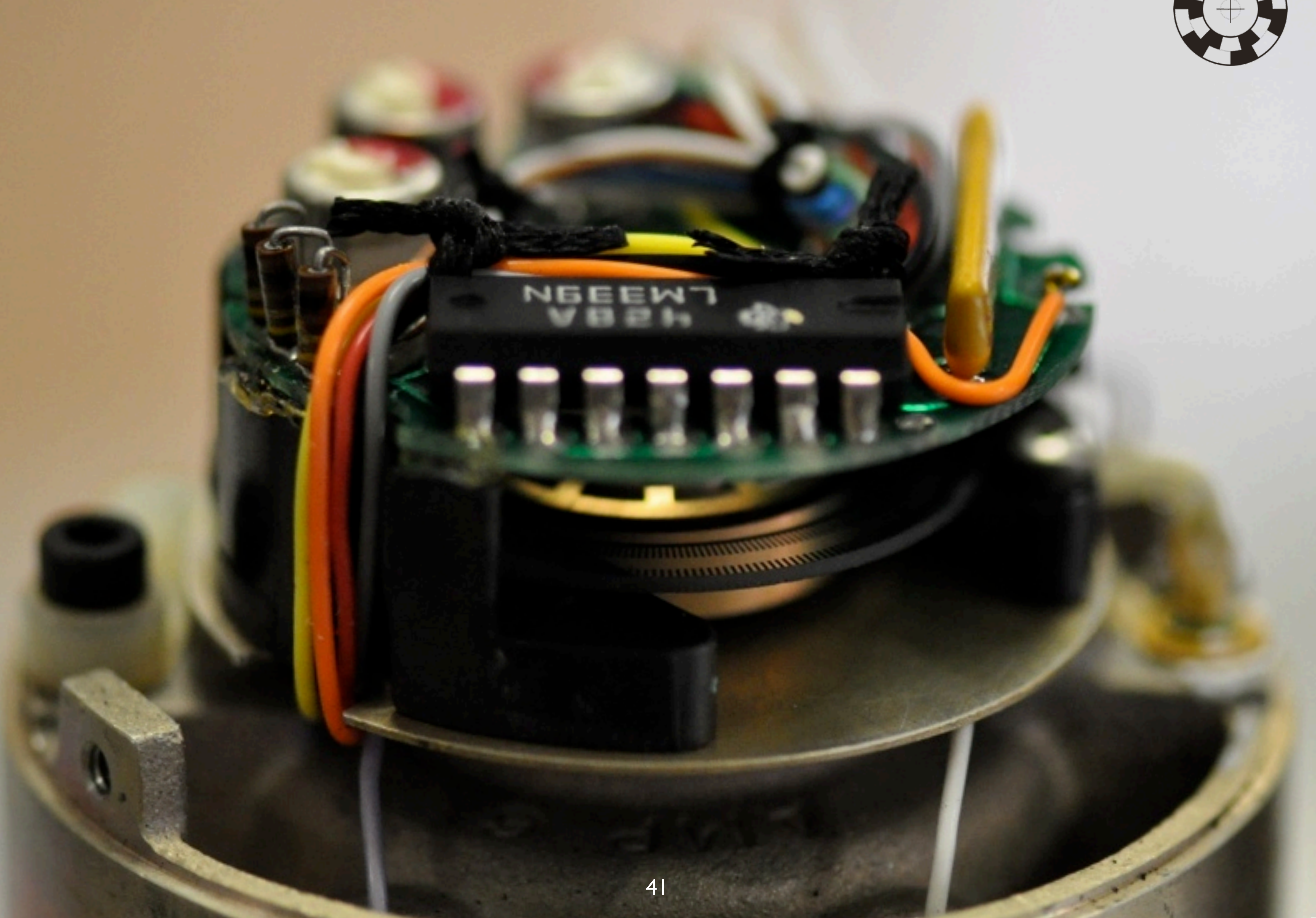


The most common motion sensor in haptics and robotics is the incremental optical encoder.

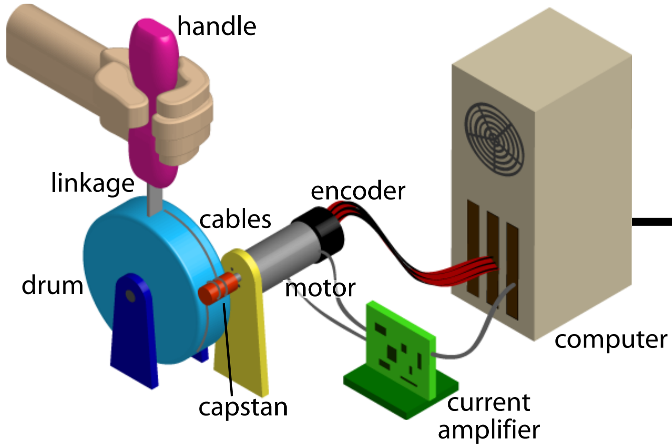
- A thin disk is attached to the rotating shaft whose angle you want to measure, usually the motor.
- The disk has slits cut into it in a regular pattern.
- A light shines on the disk on one side, and photo sensors are located on the opposite side.
- Produces a number of pulses per revolution, with higher resolution being more expensive.

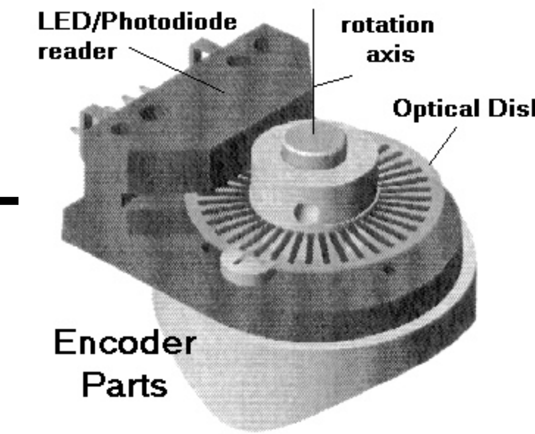
Some material adapted from slides by A. Okamura and W. Provancher

