MEAM 520

Inverse Kinematics

Katherine J. Kuchenbecker, Ph.D.

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

MEAM Department, SEAS, University of Pennsylvania

GRASP LABORATORY

Lecture 20: November 12, 2013

Name ______________________

Resubmission of Midterm Exam

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

November 8, 2013

If you doubt the correctness of any of the answers you submitted on the in-class midterm, you may rework those problems to try to earn back a proportion of the points you may have lost. You must decide whether to submit new answers for each of the five problems on the exam; if you do any lettered sub-question in a problem, you should resubmit all of them, as they are interrelated. Your final score on each problem will be a weighted average of your in-class score and your resubmission score: $s_{\text{final}} = (1-p)\, s_{\text{in-class}} + p\, s_{\text{resubmission}}$. We anticipate that this proportion p will be about 30%, but it may be raised or lowered to match overall class performance. If you do not submit new answers for a certain problem, your in-class score will be your final score. Completing this exam resubmission is completely optional.

You must do this exam resubmission independently, without talking about it with anyone else. You may use a calculator, your notes, the textbook, the Internet, and any other reference materials you find useful. However, you must not take assistance from any individual (including electronic correspondence of any kind), and you must not give assistance to other students in the class. If you accidentally discuss part of the exam with someone, do not fill out that part of the exam resubmisson. Any suspected violations of Penn's Code of Academic Integrity will be reported to the Office of Student Conduct for investigation.

This resubmission is due **by the start of class (noon) on Tuesday, November 12**. Because we will be discussing the exam in class that day, late resubmissions cannot be accepted. If you need clarification on any question, please post a private note on Piazza. When you work out each problem, please show all steps and $\boxed{\text{box your answer}}$.

	Points	Score
Problem 1	20	
Problem 2	15	
Problem 3	10	
Problem 4	15	
Problem 5	40	
Total	100	

I agree to abide by the University of Pennsylvania Code of Academic Integrity during this exam resubmission. I pledge that all work is my own and has been completed without the use of unauthorized aid or materials.

Signature ______________________ Date __________

1

Please turn in your resubmission of the midterm exam.

If you missed the announcements about the resubmission, you can still ask to do it by Thursday - email KJK.

MEAM 520

https://piazza.com/class/hf935b0sz1m5r3?cid=238

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Note History:

note   stop following   75 views   Actions

Midterm Resubmission - Optional Opportunity to Earn Partial Credit - Due at Lecture on Tuesday

Dear students,

Everyone has now taken the MEAM 520 midterm. I recognize that the test was very long and that many of you did not have time to answer all of the questions. I apologize for misjudging the length of the test in this way; you should take it as a compliment that I thought you could all solve so many problems in an hour and twenty minutes.

I have thought about various ways to handle this situation, and I have settled on the following. I have just posted the midterm exam with a new page of instructions, repeated below. The title of the file is midterm_resubmission.pdf, and you can view it on the course page under general resources: https://piazza.com/upenn/fall2013/meam520/resources

If you doubt the correctness of any of the answers you submitted on the in-class midterm, you may rework those problems to try to earn back a proportion of the points you may have lost. You must decide whether to submit new answers for each of the five problems on the exam; if you do any lettered sub-question in a problem, you should resubmit all of them, as they are interrelated. Your final score on each problem will be a weighted average of your in-class score and your resubmission score: $s_{final} = (1-p)s_{in-class} + ps_{resubmission}$. We anticipate that this proportion p will be about 30%, but it may be raised or lowered to match overall class performance. If you do not submit new answers for a certain problem, your in-class score will be your final score. Completing this exam resubmission is completely optional.

You must do this exam resubmission independently, without talking about it with anyone else. You may use a calculator, your notes, the textbook, the Internet, and any other reference materials you find useful. However, you must not take assistance from any individual (including electronic correspondence of any kind), and you must not give assistance to other students in the class. If you accidentally discuss part of the exam with someone, do not fill out that part of the exam resubmisson. Any suspected violations of Penn's Code of Academic Integrity will be reported to the Office of Student Conduct for investigation.

This resubmission is due **by the start of class (noon) on Tuesday, November 12**. Because we will be discussing the exam in class that day, late resubmissions cannot be accepted. If you need clarification on any question, please post a private note on Piazza. When you work out each problem, please show all steps and box your answer.

See @245 for the clarifications that were written on the screen during the exam.

If you felt overly rushed during the in-class exam, I hope this midterm resubmission gives you the chance to demonstrate your comprehension. I believe that revisiting the midterm questions in this way will be useful for everyone interested in really understanding this material. And I'm hopeful someone may be able to answer every question correctly - a good objective! I am also interested in hearing your thoughts on this process - please send me a private Piazza note or an email if you'd like to tell me what you think.

- KJK

midterm_exam

Average Response Time: 11 min

Special Mentions: Katherine J. Kuchenbecker answered Can we print the... in 4 min. 7 days ago

Online Now | This Week: 10 | 105

MEAM 520

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Note History:

note

stop following | 50 views

Actions

Three Clarifications on Midterm Resubmission

1. You may use MATLAB or any other computational tool on the midterm resubmission. Please include a print-out of your code or a hand-written description of what it does and attach to your resubmission.

2. You should do a numbered problem on the resubmission if you think your new score will be better than your original score. If you get 100% on a question on the resubmission, you will get back a portion of the points you lost in class. The only way the resubmission can hurt you is if you get a lower score on a problem in the resubmission than you did during the in-class exam.

3. Several people have asked to have until Thursday's lecture to turn in the resubmission, and I have granted their requests. Thus we won't be talking about the exam until Thursday; we will pass back graded in-class tests and release scores that day in class. If you would also like to have until noon on Thursday to do the resubmission, just send me a private Piazza message or an email with a brief explanation why. Send this request before 6am on Tuesday so I have time to consider it before the deadline.

Please let me know what other questions you may have!

midterm_exam

edit · good note | 0

19 hours ago by Katherine J. Kuchenbecker

followup discussions *for lingering questions and comments*

Resolved Unresolved

Mabel Zhang 17 hours ago
Quick question. Is Q5g asking for linear singularities or both linear and angular singularities?

Katherine J. Kuchenbecker 16 hours ago Q5g is asking for linear velocity singularities only, not angular velocity singularities. Good question.

Reply to this followup discussion

Start a new followup discussion

Compose a new followup discussion

Average Response Time: 11 min

Special Mentions: Katherine J. Kuchenbecker answered Can we print the... in 4 min. 7 days ago

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MEAM 520

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hw2 hw4 hw6 hw7 hw8 final_exam lecture10 lecture11 lecture12 lecture13 lecture14 project1 midterm_exam other office_hours textbook matlab puma talks lecture_recordings

Note History:

note stop following 70 views

Actions

Additional Comments About Midterm Resubmission

Three of you have privately written to me to express your concerns about the midterm resubmission. You have raised some good points, so I wanted to share a summary of these discussions with the whole class.

My Motivation for Offering a Resubmission
The midterm submission is different from how most graduate courses are run in engineering. I know that students appreciate knowing what to expect and that changes can be uncomfortable. I am trying to balance that preference for familiarity with my goal of having everyone in the class learn the material.

I have used midterm resubmissions six times before here at Penn, and they have been very effective at getting students to look back over the material and figure it out for themselves - more effective than simply distributing solutions. I was first inspired to try this by reading a paper that showed it was highly effective to have undergraduate physics students take the same midterm exam twice in close succession; students who struggled in the first test learned what they needed to study and work on to improve for the second test. These improvements transferred to a separate assessment of student learning. Another study on a graduate-level science course showed that taking the same test with more time and more resources enabled students to do much better on the calculation-based questions, of which there were many on the exam I gave.

Academic Integrity
Students may be tempted to work together on the resubmission. Just as it is a violation of Penn's Code of Academic Integrity to collaborate during the in-class exam, it is a violation to collaborate out of class on this exam. Students are all required to sign an affirmation of the Code of Academic Integrity on the resubmission. I will send all suspicious cases to the Office of Student Conduct; I have already reported one academic integrity violation in our class this semester. Because I have made the rules very clear, it is not inevitable that people will collaborate. I expect everyone to behave with integrity, and I think the benefits of the resubmission exercise outweigh the negative effects of people talking undetected.

It is fine if you had already talked with one or more classmates about the particulars of the midterm exam before the resubmission was announced. If you want to resubmit those questions, simply write on the first page of your exam a list of who you talked with for each problem. However, it is not acceptable to talk to others about any of the problems on the exam now that the resubmission has been announced.

Optional vs. Required
The exam resubmission is optional. I expect that some students will opt not to do it. When I have done this before, about 90% of the students have done the resubmission. I believe doing the resubmission is useful for everyone, even those who did quite well in class, and I am leaving room for it in the schedule by not assigning a homework at this time. I am delaying releasing the next homework so that everyone who wants to do the resubmission has the time. If you want to do the resubmission but don't have time before noon on Tuesday, please let me know, and I will give you an extension and delay discussing the exam in class.

Impact on Grade
Nothing will erase or change the scores that everyone earned in class. The in-class test was a good way for me to see how well students did in a resource-limited and time-limited context. The resubmission portion provides a different set of constraints and reflects a somewhat different aspect of a student's skills, both of which are important. Because the resubmission was not announced for several days after the test, due to the make-up exams, and because people may already have talked about some of the problems, I think the weighting will be less than the tentative 30% listed in the instructions. I will probably make it equal to about one homework assignment, so you can look at it as optional extra credit for students who want to attempt to demonstrate their comprehension after an exam performance they weren't proud of. The in-class exam score will still dictate a substantial portion of each student's grade in this class at the end of the semester. It's also important to know that I

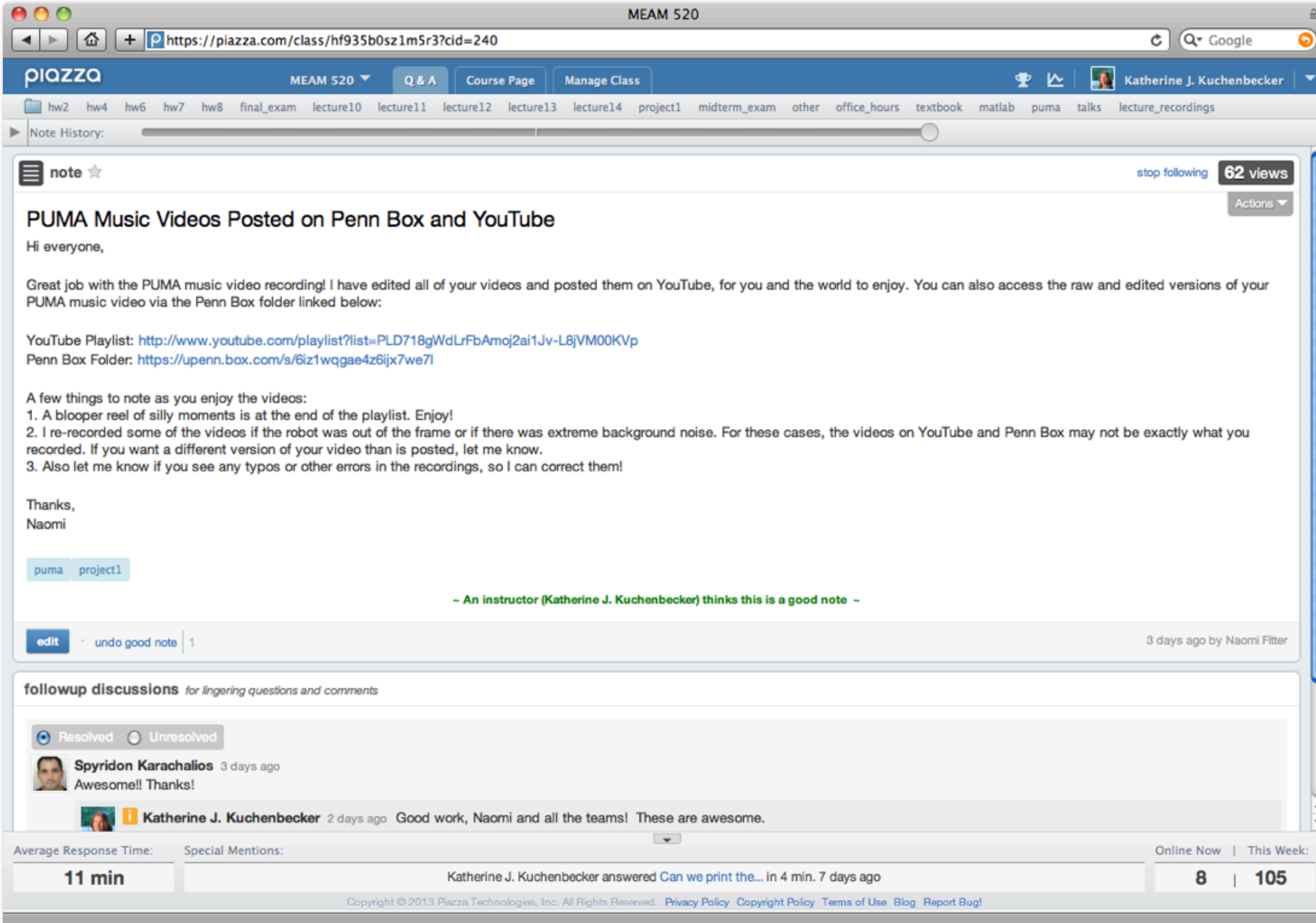
Average Response Time: 11 min

Special Mentions: Katherine J. Kuchenbecker answered Can we print the... in 4 min. 7 days ago

Online Now | This Week: 11 | 105

We will hand back graded midterms
in class on Thursday.

The solutions will also be posted on Piazza.



