MEAM 520
Lecture 18: Jacobians and Forces

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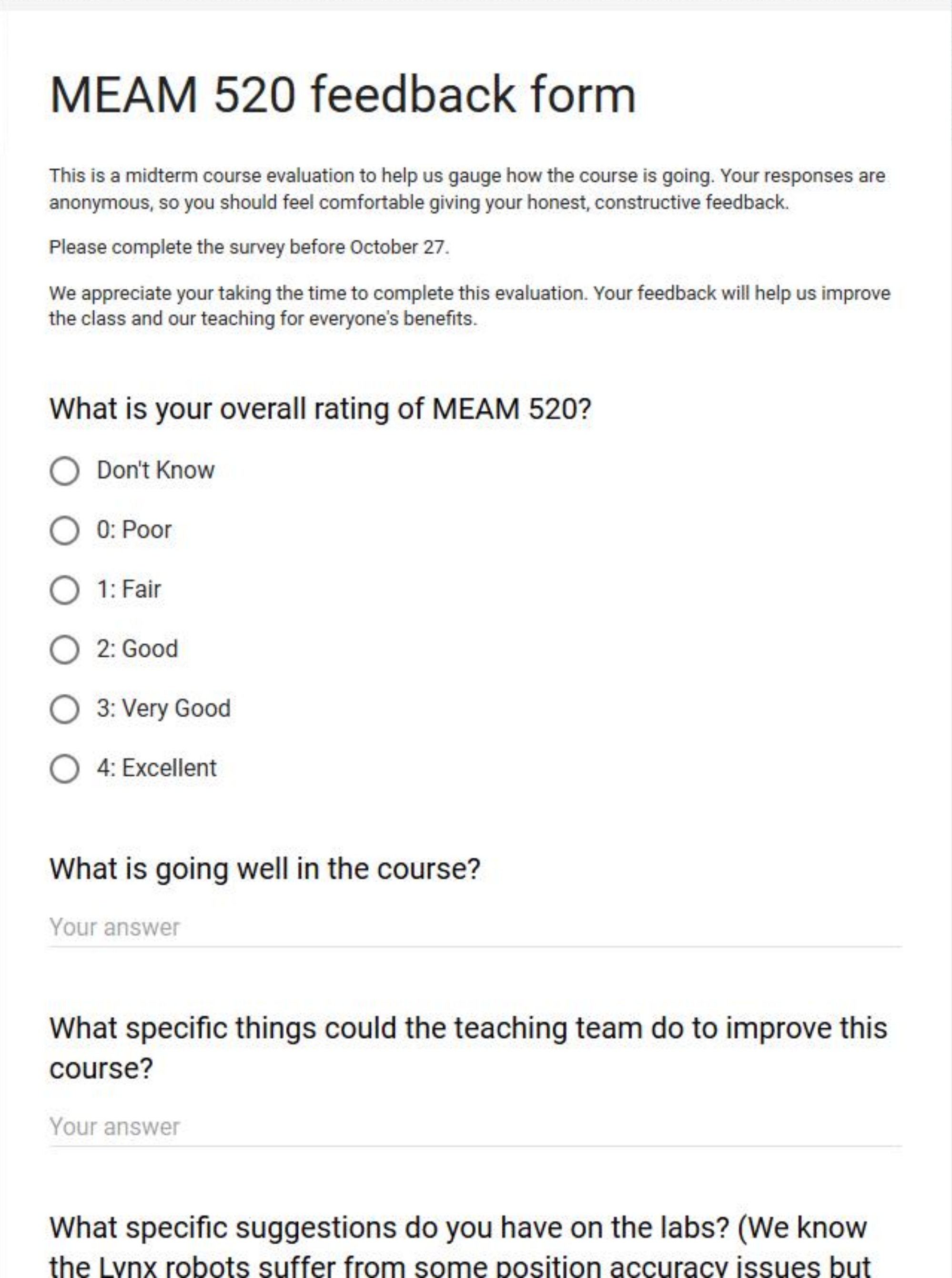
Robotics-Relevant Courses Spring 2019 (Adv Reg 10/29-11/11)