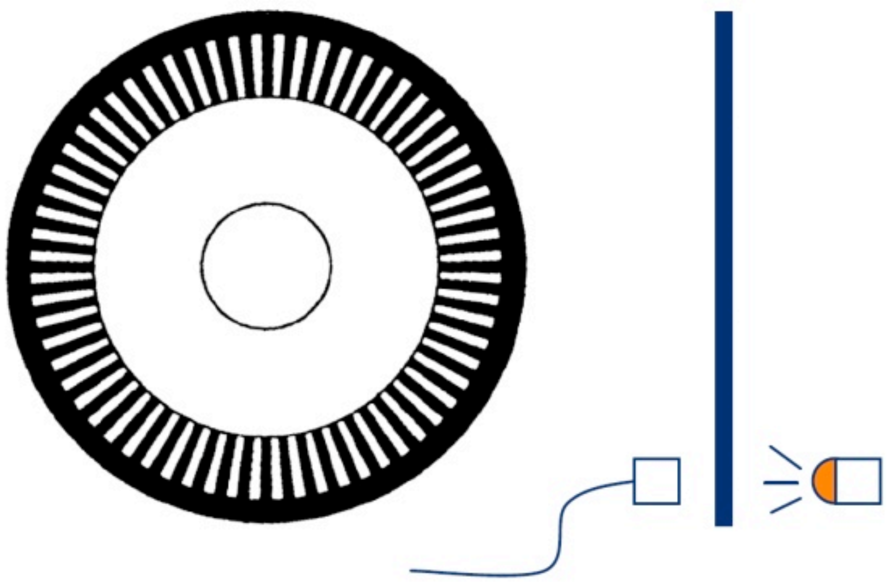
Puma260 base-joint optical encoder

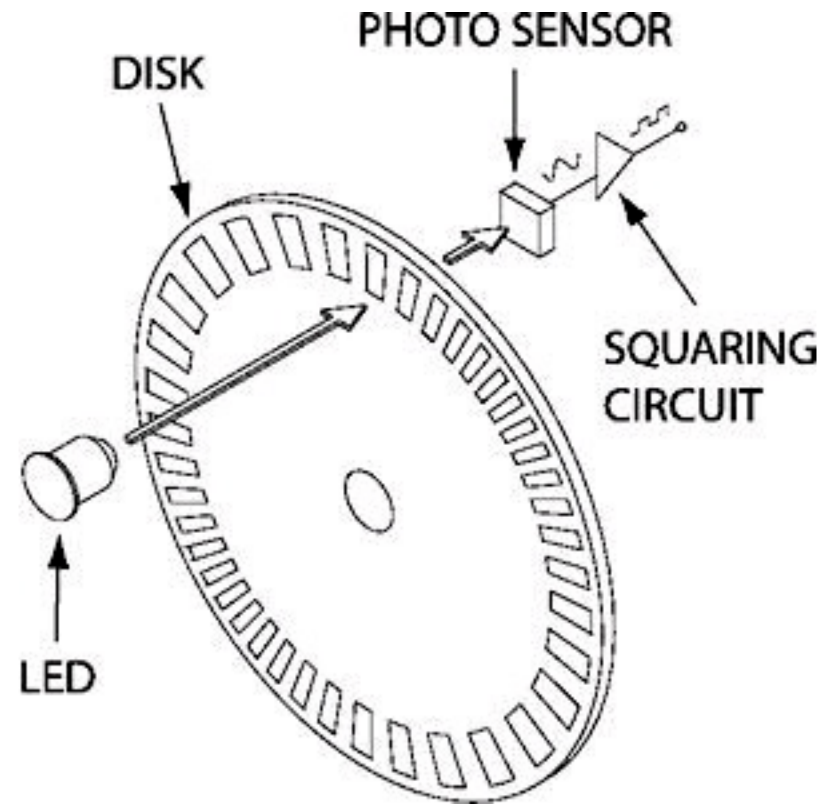


Encoder



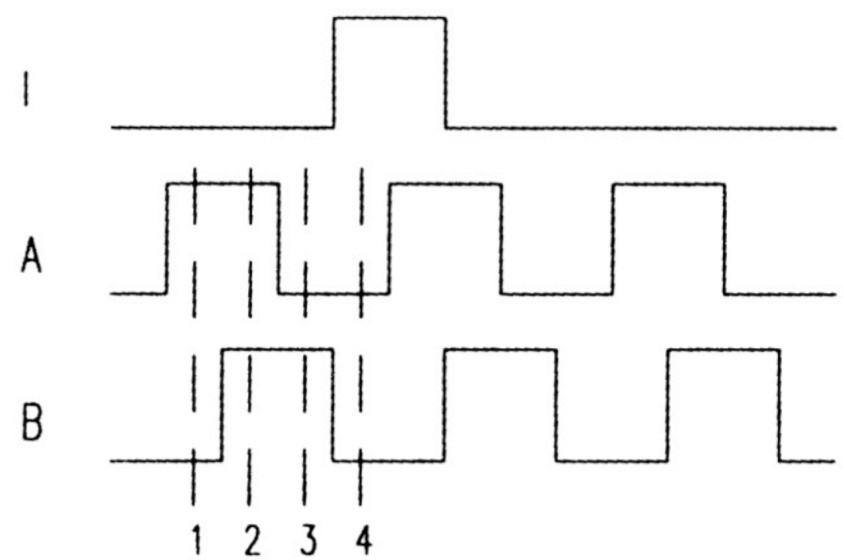






$$\Delta = \frac{2\pi}{4n}$$

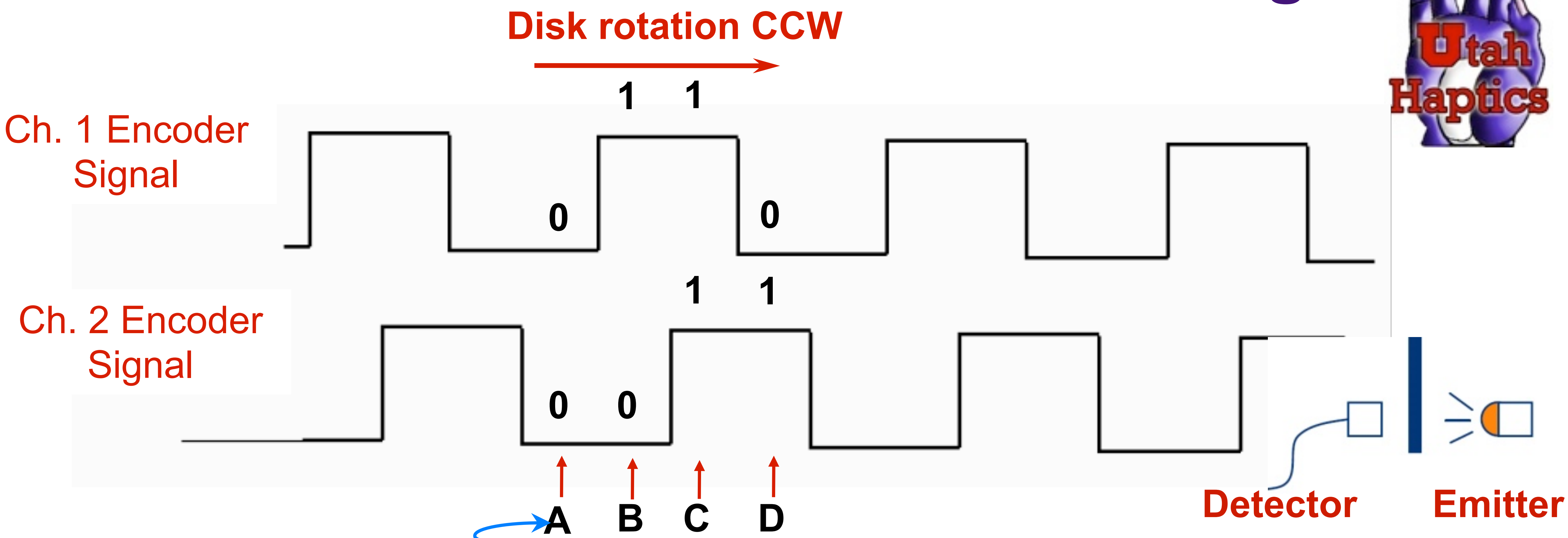
Two channels of pulses, 90 degrees out of phase: quadrature