MEAM 520

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Note History:

note | stop following | 62 views | Actions

PUMA Music Videos Posted on Penn Box and YouTube

Hi everyone,

Great job with the PUMA music video recording! I have edited all of your videos and posted them on YouTube, for you and the world to enjoy. You can also access the raw and edited versions of your PUMA music video via the Penn Box folder linked below:

YouTube Playlist: http://www.youtube.com/playlist?list=PLD718gWdLrFbAmoj2ai1Jv-L8jVM00KVp
Penn Box Folder: https://upenn.box.com/s/6iz1wqgae4z6ijx7we7l

A few things to note as you enjoy the videos:
1. A blooper reel of silly moments is at the end of the playlist. Enjoy!
2. I re-recorded some of the videos if the robot was out of the frame or if there was extreme background noise. For these cases, the videos on YouTube and Penn Box may not be exactly what you recorded. If you want a different version of your video than is posted, let me know.
3. Also let me know if you see any typos or other errors in the recordings, so I can correct them!

Thanks,
Naomi

puma project1

~ An instructor (Katherine J. Kuchenbecker) thinks this is a good note ~

edit · undo good note | 1 | 3 days ago by Naomi Fitter

followup discussions *for lingering questions and comments*

Resolved | Unresolved

Spyridon Karachalios 3 days ago
Awesome!! Thanks!

Katherine J. Kuchenbecker 2 days ago Good work, Naomi and all the teams! These are awesome.

Average Response Time: 11 min | Special Mentions: Katherine J. Kuchenbecker answered Can we print the... in 4 min. 7 days ago | Online Now 8 | This Week: 105

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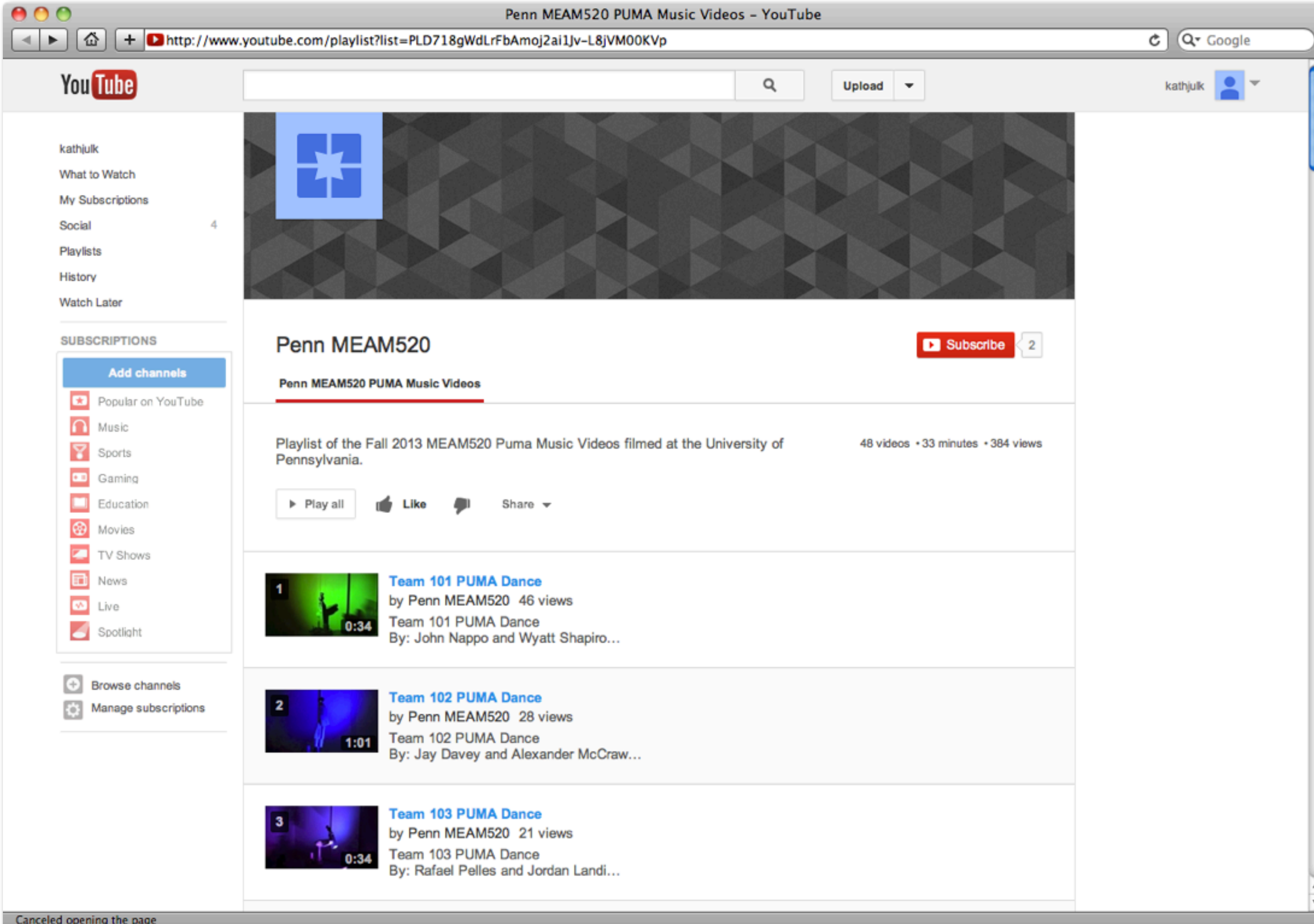
Penn MEAM520 PUMA Music Videos - YouTube
http://www.youtube.com/playlist?list=PLD718gWdLrFbAmoj2ai1Jv-L8jVM0OKVp
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kathjulk
What to Watch
My Subscriptions
Social 4
Playlists
History
Watch Later
SUBSCRIPTIONS
Add channels
Popular on YouTube
Music
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Education
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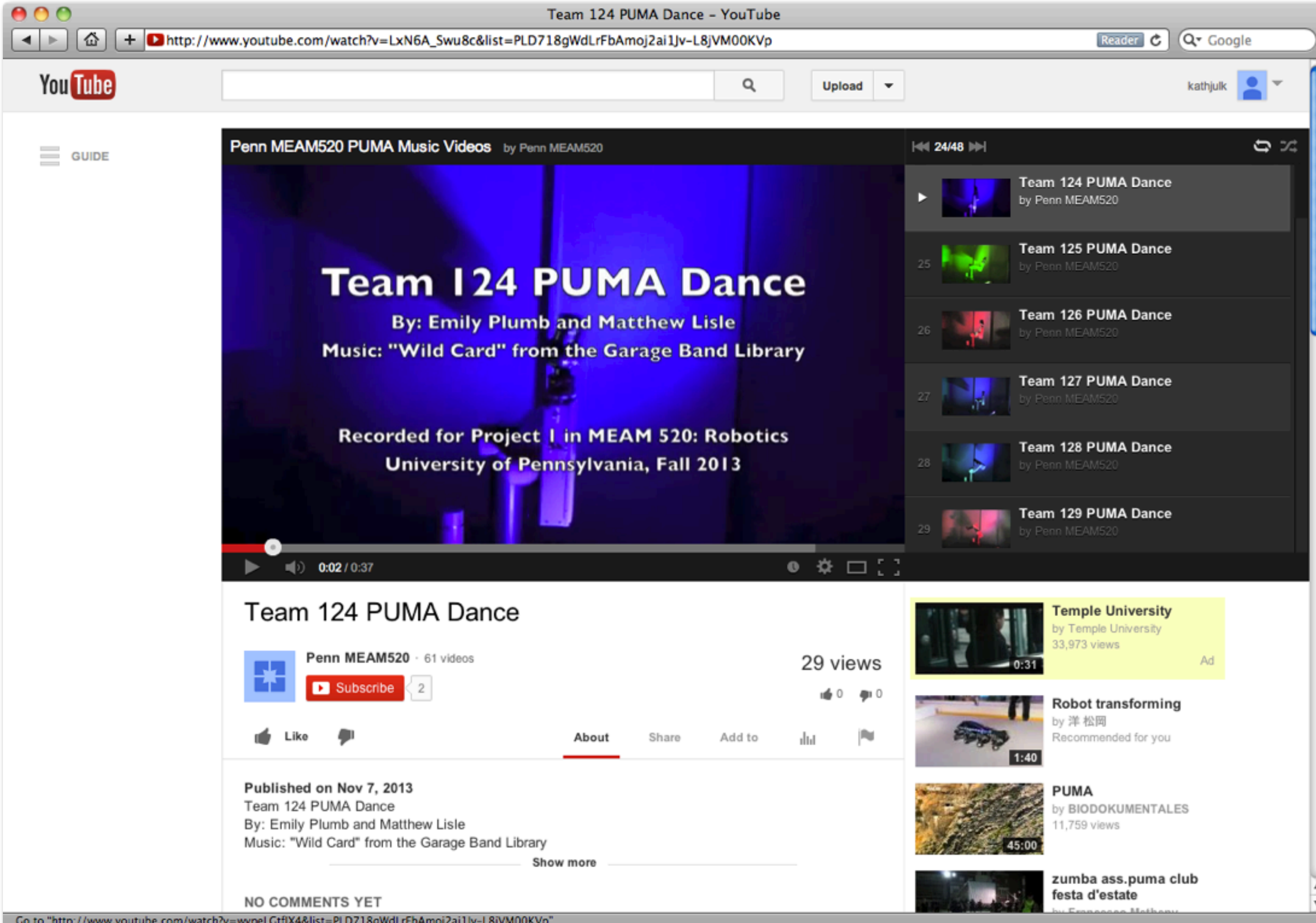
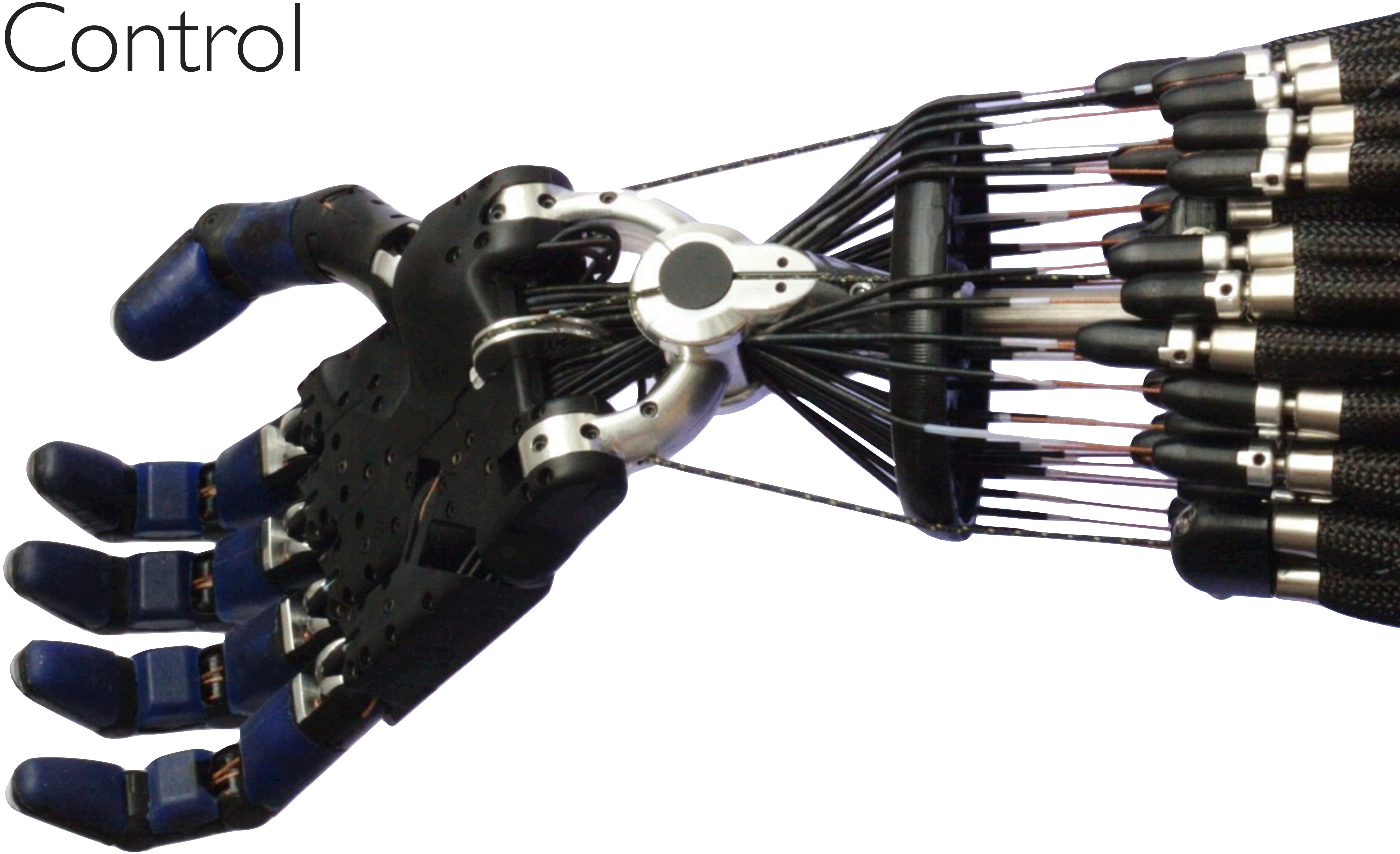
Share
1
0:34
Team 101 PUMA Dance
by Penn MEAM520 46 views
Team 101 PUMA Dance
By: John Nappo and Wyatt Shapiro...
2
1:01
Team 102 PUMA Dance
by Penn MEAM520 28 views
Team 102 PUMA Dance
By: Jay Davey and Alexander McCraw...
3
0:34
Team 103 PUMA Dance
by Penn MEAM520 21 views
Team 103 PUMA Dance
By: Rafael Pelles and Jordan Landi...
Canceled opening the page

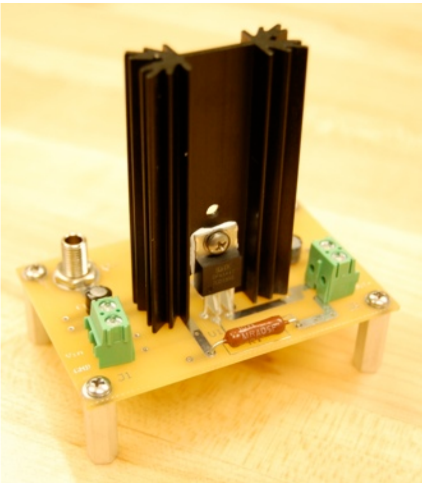
Let's watch Teams 124, 125, 126, and 127.