State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

Some material adapted from slides by A. Okamura and W. Provancher

Quadrature Encoder States & Decoding



Encoder States

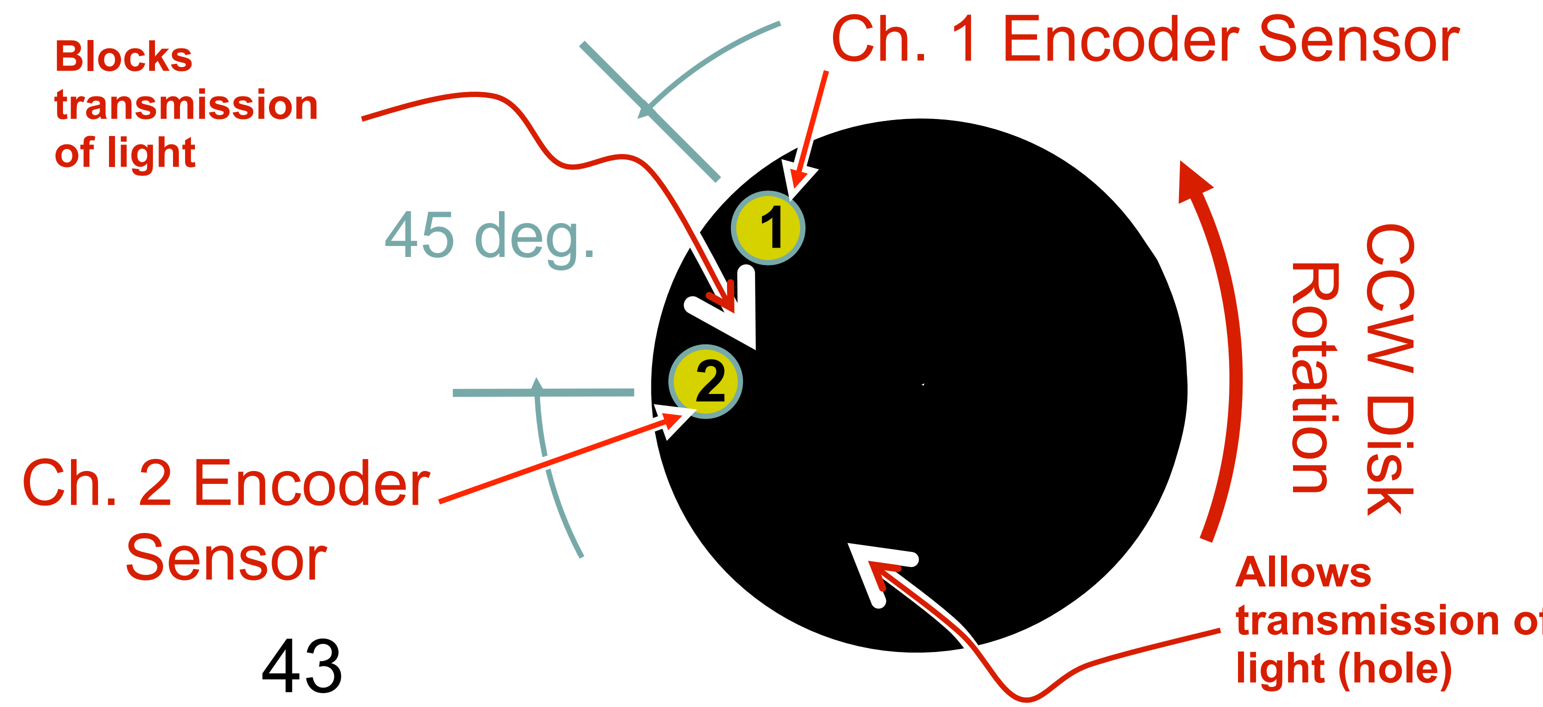
Disk rotation CCW

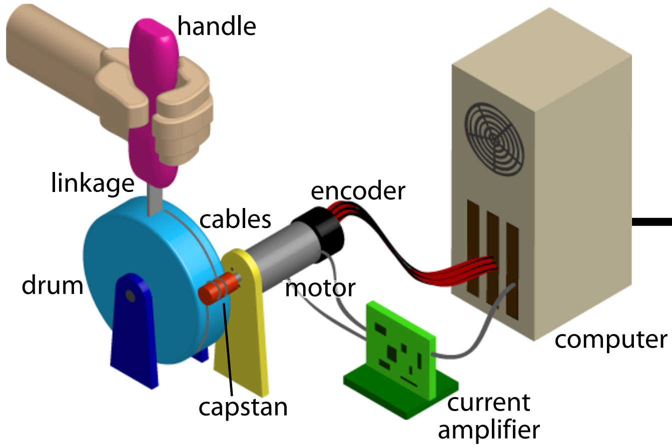
	A	B	C	D
Ch. 1	0	1	1	0
Ch. 2	0	0	1	1
	A	B	C	D

Disk rotation CW

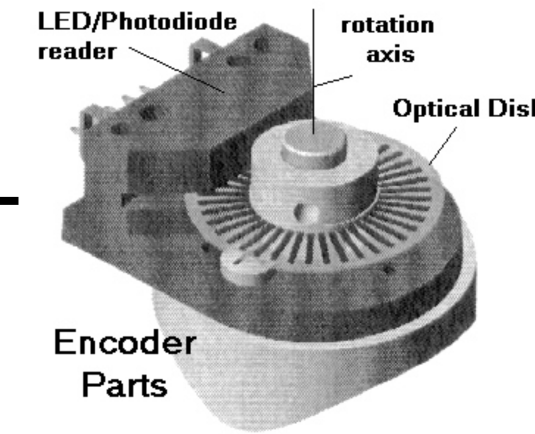
Simplified Encoder Disk

(2 CPR, 8 PPR) (shown in state A)





Encoder

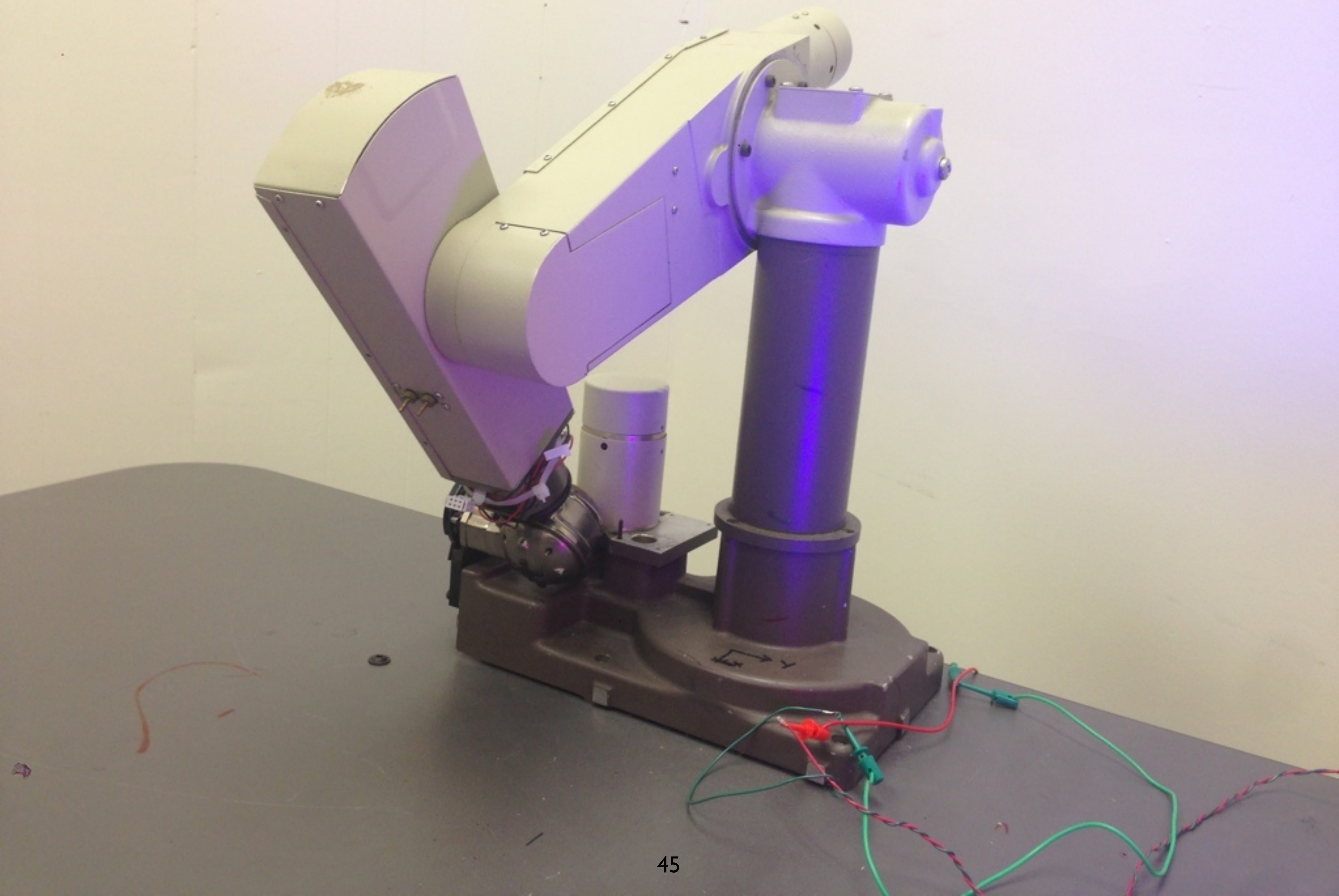


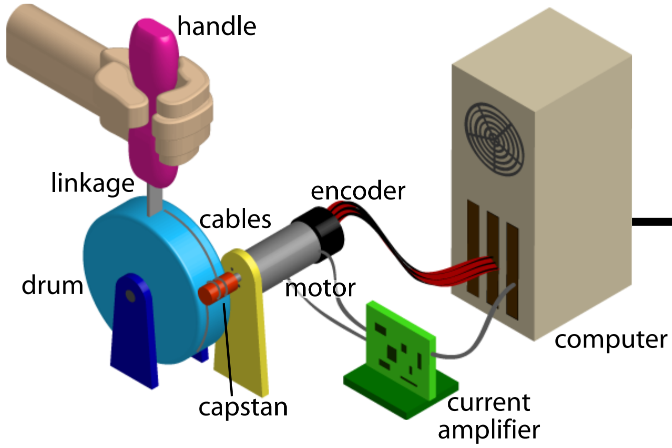
Ramifications of using incremental of optical encoders:

- The system has no knowledge of absolute position, because it's always just counting pulses.
- How can you solve this?
  - Calibration pose (SensAble, PUMA)

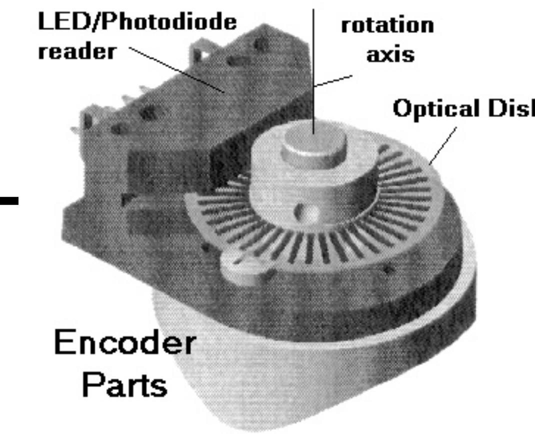
Some material adapted from slides by A. Okamura and W. Provancher

PUMA calibration pose





Encoder



Ramifications of using incremental of optical encoders:

- The system has no knowledge of absolute position, because it's always just counting pulses.
- How can you solve this?

$$\theta_m = \Delta(Q - Q_{zero})$$

  - Calibration pose (SensAble, PUMA)
  - Secondary sensors with absolute readings (da Vinci)
- Sometimes problems occur at high velocities.
- No noise on position, but uncertainty due to resolution, and significant noise on velocity.