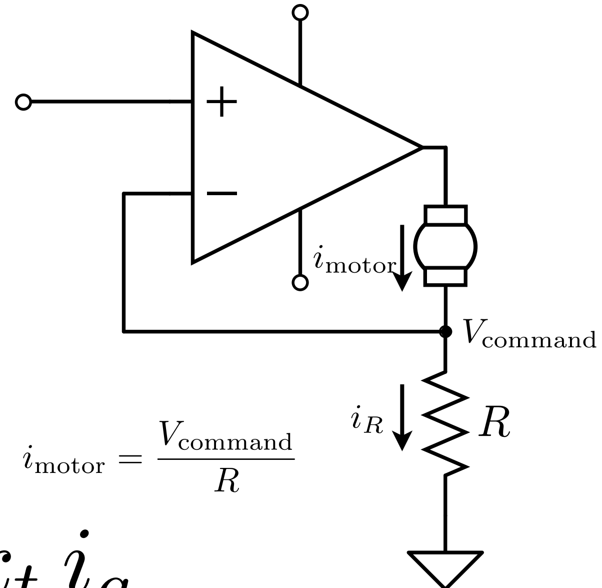


Manipulator Hardware and Control



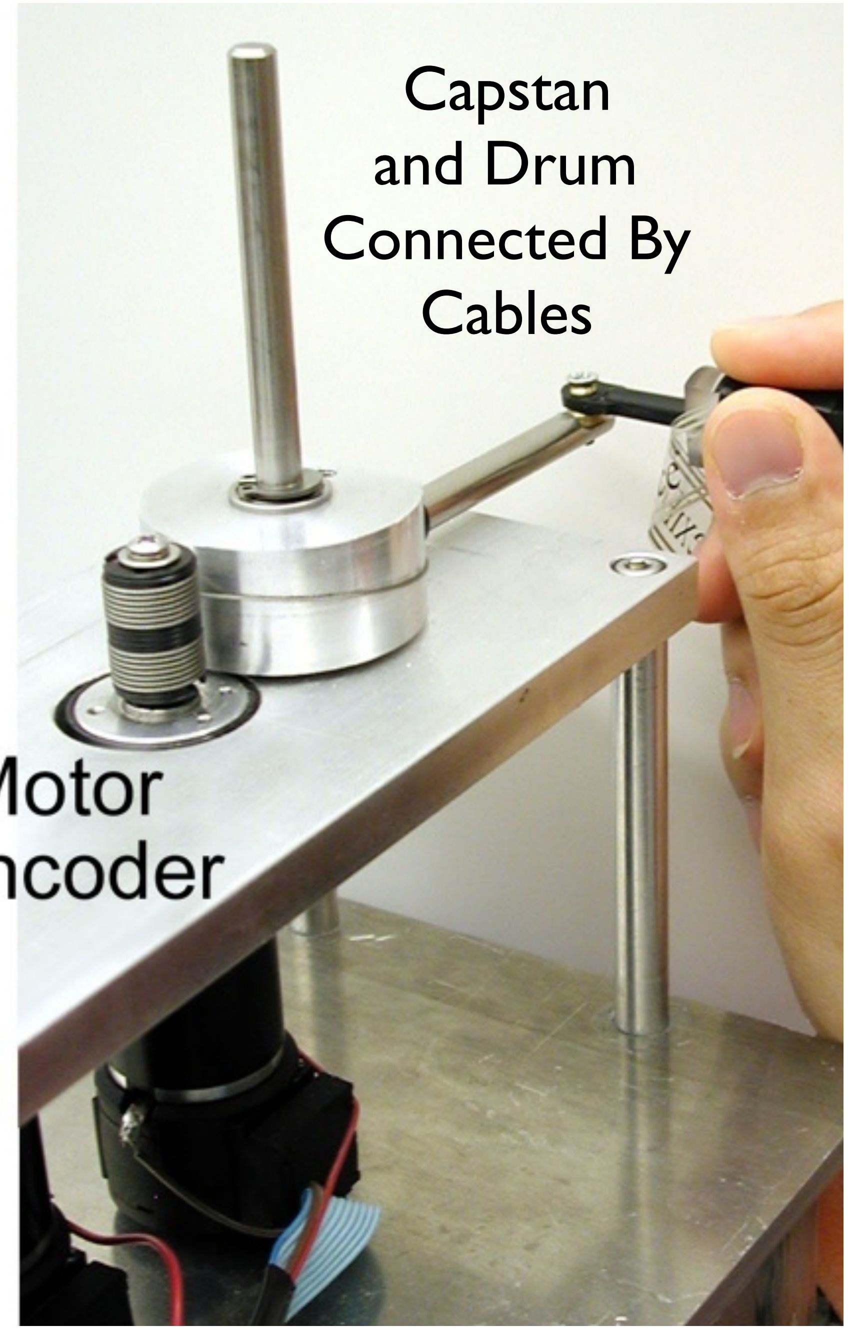
Current Amplifier





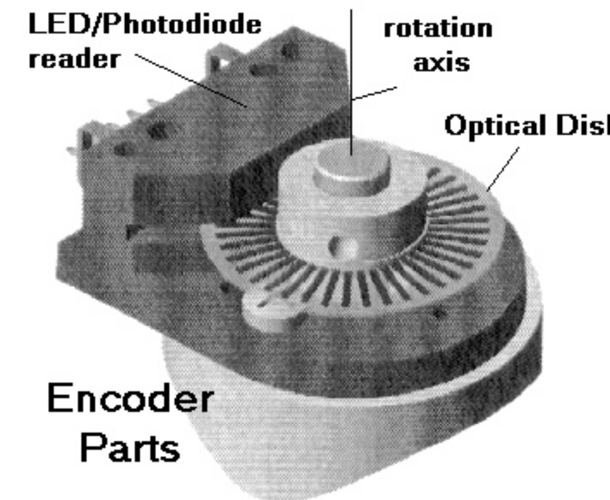
$$i_{\text{motor}} = \frac{V_{\text{command}}}{R}$$

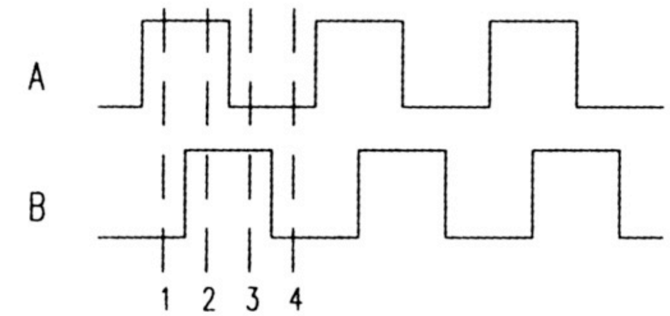
$$\tau_m = k_t\, i_a$$



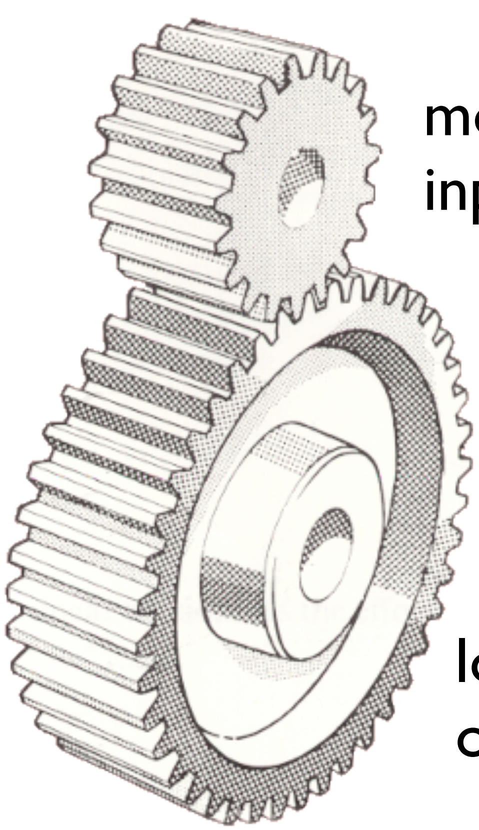
DC Motor
with Encoder

Incremental Optical Encoder





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



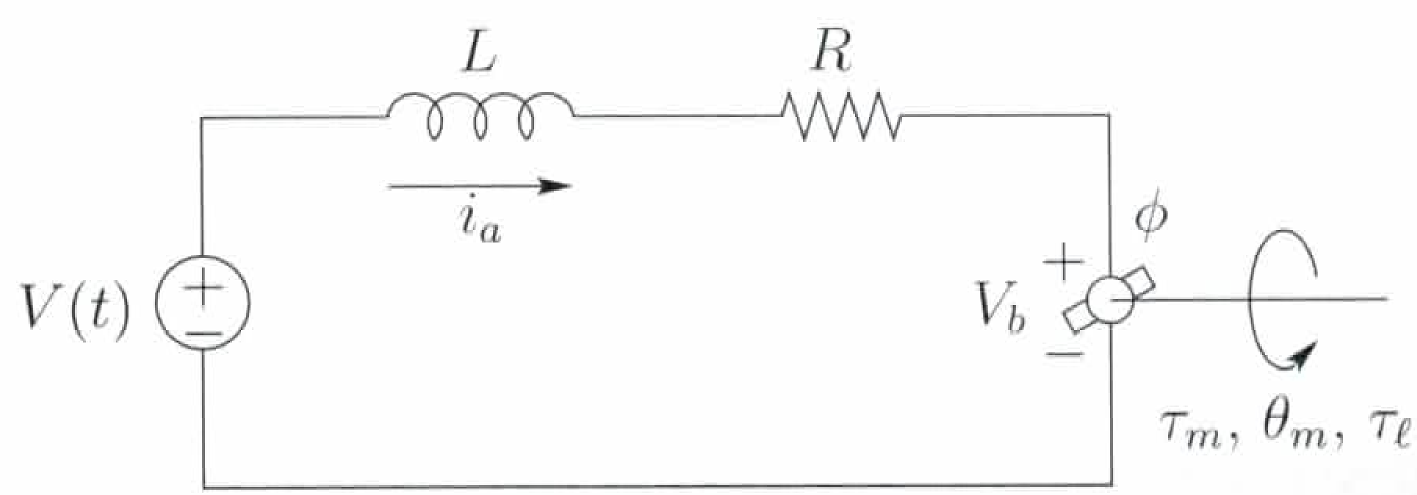
Gear Ratio

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

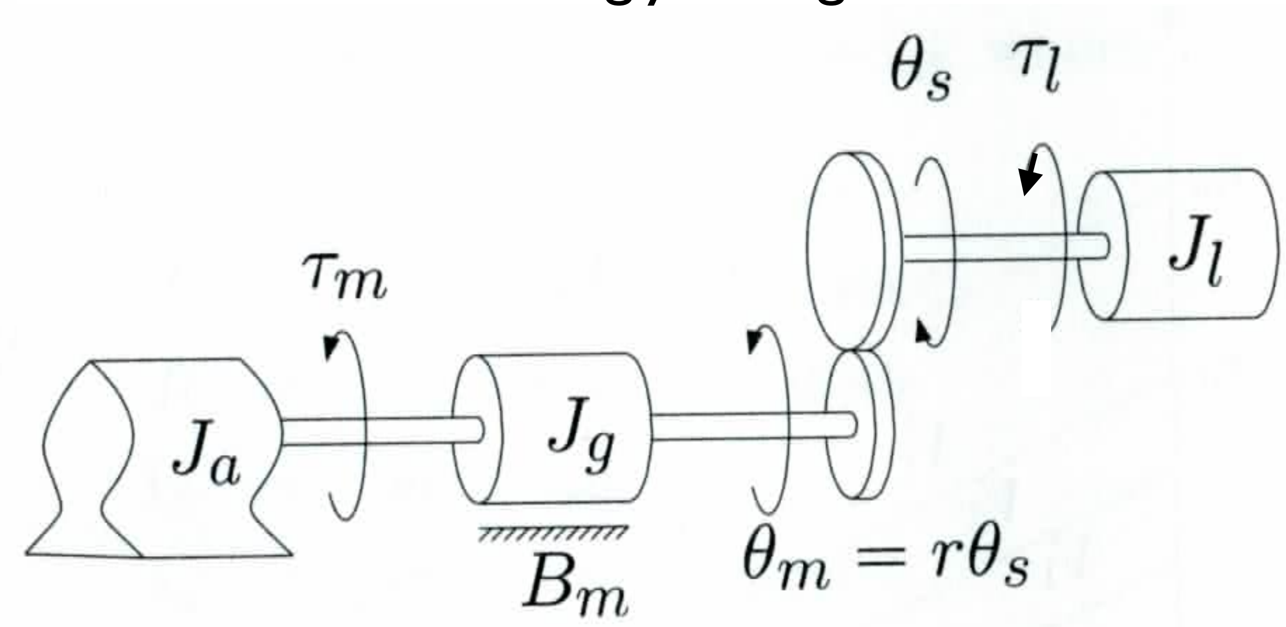
Speed Torque Teeth Radius

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"



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

$$\tau_m = k_t\, i_a$$

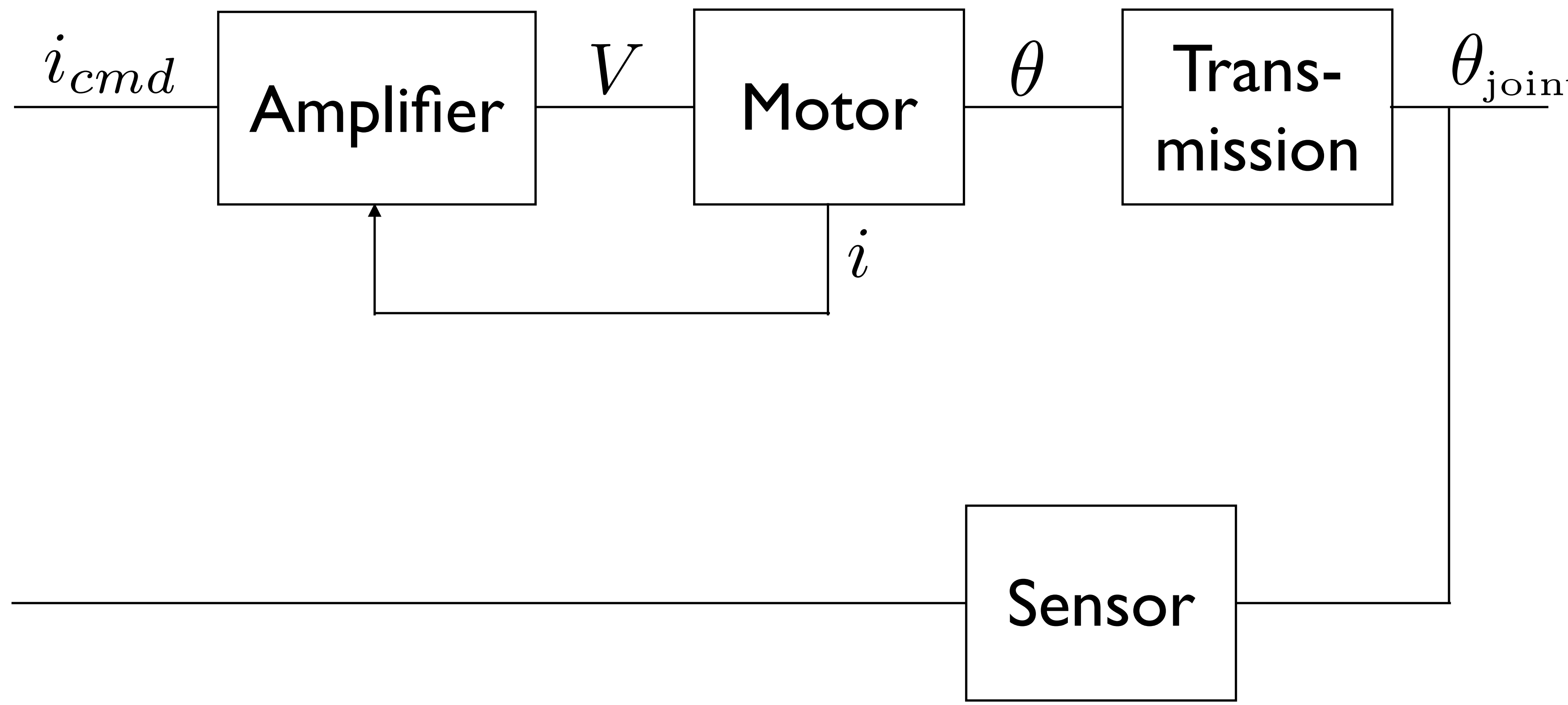
gearhead inertia

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

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.


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

A Biological Inspiration

Mechanical Structure

Bones	Frame / Links
Joints	Joints

Actuators

Muscles	Electric Motors
	Hydraulics
	Pneumatics
	SMA, etc.

Sensors

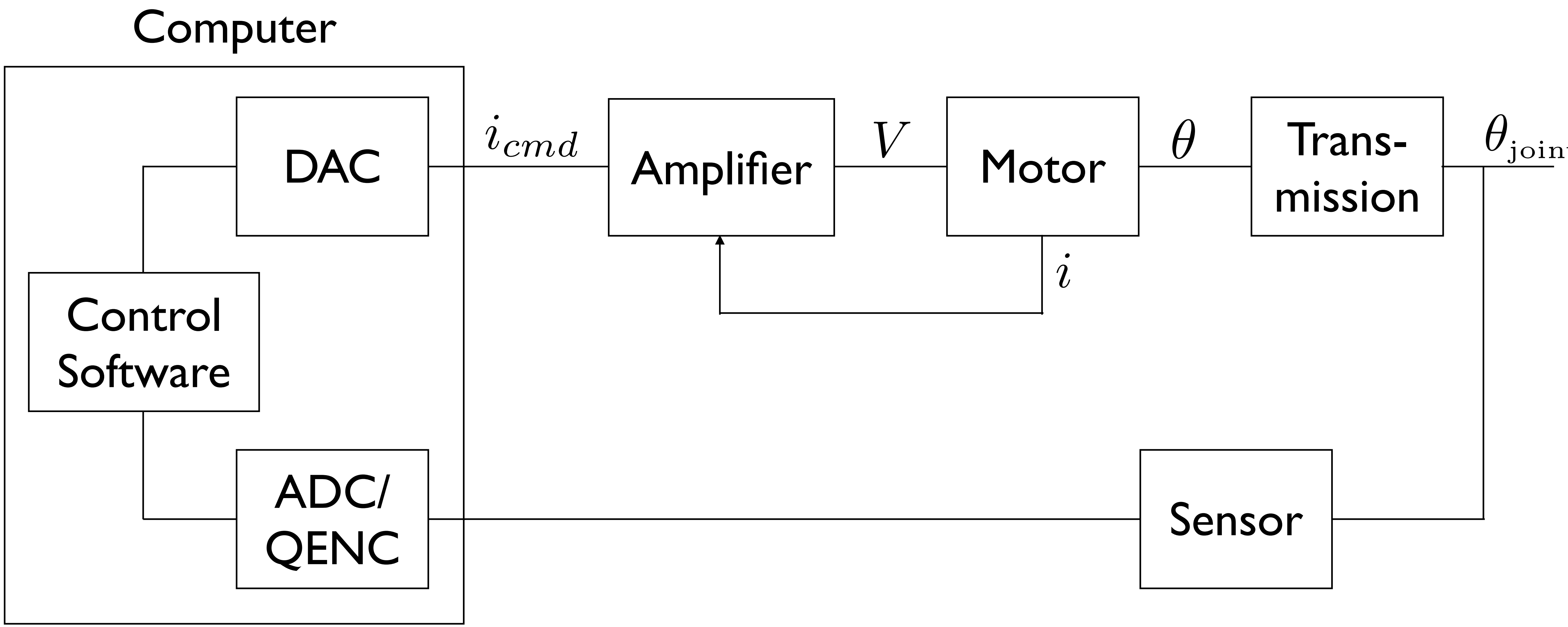
Kinesthetic	Encoders
Tactile	Load Cells
Vision	Vision
Vestibular	Accelerometers

Controller

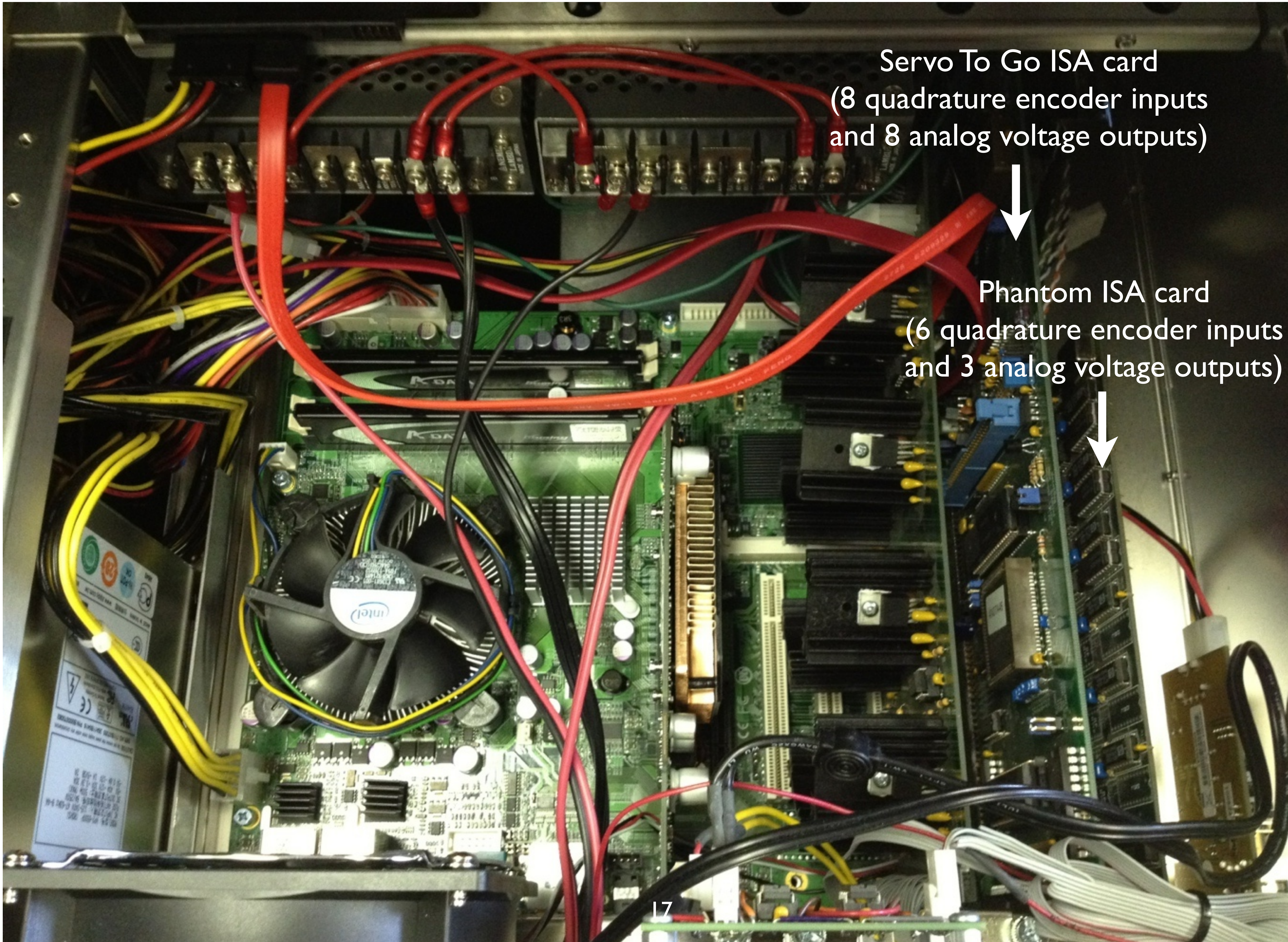
Brain	Computer
Spinal Cord Reflex	Local feedback

Computer

- Runs a servo loop at a fixed rate, often 1000 Hz
- Electrically connects to your hardware through an ISA card, PCI card, Firewire cable, USB cable, or other.
- At each iteration, samples all of the sensors, computes the location of the robot, determines the forces and torques that should be exerted in response, and sends appropriate current commands to all of the system's actuators.
- We are going to hold off on talking about control architectures so that we can get started on IK.


Computer
DAC
Control Software
ADC/ QENC
i_{cmd}
Amplifier
V
Motor
i
θ
Trans-mission
θ_{joint}
Sensor

inside the PUMA 260 controller



Elements of Haptic Interfaces
and Other High-Performance Robots

Katherine J. Kuchenbecker
Department of Mechanical Engineering and Applied Mechanics
University of Pennsylvania
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Course Notes for MEAM 520, University of Pennsylvania
Adapted from Section 3.1 of Professor Kuchenbecker's Ph.D. thesis [3].

A haptic interface plays the important role of connecting the user to the controller during interactions with remote and virtual objects. Such systems incorporate mechanical, electrical, and computational elements, which all interact to create the touch-based sensations experienced by the user. This document is concerned specifically with actuated impedance-type interfaces, which currently dominate the field due to their excellent free-space characteristics and their widespread use in a variety of applications. During an interaction, the controller of an impedance-type device must measure the user's hand motion and apply an appropriate force in response. Impedance-type haptic interfaces vary in design, but they usually include a series of electrical and mechanical elements between the handle and the computer, as described below. High-performance robotic manipulators intended for use around humans, such as the Barrett WAM and the Willow Garage PR2, are often constructed in a similar manner.

Overview

Haptic interfaces typically provide two or three degrees of freedom in position, sensing the user's motion and applying feedback forces within this workspace. Many devices also permit changes in the orientation of the end effector; these rotational degrees of freedom can be unsensed, sensed but not actuated, or sensed and actuated. The remainder of this discussion will focus on translation rather than orientation, although the described design features can be applied to either.

Figure 1 illustrates the chain of elements typically present in each axis of a haptic interface. For clarity, the illustration depicts a device with a single degree of freedom, but typical systems combine several degrees of freedom in parallel or series to allow unrestricted translation and/or orientation. Although differences exist, individual position axes of most mechanisms can be represented by such an arrangement. The terms "haptic interface" and "master" are often used

This document explains how impedance-type haptic interfaces and high-performance robot arms are designed.