Some material adapted from slides by A. Okamura and W. Provancher

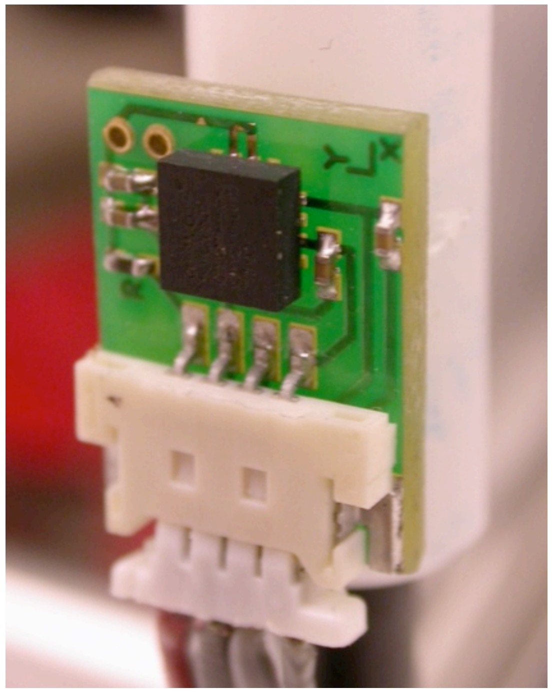
absolute encoders

Unique combination of values for each orientation.

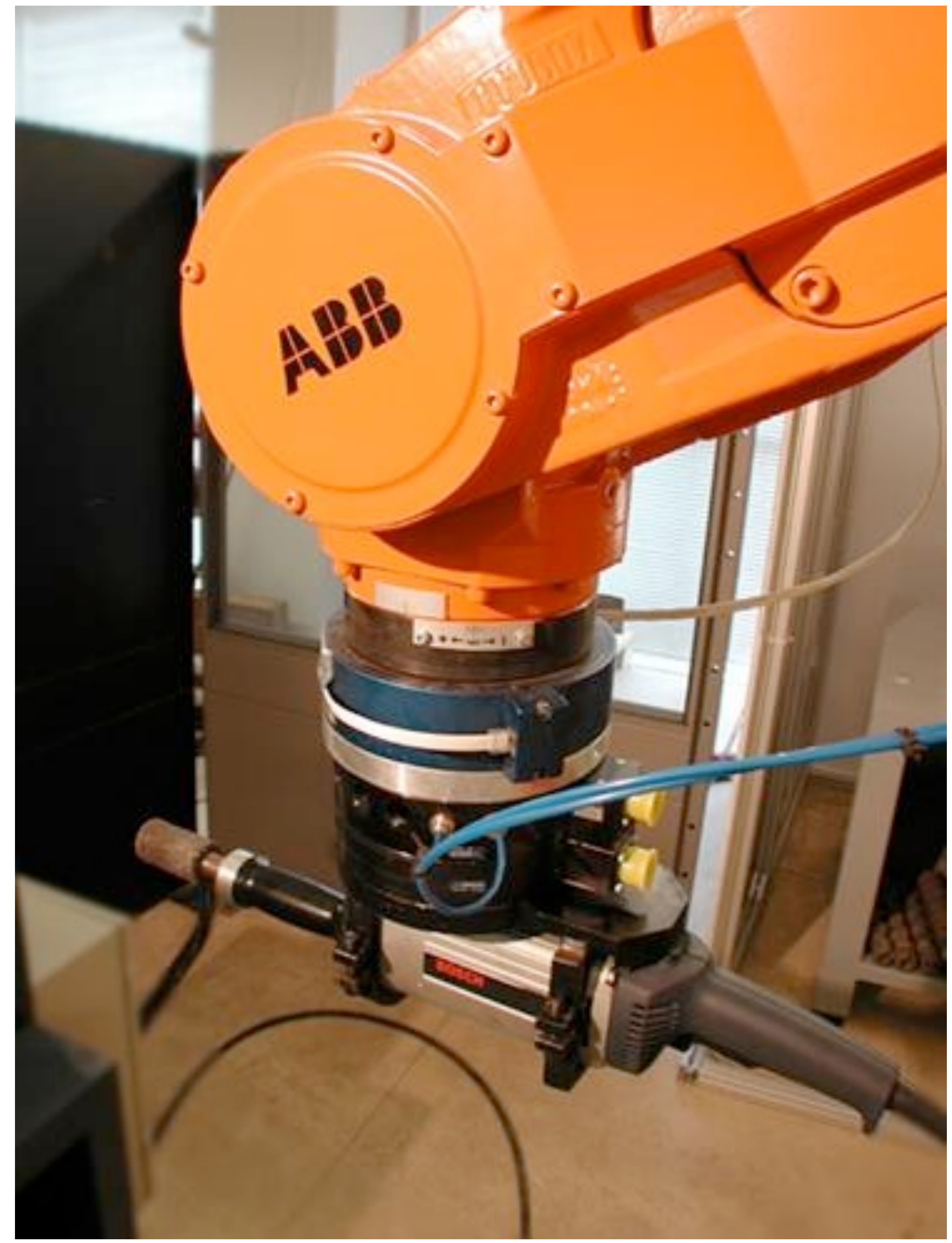
Benefit: don’t have to recalibrate
Drawbacks: complexity, cost, wiring