Homework 8: Input/Output Calculations for the Phantom Robot

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

November 12, 2013

This assignment is due on **Tuesday, November 19, by midnight (11:59:59 p.m.)**. You should aim to turn the paper part in during class that day. If you don't finish before class, you can turn the paper part in to the bin outside Professor Kuchenbecker's office, Towne 224. Your code should be submitted via email according to the instructions at the end of this document. Late submissions will be accepted until Thursday, November 21, by midnight (11:59:59 p.m.), but they will be penalized by 10% for each partial or full day late, up to 20%. 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 team. 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!

Individual vs. Pair Programming

You may do this assignment either individually or with a partner. If you do this homework with a partner, you may work with anyone in the class. If you are in a pair, you should work closely with your partner throughout this assignment, following the paradigm of pair programming. You will turn in one paper assignment and one set of MATLAB files for which you are both jointly responsible, and you will both receive the same grade. Please follow the pair programming guidelines that have been shared before, and name your files with both of your PennKeys separated by an underscore character. Do not split the assignment in half; both of you should understand all steps of this assignment.

SensAble Phantom Premium 1.0

This entire assignment is focused on a particular robot – the SensAble Phantom Premium 1.0. As shown in the photo below, the Phantom is an impedance-type haptic interface with three actuated rotational joints. Designed to be lightweight, stiff, smooth, and easily backdrivable, this type of robotic device enables a human user to interact with a virtual environment or control the movement of a remote robot through the movement of their fingertip while simultaneously feeling force feedback.

1

Homework 8

Due by midnight on Tuesday, November 19.

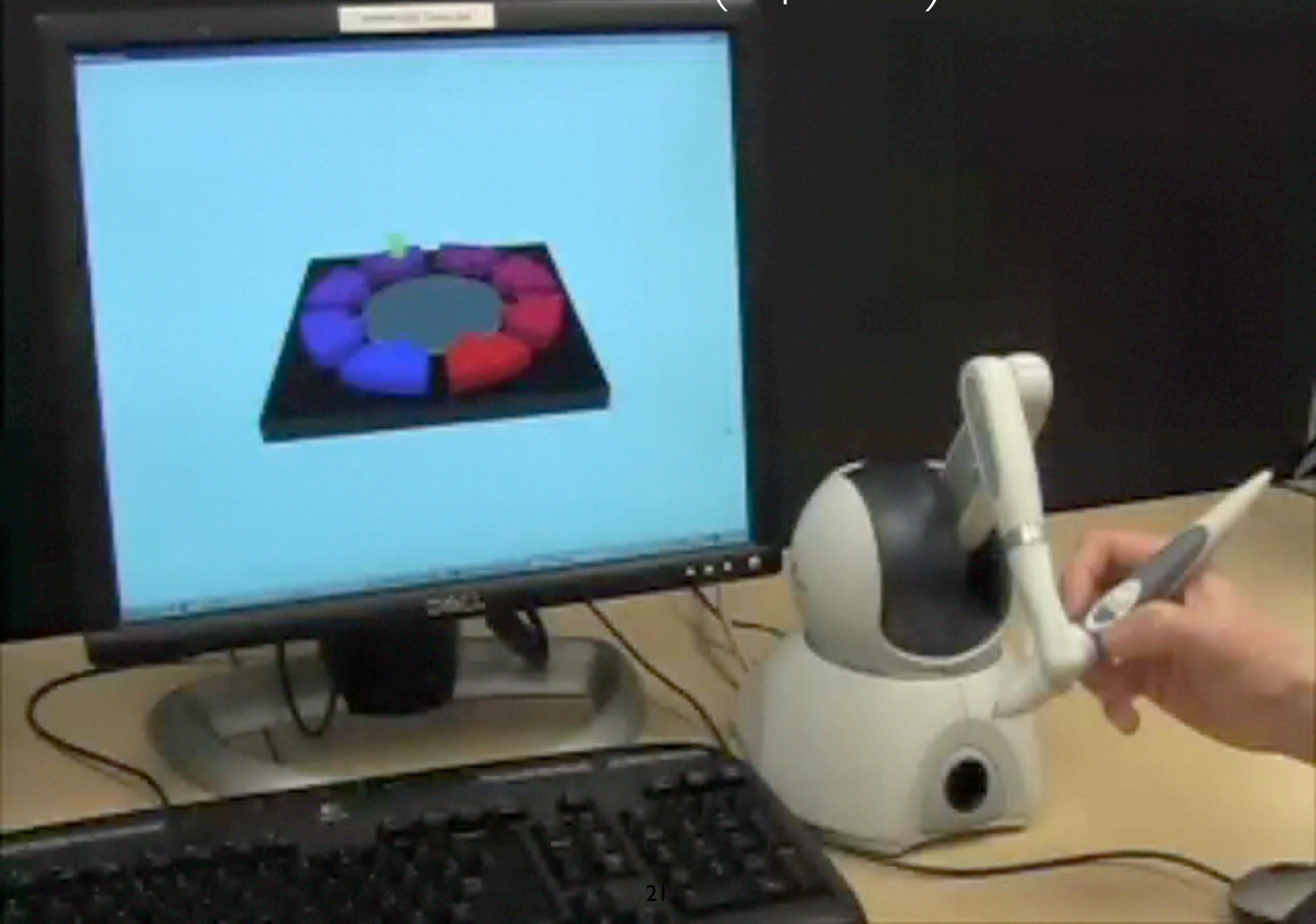
Has both written and MATLAB parts.

Done individually or with any partner.

All about the SensAble Phantom Premium 1.0

SensAble Phantom Premium 1.0 (~$25,000)

A SensAble Phantom Omni (~$2500)



MEAM 520 | Class Profile | Piazza

https://piazza.com/upenn/fall2013/meam520/resources

Reader

Google

Homework (10 out of 19 resources displayed)

Homework	Due Date	Actions
phantom_files.zip	Nov 19, 2013	Edit Post a note Delete
hw08.pdf	Nov 19, 2013	Edit Post a note Delete
dh_kuchenbe.m	Nov 3, 2013	Edit Post a note Delete
plot_puma_starter.m	Nov 3, 2013	Edit Post a note Delete
analyze_puma_starter.m	Nov 3, 2013	Edit Post a note Delete
hw07.pdf	Nov 3, 2013	Edit Post a note Delete
hw06.pdf	Oct 27, 2013	Edit Post a note Delete
pumadancesim_v2.zip	Oct 20, 2013	Edit Post a note Delete
puma_motions.zip	Oct 1, 2013	Edit Post a note Delete
hw05.pdf	Oct 1, 2013	Edit Post a note Delete

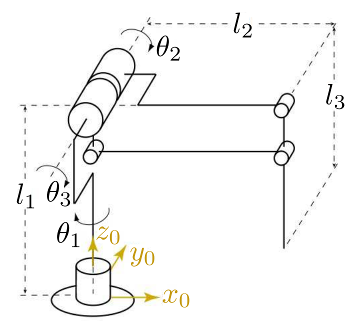
Show all resources

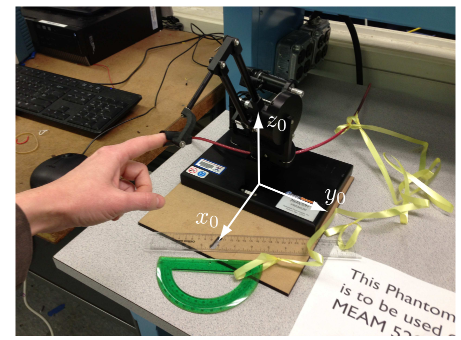
Add Links Add Files

General Resources

General Resources	Actions
midterm_resubmission.pdf	Edit Post a note Delete

A thimble is attached to the tip of the robot via a passive non-encoded three-axis gimbal to allow the user to move the robot around while freely rotating their fingertip. As shown in the diagram below left, the Phantom haptic device looks similar to the standard RRR articulated manipulator base, but it uses a unique four-bar mechanism to co-locate the shoulder and elbow joints while also keeping the upper arm and forearm in the plane that intersects the axis of the waist joint.





As shown in the photo above right, a Phantom is available on a table on the left side of the GM Lab (Towne 193) for you to look at. Many students in this class already have card-swipe access to the GM Lab; the door to this room is often open, or someone inside can let you in. Note that you do not need to connect the Phantom to a computer for any part of this assignment. You should just examine the Phantom to understand how it works and measure any parameters you need. A ruler and a protractor are available at the robot; please leave them attached to the robot's security cable.

Each of the five questions below includes both a written explanation and the programming of a specific MATLAB function. For the paper parts, write in pencil, show your work clearly, $\boxed{\text{box your answers}}$, and staple your pages together. For the programming, download the starter code from the assignment resources section on Piazza, change all function and file names to include your team's PennKeys, comment your code, and follow the instructions at the end of this document to submit all of your MATLAB files.

1. **From Encoder Counts to Joint Angles**

   Imagine your boss bought this robot on eBay and has asked you to get it working. Each of the Phantom's motors includes a shaft-mounted HEDM-5500-B02 optical encoder. The data sheet for this family of encoders is available as `HEDM-5500.pdf` inside the zip file `phantom_files.zip` under assignment resources on Piazza. Drum-and-capstan cable drives are used to connect the motors to the respective joints.

   After figuring out the wiring, imagine you connected all three of the Phantom's incremental optical encoders to a quadrature encoder input card on your computer. You zeroed all of the encoders when the device was in the configuration shown in the schematic above, where the upper arm is horizontal, the lower arm is vertical, and the tip is located above the x_0-axis. This is the Phantom's zero configuration. Our Phantom sits on a board that includes a cut-out into which you can place the gimbal for more repeatable zeroing.

   As you played with the Phantom, you noticed that the encoder counts increase when each joint is rotated in the direction indicated on the schematic. You decide you will use these positive directions for your joint angles as well. You then moved the robot through an interesting trajectory (writing the word "phantom" in cursive in the horizontal plane; the text is written along a straight line that is parallel to the y_0-axis) and recorded the triplets of encoder count values $[Q_1 \;\; Q_2 \;\; Q_3]^T$ that occurred at 206 points along the way. This list of values is provided with the starter code as `phantom_encoder_counts.txt` and is automatically loaded into the `phantom_robot_yourpennkeys.m` script.

Where is the MEAM 520 Phantom?

CyberCafé between Towne and Levine


EXIT
Go under the platform


Go back here

293 Towne

Go inside the GM Lab


SensAble Phantom
Premium 1.0
Go down the left aisle


Don't steal the measuring tools.
Or the Phantom.
phantom
This Phantom robot is to be used only by MEAM 520 students.
Questions?
Contact Professor Kuchenbecker at kuchenbe@seas.upenn.edu

Editor – /Users/kuchenbe/Documents/teaching/meam 520/assignments/08 phantom/phantom_files/phantom_robot_starter.m

EDITOR PUBLISH VIEW

phantom_robot_starter.m

```
%% phantom_robot_starter.m
%
% This Matlab script provides the main starter code for the Phantom robot
% on Homework 8 in MEAM 520 at the University of Pennsylvania.
%
% The original was written by Professor Katherine J. Kuchenbecker. Students
% will modify this code to create their own script. Post questions on the
% class's Piazza forum.
%
% Change the name of this file to replace "starter" with your PennKey(s).


%% SETUP

% Clear all variables from the workspace.
clear all

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

% Input your names and PennKeys as strings.
studentNames = 'PUT YOUR NAMES HERE';
yourpennkeys = 'starter'; % Replace starter with your PennKey or PennKeys.

% Create function names for four main functions bassed on your PennKeys.
f1 = ['@phantom_counts_to_angles_' yourpennkeys];
phantom_counts_to_angles = eval(f1);
f2 = ['@phantom_angles_to_positions_' yourpennkeys];
phantom_angles_to_positions = eval(f2);
f3 = ['@phantom_force_to_torques_' yourpennkeys];
phantom_force_to_torques = eval(f3);
f4 = ['@phantom_torques_to_voltages_' yourpennkeys];
phantom_torques_to_voltages = eval(f4);

% Set whether to animate the robot's movement and how much to slow it down.
pause on; % Set this to off if you don't want to watch the animation.
GraphingTimeDelay = 0.001; % The length of time that Matlab should pause between positions when graphing

% Set the amount by which to scale forces for the plot.
force_scale = 50; % mm/N

```

script Ln 29 Col 40

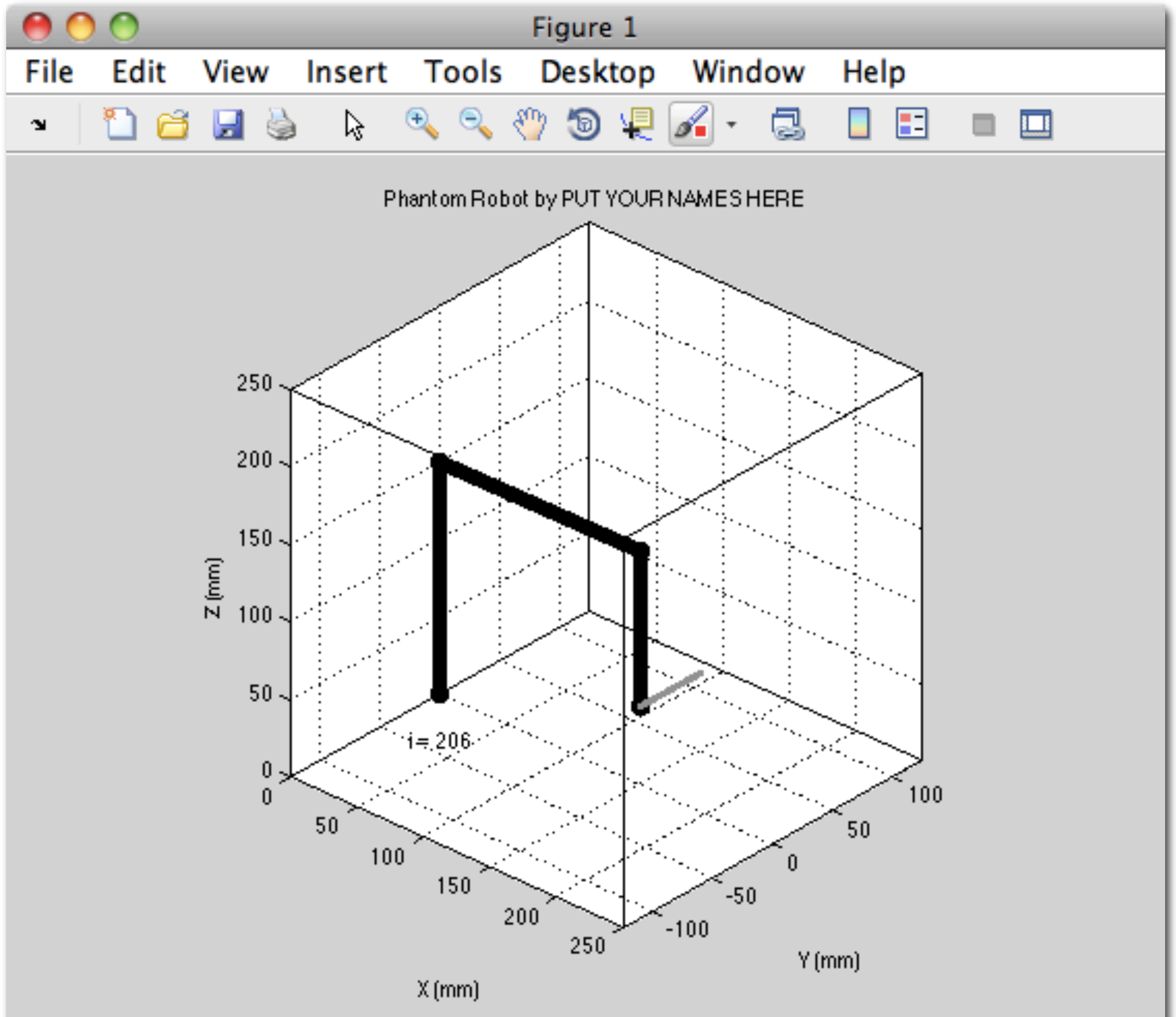


Figure 1
File Edit View Insert Tools Desktop Window Help
Phantom Robot by PUT YOUR NAMES HERE
Z (mm)
X (mm)
Y (mm)
i = 206

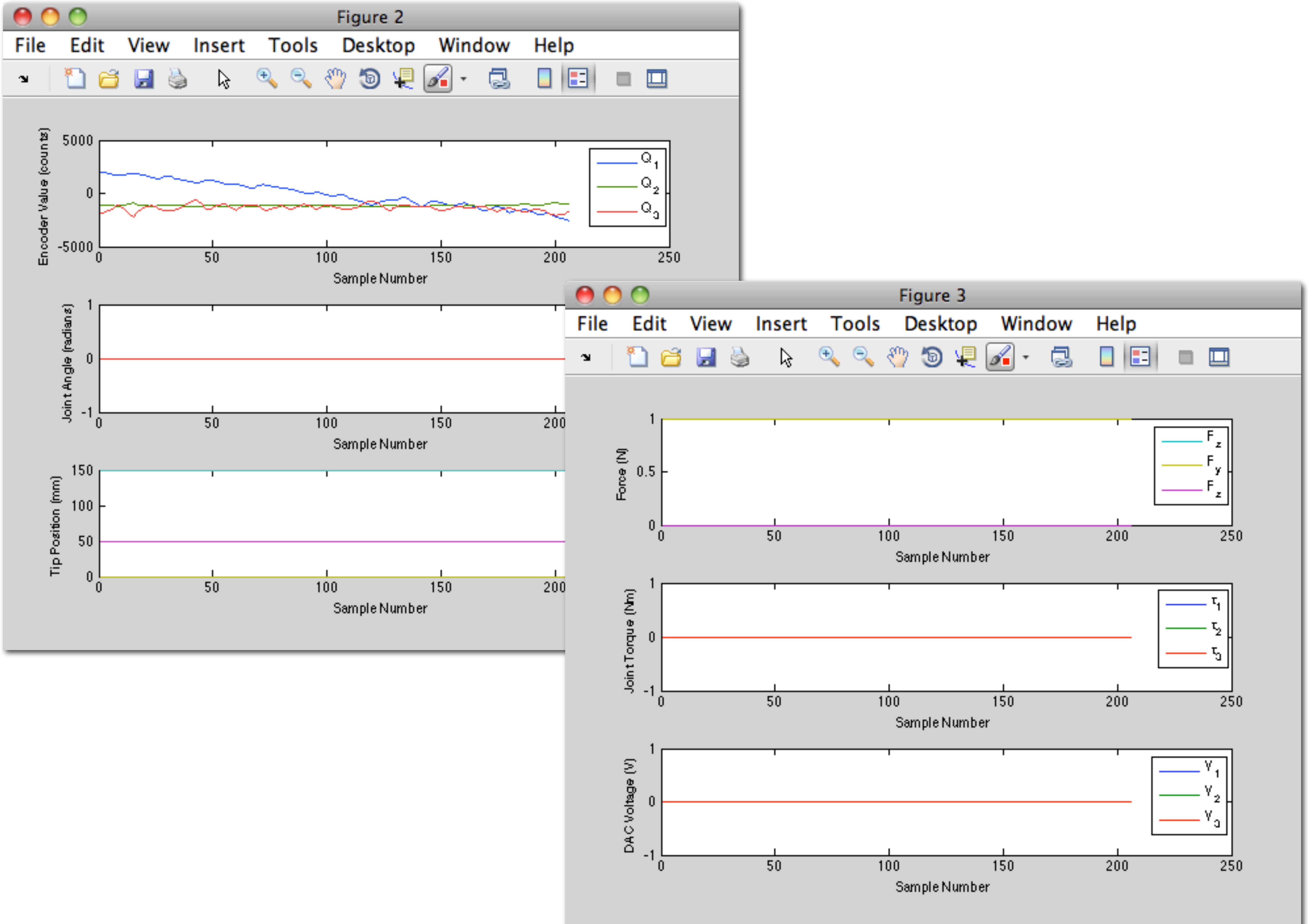


Figure 2
File Edit View Insert Tools Desktop Window Help
Encoder Value (counts)
Sample Number
Joint Angle (radians)
Tip Position (mm)
Figure 3
Force (N)
Joint Torque (Nm)
DAC Voltage (V)

Data Sheets

Agilent Technologies

Quick Assembly Two and Three Channel Optical Encoders

Technical Data

HEDM-550x/560x
HEDS-550x/554x
HEDS-560x/564x

Features

- **Two Channel Quadrature Output with Optional Index Pulse**
- **Quick and Easy Assembly**
- **No Signal Adjustment Required**
- **External Mounting Ears Available**
- **Low Cost**
- **Resolutions Up to 1024 Counts Per Revolution**
- **Small Size**
- **-40°C to 100°C Operating Temperature**
- **TTL Compatible**
- **Single 5 V Supply**

Description

The HEDS-5500/5540, HEDS-5600/5640, and HEDM-5500/5600 are high performance, low cost, two and three channel optical incremental encoders. These encoders emphasize high reliability, high resolution, and easy assembly.

Each encoder contains a lensed LED source, an integrated circuit with detectors and output circuitry, and a codewheel which rotates between the emitter and detector IC. The outputs of the HEDS-5500/5600 and HEDM-5500/ 5600 are two square waves in quadrature. The HEDS-5540 and 5640 also have a third channel index output in addition to the two channel quadrature. This index output is a 90 electrical degree, high true index pulse which is generated once for each full rotation of the codewheel.

The HEDS series utilizes metal codewheels, while the HEDM series utilizes a film codewheel allowing for resolutions to 1024 CPR. The HEDM series is nont available with a third channel index.

These encoders may be quickly and easily mounted to a motor. For larger diameter motors, the HEDM-5600, and HEDS-5600/ 5640 feature external mounting ears.

The quadrature signals and the index pulse are accessed through five 0.025 inch square pins located on 0.1 inch centers.

Standard resolutions between 96 and 1024 counts per revolution are presently available. Consult local Agilent sales representatives for other resolutions.

Applications

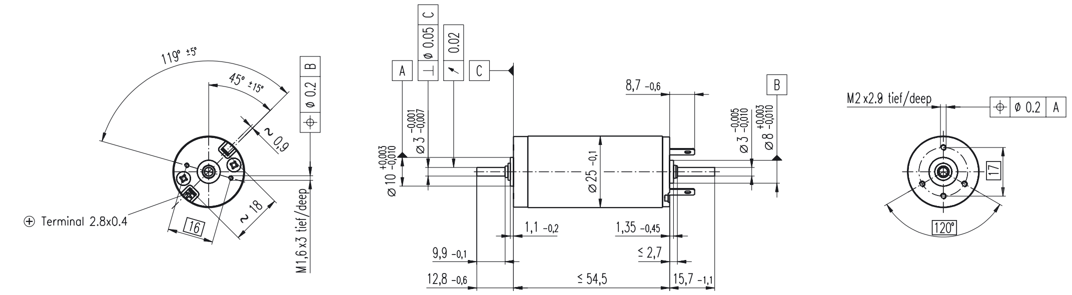
The HEDS-5500, 5540, 5600, 5640, and the HEDM-5500, 5600 provide motion detection at a low cost, making them ideal for high volume applications. Typical applications include printers, plotters, tape drives, positioning tables, and automatic handlers.

Note: Agilent Technologies encoders are not recommended for use in safety critical applications. Eg. ABS braking systems, power steering, life support systems and critical care medical equipment. Please contact sales representative if more clarification is needed.

ESD WARNING: NORMAL HANDLING PRECAUTIONS SHOULD BE TAKEN TO AVOID STATIC DISCHARGE.

RE 25 ∅25 mm, Precious Metal Brushes CLL, 10 Watt, CE approved

maxon DC motor



M 1:2

Stock program
Standard program
Special program (on request!)

Order Number

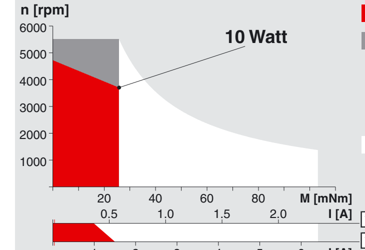
Motor Data		Unit	118740	118741	118742	118743	118744	118745	118746	118747	118748
1	Assigned power rating	W	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
2	Nominal voltage	Volt	4.5	8.0	9.0	12.0	15.0	18.0	24.0	32.0	48.0
3	No load speed	rpm	5370	5330	5240	4860	4990	4790	5200	5530	5090
4	Stall torque	mNm	131	132	119	129	131	126	136	144	132
5	Speed / torque gradient	rpm / mNm	41.1	40.6	44.2	37.9	38.4	38.4	38.4	38.6	38.7
6	No load current	mA	80	45	39	26	22	17	14	12	7
7	Starting current	mA	16500	9230	7310	5500	4570	3520	3100	2610	1470
8	Terminal resistance	Ohm	0.273	0.867	1.23	2.18	3.28	5.11	7.73	12.3	32.6
9	Max. permissible speed	rpm	5500	5500	5500	5500	5500	5500	5500	5500	5500
10	Max. continuous current	mA	1500	1500	1500	1250	1020	815	662	526	322
11	Max. continuous torque	mNm	12.0	21.4	24.5	29.3	29.1	29.1	29.0	28.9	28.9
12	Max. power output at nominal voltage	mW	18400	18300	16300	16400	17000	15700	18500	20700	17500
13	Max. efficiency	%	87	87	86	87	87	87	87	87	87
14	Torque constant	mNm / A	7.97	14.3	16.3	23.4	28.5	35.7	43.8	55.0	89.7
15	Speed constant	rpm / V	1200	669	585	407	335	268	218	173	106
16	Mechanical time constant	ms	5	4	4	4	4	4	4	4	4
17	Rotor inertia	gcm^2	11.3	10.00	9.11	10.3	10.1	10.1	10.00	9.96	9.91
18	Terminal inductance	mH	0.03	0.09	0.12	0.24	0.35	0.55	0.83	1.31	3.48
19	Thermal resistance housing-ambient	K / W	14	14	14	14	14	14	14	14	14
20	Thermal resistance rotor-housing	K / W	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
21	Thermal time constant winding	s	13	11	10	12	12	12	12	11	11

Specifications

- Axial play 0.05 - 0.15 mm
- Max. ball bearing loads
  axial (dynamic)
  not preloaded 3.2 N
  preloaded 3.2 N
  radial (5 mm from flange) 16 N
  Force for press fits (static) 64 N
  (static, shaft supported) 270 N
- Radial play ball bearing 0.025 mm
- Ambient temperature range -20 ... +85°C
- Max. rotor temperature +100°C
- Number of commutator segments 11
- Weight of motor 130 g
- 2 pole permanent magnet
- Values listed in the table are nominal. For applicable tolerances see page 43. For additional details please use the maxon selection program on the enclosed CD-ROM.
- CLL = Capacitor Long Life

Operating Range

Comments Details on page 49



Recommended operating range

Continuous operation
In observation of above listed thermal resistances (lines 19 and 20) the maximum permissible rotor temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