other sensors

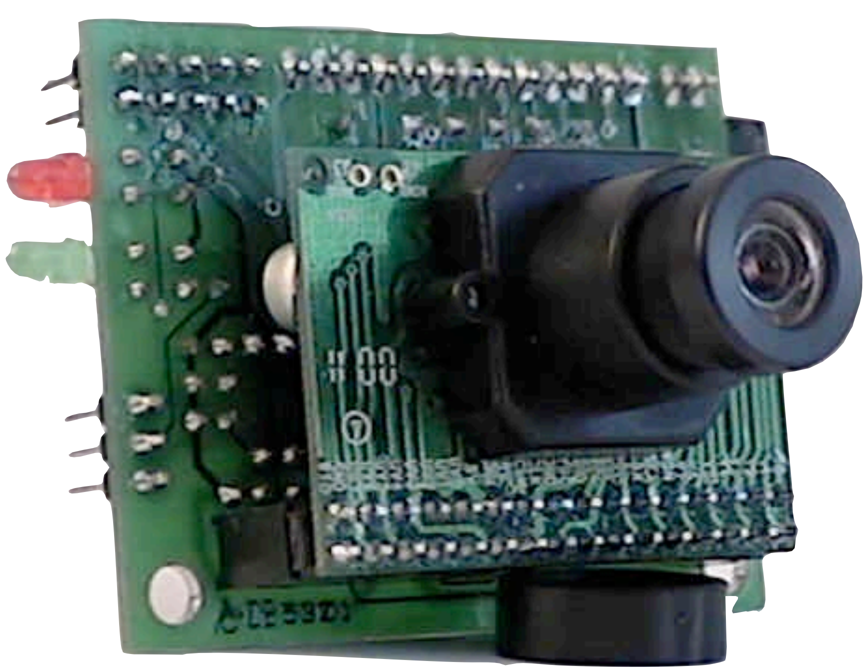
Acceleration



Force / Torque



Vision



What sensors do you see?

Optical encoder

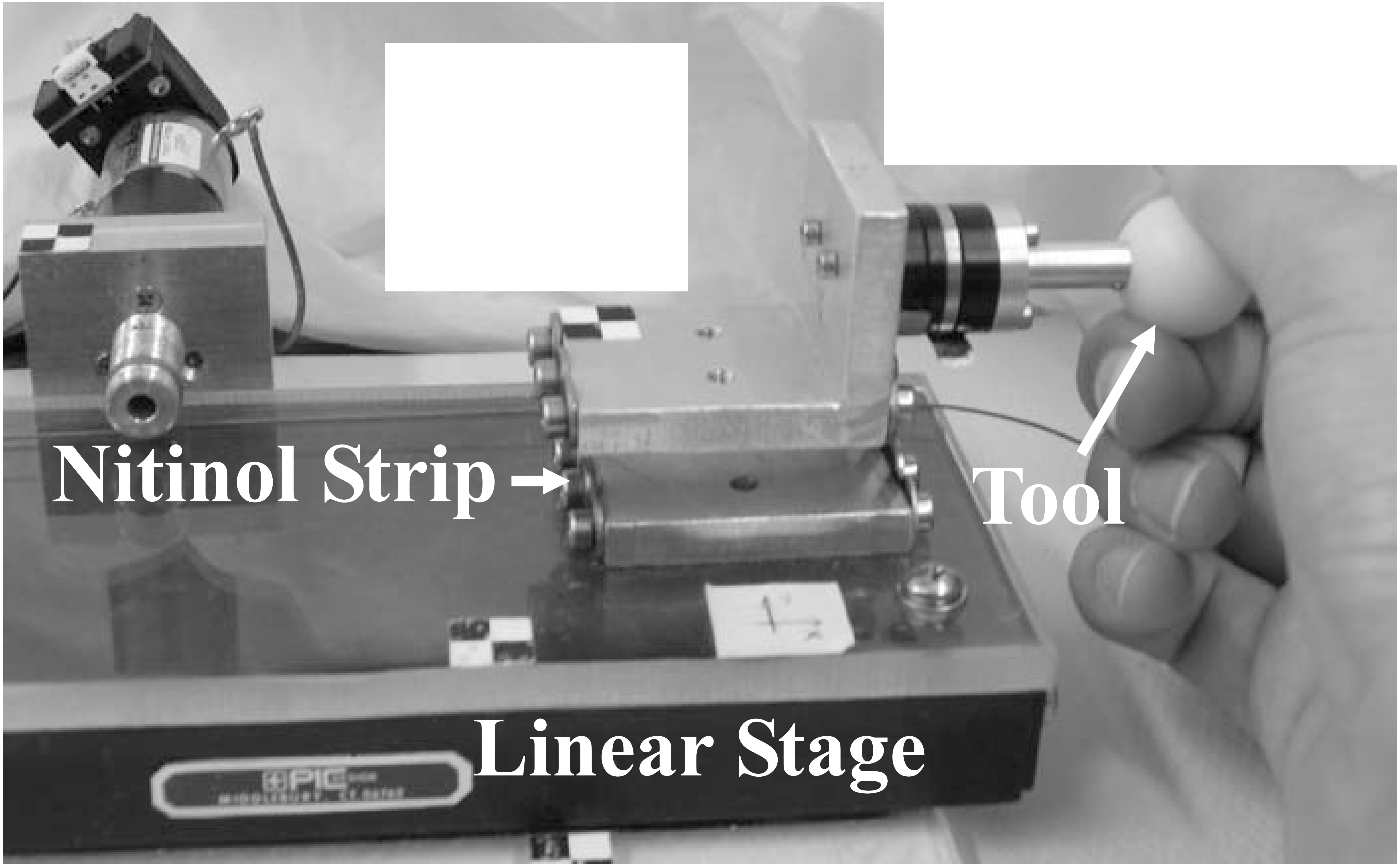
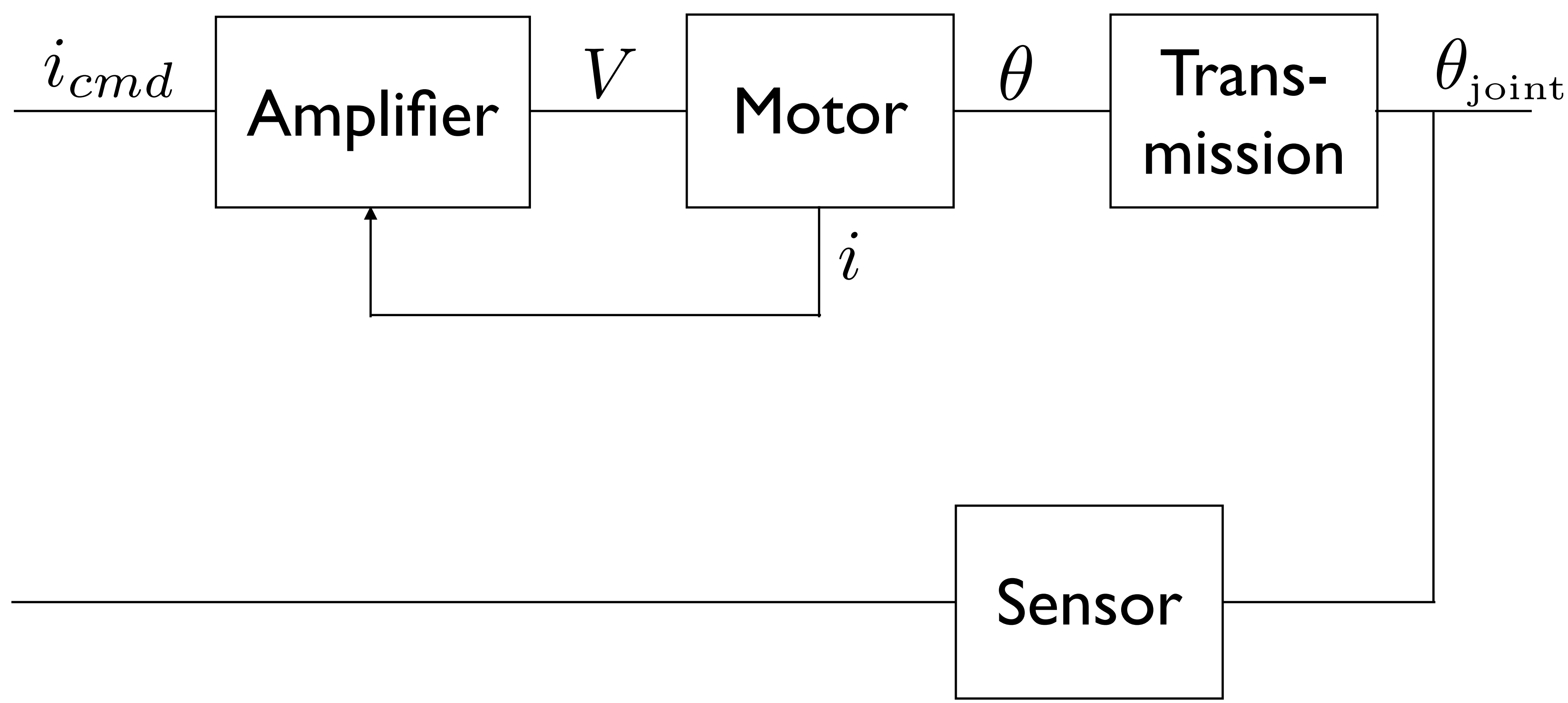