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

118748 Motor with high resistance winding
118740 Motor with low resistance winding

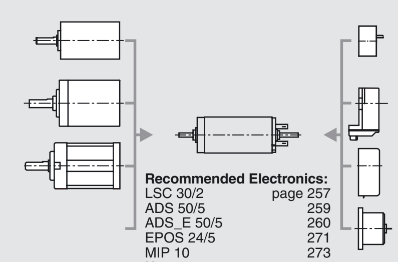
maxon Modular System

Overview on page 17 - 21

Planetary Gearhead
∅26 mm
0.5 - 2.0 Nm
Details page 216

Planetary Gearhead
∅32 mm
0.75 - 6.0 Nm
Details page 218 / 220

Planetary Gearhead
∅32 mm
0.4 - 2.0 Nm
Details page 222



Recommended Electronics:

LSC 30/2	page 257
ADS 50/5	259
ADS_E 50/5	260
EPOS 24/5	271
MIP 10	273
Notes	**17**

Encoder MR
128 - 1000 CPT,
3 channels
Details page 238

Encoder Enc
∅22 mm
100 CPT, 2 channels
Details page 240

Encoder HED_ 5540
500 CPT,
3 channels
Details page 242 / 244

DC-Tacho DCT
∅22 mm
0.52 V
Details page 252

Editor – /Users/kuchenbe/Documents/teaching/meam 520/assignments/08 phantom/phantom_files/simulate_motor_starter.m

EDITOR PUBLISH VIEW

simulate_motor_starter.m

```
%% simulate_motor_starter.m
%
% This Matlab script provides the main starter code for the motor
% simulation on Homework 8 in MEAM 520 at the University of Pennsylvania.
%
% The original was written by Professor Katherine J. Kuchenbecker. Students
% will modify this code to create their own script. Post questions on the
% class's Piazza forum.
%
% Change the name of this file to replace "starter" with your PennKey(s).


%% SETUP

% Clear all variables from the workspace.
clear all

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

% Input your names.
studentNames = 'PUT YOUR NAMES HERE';


%% Parameters
% Set parameters of the system we want to simulate, noting units.
% Make them global so that the compute derivatives function can see them.
global Vperiod Vpulse
Vperiod = 0.5; % s, period of the pulse waveform being applied to the motor.
Vpulse = 12; % V, voltage of the pulse waveform being applied to the motor.


%% Time
% Define the simulation's start time, end time, and maximum time step.
tstart = 0;
tfinal = 1;
tstepmax = 0.001; % Maximum time step, in seconds.

% Set the time step for the graphical display to control playback speed.
graphical_tstep = 0.001; % s

```

script Ln 30 Col 10

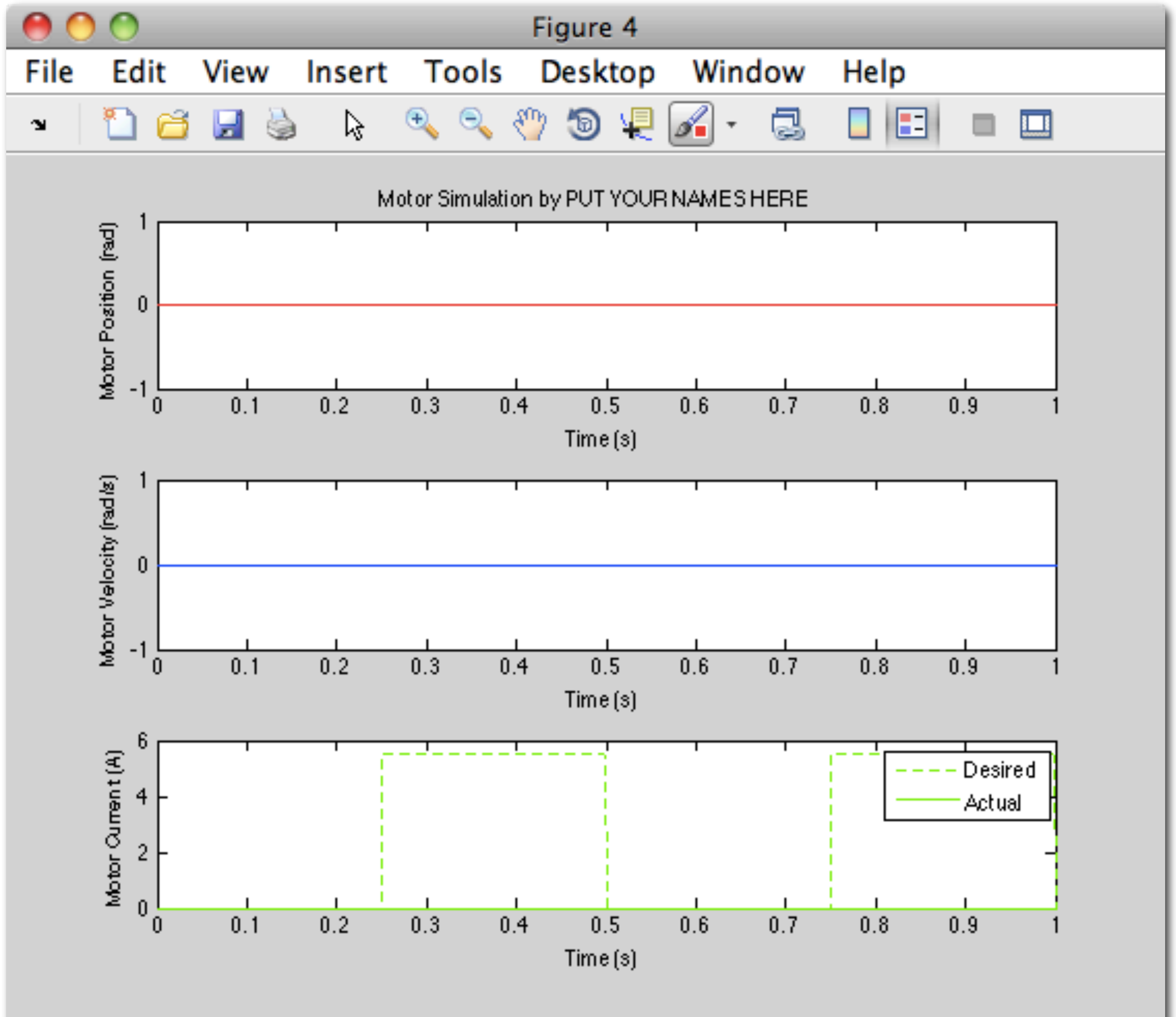


Figure 4
File Edit View Insert Tools Desktop Window Help
Motor Simulation by PUT YOUR NAMES HERE
Motor Position (rad)
Time (s)
Motor Velocity (rad/s)
Time (s)
Motor Current (A)
Desired
Actual
Time (s)

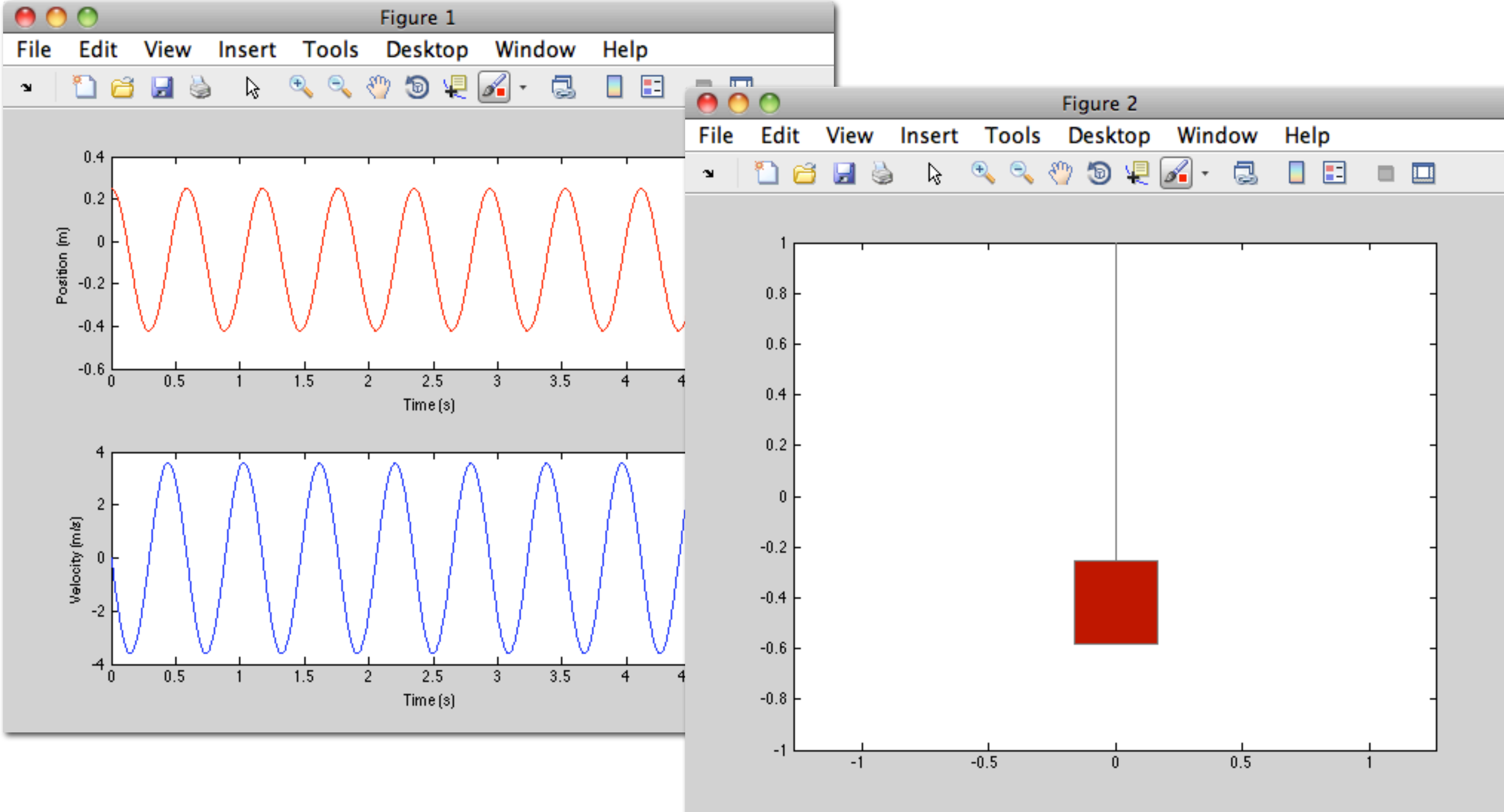
Editor – /Users/kuchenbe/Documents/teaching/meam 520/lectures/20 ik/robotics20ik_code/simulate_mass_on_a_spring.m

EDITOR PUBLISH VIEW

simulate_mass_on_a_spring.m compute_mass_derivatives.m

```matlab
%% Simulate a mass bouncing on a spring using ode45
% Class example for MEAM 520 on November 12, 2013 by KJK.

close all
clear;

%% Parameters
% Set parameters of the system we want to simulate, noting units.
% Make them global so that the compute derivatives function can see them.
global m k g
m = 3.5; % kg
k = 400; % N/m
g = 9.81; % m/s^2

%% Time
% Define the simulation's start time, end time, and maximum time step.
tstart = 0;
tfinal = 5;
tstepmax = 0.01; % Maximum time step, in seconds.

% Set the time step for the graphical display to control playback speed.
graphical_tstep = 0.01; % s

%% Initial Conditions
% Define the initial conditions for the mass.
y0 = .25; % m
v0 = 0; % m/s

% Put initial conditions into vector.
X0 = [y0; v0];

%% Simulation
% Show a message to explain how to cancel the graph.
disp('Click in this window and press control-c to cancel simulation or graphing if it is taking too lon

% Run the simulation using ode45.
% The state equation function must be in the same directory as this script
% for Matlab to find it.  The @ makes the name a function handle, so ode45
% can call it over and over.  The other two inputs are the time span and
% the initial condition5s.  The outputs are the resulting time vector (nx1)
% and the resulting state vector (nx4).
```

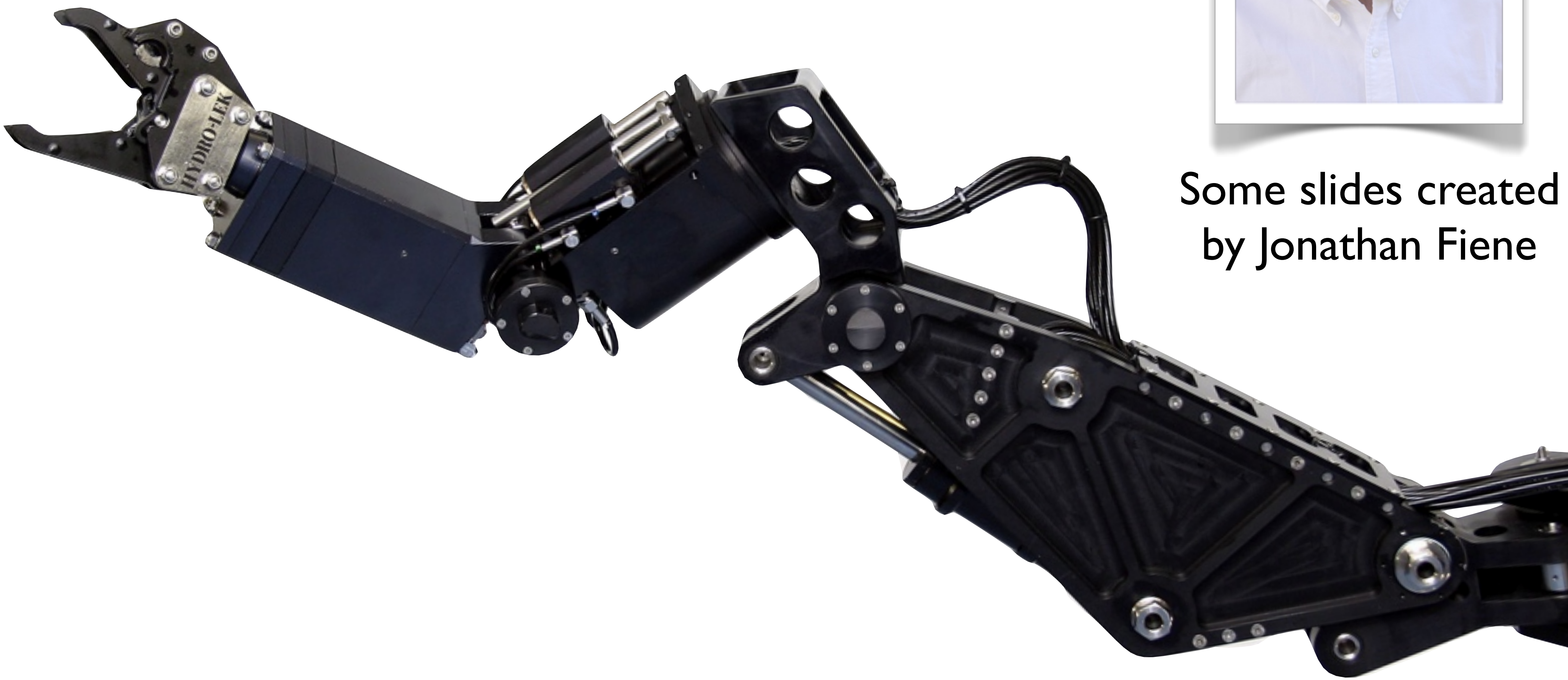
script Ln 31 Col 1

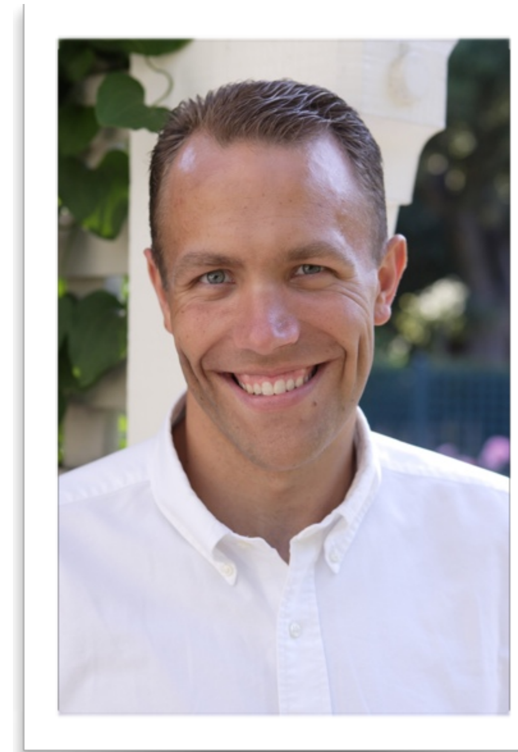


Define state variables
Write calculate derivatives function
Use ode45 to integrate

What questions do you have about Homework 8?

Inverse Kinematics





Some slides created by Jonathan Fiene

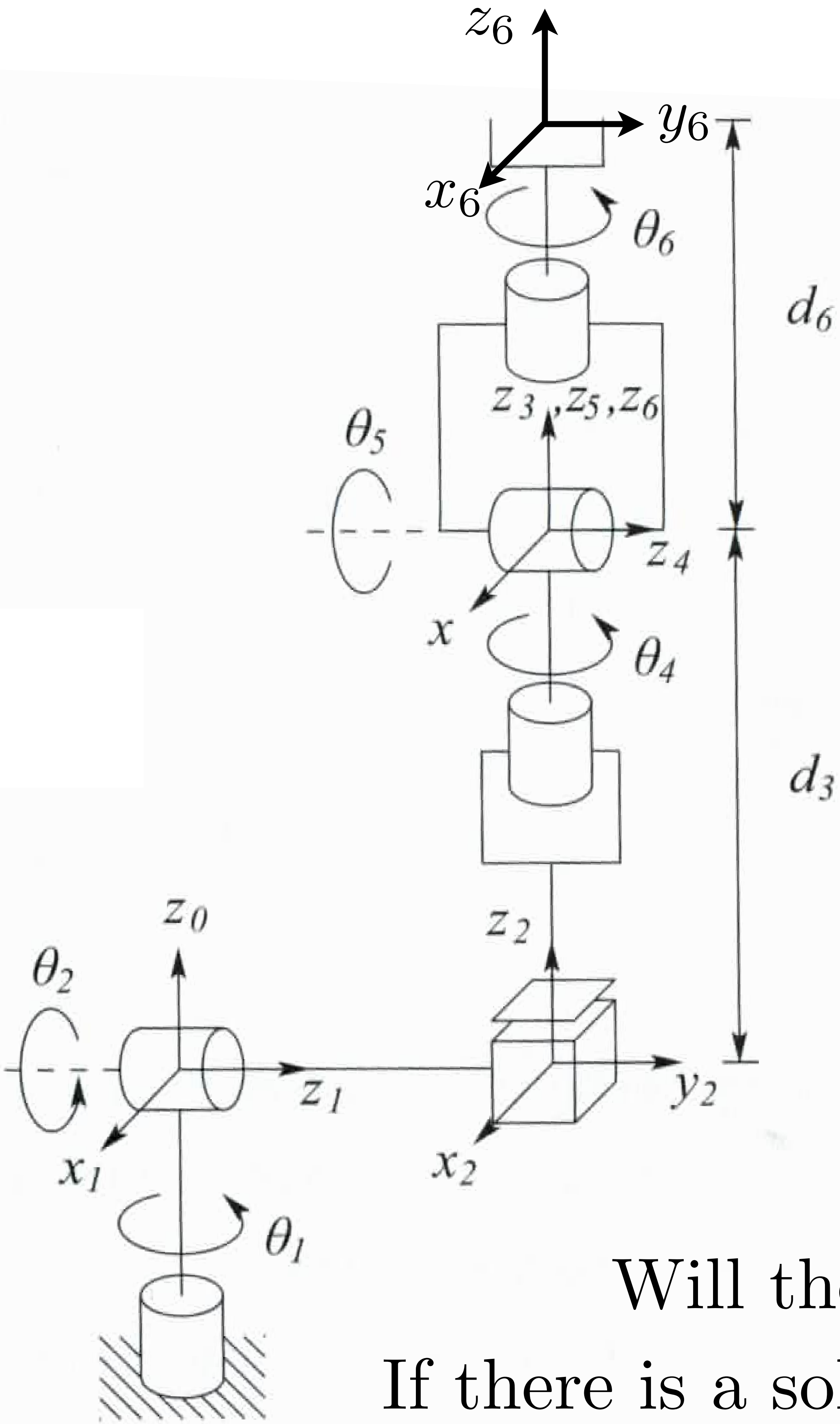
$$\text{given } \mathbf{H} = \begin{bmatrix} \mathbf{R} & o \\ 0 & 1 \end{bmatrix}$$

and a certain manipulator with n joints

find $q_1, \ldots, q_n$ such that $\mathbf{T}_n^0(q_1, \ldots, q_n) = \mathbf{H}$

This yields 12 nonlinear equations in n unknown variables.

Yuck.



$$T_6^0 = A_1 \cdots A_6 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & d_x \\ r_{21} & r_{22} & r_{23} & d_y \\ r_{31} & r_{32} & r_{33} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

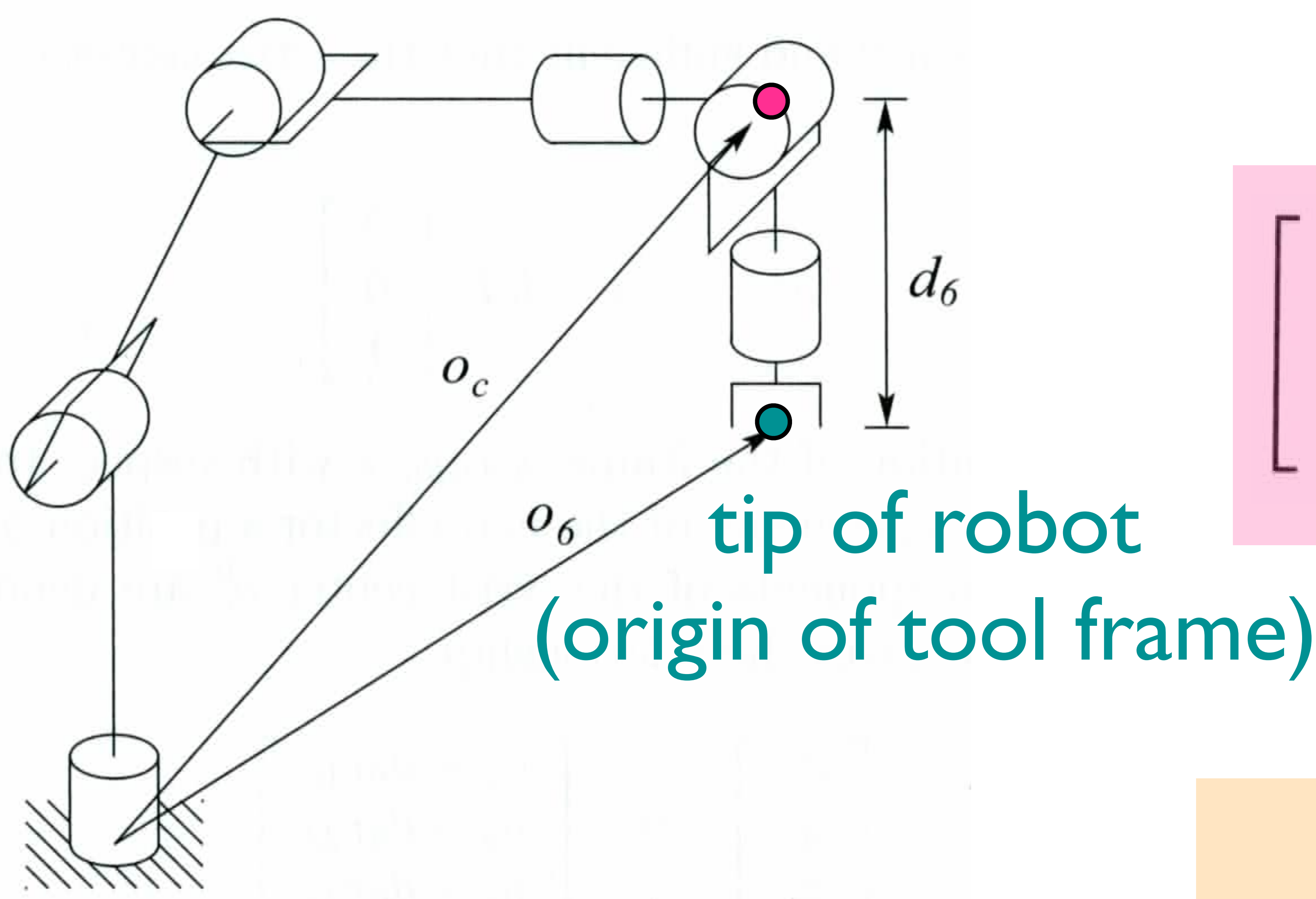
in which

$$\begin{aligned}
r_{11} &= c_1[c_2(c_4c_5c_6 - s_4s_6) - s_2s_5c_6] - d_2(s_4c_5c_6 + c_4s_6) \\
r_{21} &= s_1[c_2(c_4c_5c_6 - s_4s_6) - s_2s_5c_6] + c_1(s_4c_5c_6 + c_4s_6) \\
r_{31} &= -s_2(c_4c_5c_6 - s_4s_6) - c_2s_5c_6 \\
r_{12} &= c_1[-c_2(c_4c_5s_6 + s_4c_6) + s_2s_5s_6] - s_1(-s_4c_5s_6 + c_4c_6) \\
r_{22} &= -s_1[-c_2(c_4c_5s_6 + s_4c_6) + s_2s_5s_6] + c_1(-s_4c_5s_6 + c_4c_6) \\
r_{32} &= s_2(c_4c_5s_6 + s_4c_6) + c_2s_5s_6 \\
r_{13} &= c_1(c_2c_4s_5 + s_2c_5) - s_1s_4s_5 \\
r_{23} &= s_1(c_2c_4s_5 + s_2c_5) + c_1s_4s_5 \\
r_{33} &= -s_2c_4s_5 + c_2c_5 \\
d_x &= c_1s_2d_3 - s_1d_2 + +d_6(c_1c_2c_4s_5 + c_1c_5s_2 - s_1s_4s_5) \\
d_y &= s_1s_2d_3 + c_1d_2 + d_6(c_1s_4s_5 + c_2c_4s_1s_5 + c_5s_1s_2) \\
d_z &= c_2d_3 + d_6(c_2c_5 - c_4s_2s_5)
\end{aligned}$$

Will there always be a solution? No.

If there is a solution, will it always be unique? No.

A helpful approach for 6-DOF robots: Kinematic Decoupling



$$o = o_c^0 + d_6 R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \begin{bmatrix} o_x - d_6 r_{13} \\ o_y - d_6 r_{23} \\ o_z - d_6 r_{33} \end{bmatrix}$$

position

$$R = R_3^0 R_6^3$$

$$R_6^3 = (R_3^0)^{-1} R = (R_3^0)^T R$$

orientation

Questions ❓