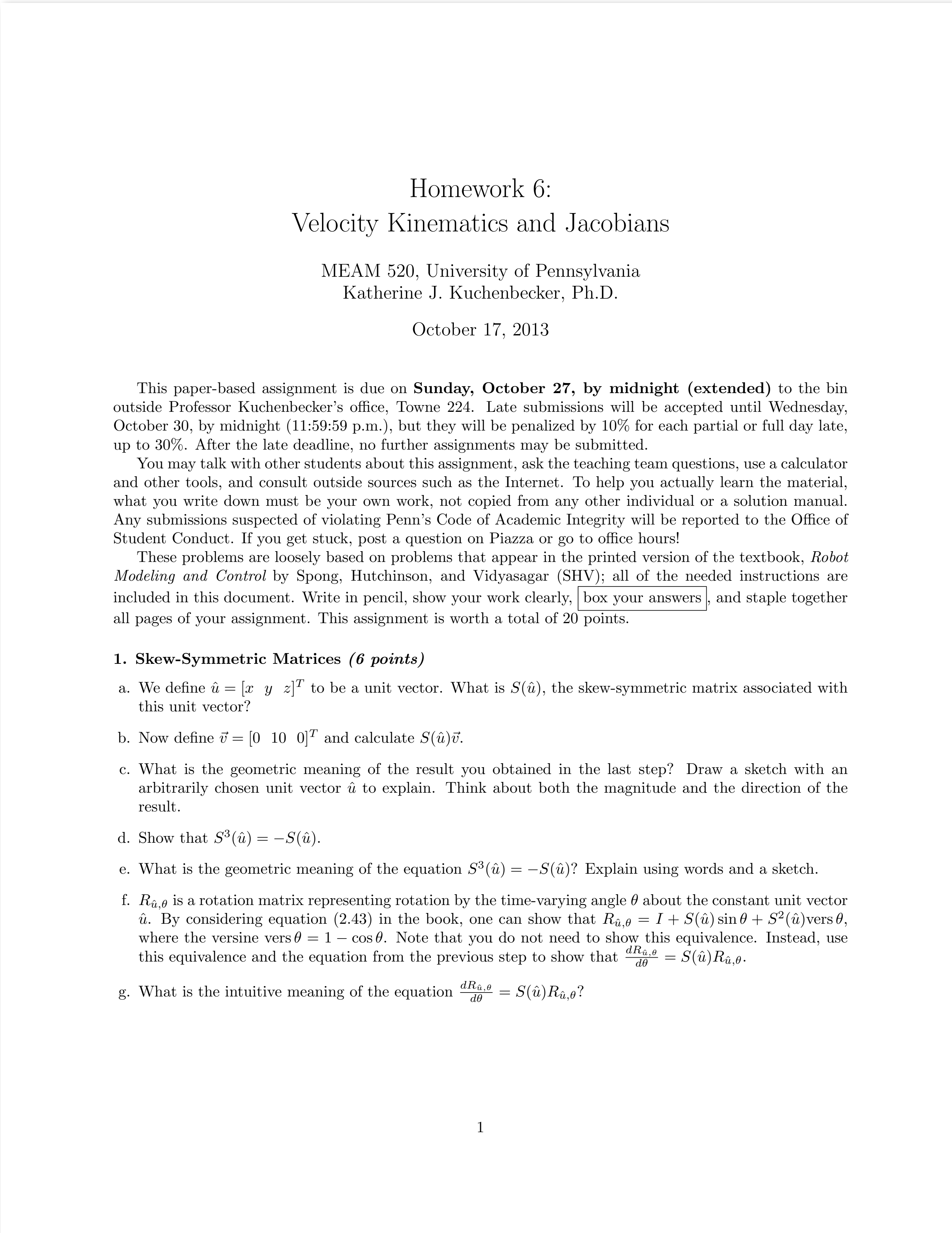
Image from Marayong, Na, and Okamura (ICRA 2007)


i_{cmd}
Amplifier
V
Motor
θ
Trans-
mission
θ_{joint}
i
Sensor

I am in the process of creating Homework 8.

It will probably ask you to characterize a simulated robot joint and design an appropriate controller.

We will start inverse kinematics on Tuesday.



Homework 6:
Velocity Kinematics and Jacobians

MEAM 520, University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

October 17, 2013

This paper-based assignment is due on **Sunday, October 27, by midnight (extended)** to the bin outside Professor Kuchenbecker's office, Towne 224. Late submissions will be accepted until Wednesday, October 30, by midnight (11:59:59 p.m.), but they will be penalized by 10% for each partial or full day late, up to 30%. After the late deadline, no further assignments may be submitted.

You may talk with other students about this assignment, ask the teaching team questions, use a calculator and other tools, and consult outside sources such as the Internet. To help you actually learn the material, what you write down must be your own work, not copied from any other individual or a solution manual. Any submissions suspected of violating Penn's Code of Academic Integrity will be reported to the Office of Student Conduct. If you get stuck, post a question on Piazza or go to office hours!

These problems are loosely based on problems that appear in the printed version of the textbook, *Robot Modeling and Control* by Spong, Hutchinson, and Vidyasagar (SHV); all of the needed instructions are included in this document. Write in pencil, show your work clearly, box your answers, and staple together all pages of your assignment. This assignment is worth a total of 20 points.

1. Skew-Symmetric Matrices ***(6 points)***

a. We define $\hat{u} = [x \;\; y \;\; z]^T$ to be a unit vector. What is $S(\hat{u})$, the skew-symmetric matrix associated with this unit vector?

b. Now define $\vec{v} = [0 \;\; 10 \;\; 0]^T$ and calculate $S(\hat{u})\vec{v}$.

c. What is the geometric meaning of the result you obtained in the last step? Draw a sketch with an arbitrarily chosen unit vector $\hat{u}$ to explain. Think about both the magnitude and the direction of the result.

d. Show that $S^3(\hat{u}) = -S(\hat{u})$.

e. What is the geometric meaning of the equation $S^3(\hat{u}) = -S(\hat{u})$? Explain using words and a sketch.

f. $R_{\hat{u},\theta}$ is a rotation matrix representing rotation by the time-varying angle θ about the constant unit vector $\hat{u}$. By considering equation (2.43) in the book, one can show that $R_{\hat{u},\theta} = I + S(\hat{u})\sin\theta + S^2(\hat{u})\text{vers}\,\theta$, where the versine $\text{vers}\,\theta = 1 - \cos\theta$. Note that you do not need to show this equivalence. Instead, use this equivalence and the equation from the previous step to show that $\frac{dR_{\hat{u},\theta}}{d\theta} = S(\hat{u})R_{\hat{u},\theta}$.

g. What is the intuitive meaning of the equation $\frac{dR_{\hat{u},\theta}}{d\theta} = S(\hat{u})R_{\hat{u},\theta}$?

1

Homework 6
is graded

Pick yours up
from Naomi

GRASP Seminar this Friday, November 8th – Aaron Ames — grasp

From: Charity Payne
Subject: **GRASP Seminar this Friday, November 8th - Aaron Ames**
Date: November 4, 2013 2:54:30 PM EST
To: grasp-seminar@lists.seas.upenn.edu , cis-faculty@lists.seas.upenn.edu , cis-postdocs@lists.seas.upenn.edu , cis-phd@lists.seas.upenn.edu , cis-ms@lists.seas.upenn.edu , cis-mcit@lists.seas.upenn.edu , cggt-ms@lists.seas.upenn.edu

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Fall 2013 GRASP Seminar

Friday, November 8th at 11am
Wu & Chen Auditorium

Aaron Ames
Texas A&M University

"Controlling the Next Generation of Bipedal Robots"

Abstract: Humans have the ability to walk with deceptive ease, navigating everything from daily environments to uneven and uncertain terrain with efficiency and robustness. Despite the simplicity with which humans appear to ambulate, locomotion is inherently complex due to highly nonlinear dynamics and forcing. Yet there is evidence to suggest that humans utilize a hierarchical subdivision among cortical control, central pattern generators in the spinal column, and proprioceptive sensory feedback. This indicates that when humans perform motion primitives, potentially simple and characterizable control strategies are implemented. If these fundamental mechanisms underlying human walking can be discovered and formally understood, human-like abilities can be imbued into the next generation of robotic devices with far-reaching applications ranging from prosthesis to legged robots for space exploration and disaster response.

This talk presents the process of formally achieving bipedal robotic walking through controller synthesis inspired by human locomotion, and demonstrates these methods through examples of experimental realization on numerous bipedal robots. Motivated by the hierarchical control present in humans, we begin by viewing the human as a "black box" and describe outputs, or virtual constraints, that appear to characterize human walking. By considering the equivalent outputs for the bipedal robot, a novel type of control Lyapunov function (CLF) can be constructed that drives the outputs of the robot to the output of the human; moreover, the parameters of this CLF can be optimized so that stable robotic walking is provably achieved while simultaneously producing outputs of the robot that are as close as possible to those of a human. This CLF forms the basis for a Quadratic Program (QP) yielding locomotion that dynamically accounts for torque and contact constraints. The end result is the generation of bipedal robotic walking that is remarkably human-like and is experimentally realizable, together with a novel control framework for highly dynamic behaviors on bipedal robots. This is evidenced by the demonstration of the resulting controllers on multiple robotic platforms, including: AMBER 1 and 2, NAO, ATRIAS and MABEL Furthermore, these methods form the basis for achieving a variety of walking behaviors—including multi-domain and rough terrain locomotion—and have demonstrated application to the control of prosthesis.

Biography: Dr. Aaron D. Ames is an Assistant Professor in Mechanical Engineering at Texas A&M University with a joint appointment in Electrical & Computer Engineering. His research interests center on robotics, nonlinear control, hybrid systems and cyber-physical systems, with special emphasis on foundational theory and experimental realization on bipedal robots. Dr. Ames received a BS in Mechanical Engineering and a BA in Mathematics from the University of St. Thomas in 2001, and he received a MA in Mathematics and a PhD in Electrical Engineering and Computer Sciences from UC Berkeley in 2006. At UC Berkeley, he was the recipient of the 2005 Leon O. Chua Award for achievement in nonlinear science and the 2006 Bernard Friedman Memorial Prize in Applied Mathematics. Dr. Ames served as a Postdoctoral Scholar in the Control and Dynamical System Department at the California Institute of Technology from 2006 to 2008. In 2010 he received the NSF CAREER award for his research on bipedal robotic walking and its applications to prosthetic devices. Dr. Ames is the head of the A&M Bipedal Experimental Robotics (AMBER) Lab that designs, builds and tests novel bipedal robots with the goal of achieving human-like bipedal robotic walking.