MEAM 516: Advanced Mechatronic Reactive Spaces (Mark Yim)
MEAM 545: Aerodynamics (Bruce Kothmann)
MEAM 620: Advanced Robotics (Kostas Daniliidis)
ESE 619: Model Predictive Control (Manfred Morari)
ESE 650: Learning in Robotics, requires machine learning experience (TBA)
CIS 519: Intro to Machine Learning (Eric Eaton)
CIS 520: Machine Learning (Shivani Agarwal)
CIS 580: Machine Perception (Kostas Daniilidis)
CIS 610: Advanced Geometric Methods (Jean Henri Gallier)
BE 521: Brain-Computer Interfaces, with recitation (Brian Litt)
IPD 501: Integrated Computer-Aided Design (Mark Yim)
IPD 515: Product Design (Karl Ulrich)
EAS 545: Engineering Entrepreneurship I (Jeffrey Babin Vanesa Chan, Thomas Cassel)
ENM 511: Foundations of Engineering Math II (Michael Carchidi)
ENM 521: Principles & Techniques of Applied Math II (Pedro Ponte-Castaneda)



MEAM 520 feedback form

This is a midterm course evaluation to help us gauge how the course is going. Your responses are anonymous, so you should feel comfortable giving your honest, constructive feedback.

Please complete the survey before October 27.

We appreciate your taking the time to complete this evaluation. Your feedback will help us improve the class and our teaching for everyone's benefits.

What is your overall rating of MEAM 520?

- Don't Know
- 0: Poor
- 1: Fair
- 2: Good
- 3: Very Good
- 4: Excellent

What is going well in the course?

Your answer

What specific things could the teaching team do to improve this course?

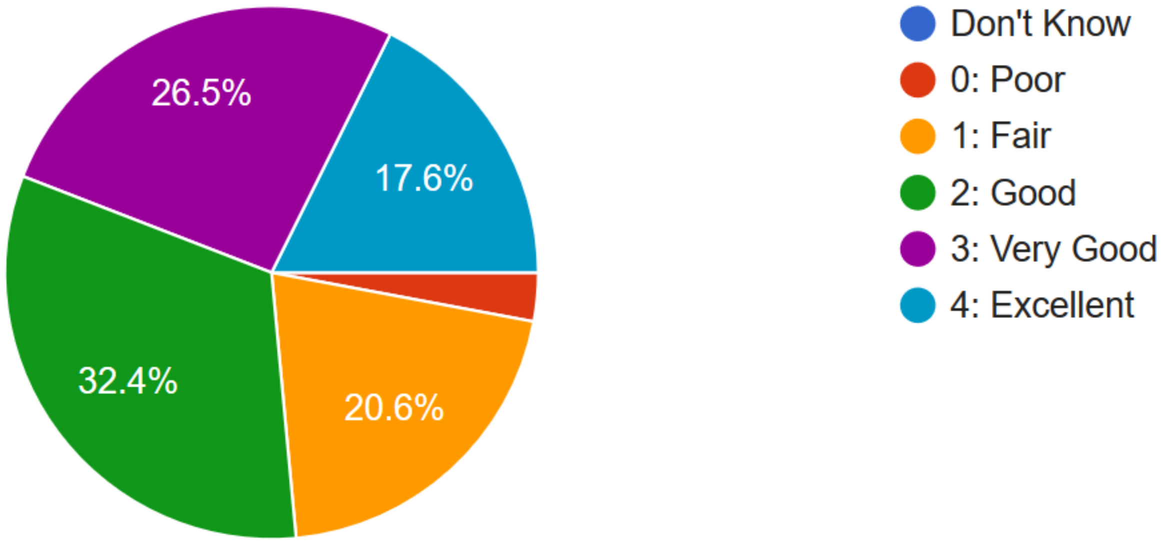
Your answer

What specific suggestions do you have on the labs? (We know the Lynx robots suffer from some position accuracy issues but

Thank you for participating

Overall Rating of MEAM 520

34 Responses (36.2% of class)
Average is 2.40/4.00



What is going well?

Hands on labs!

Clear teaching

Office hours

Group activities

Interesting content

What specific things could be improved?

Labs:

- *Lynx platform – less breaking
- Faster grading
- Robot bookings

Grading scheme

Tips for lab report

MATLAB cheat sheet

Out of everything in this class, the grading scheme is NOT going to change

- **Goal:** In the future, when you have to work with a robot yourself without a TA, you will be able to figure out if what you are doing is working

- **Rules of thumb:**
  - Do everything right but don't know why → B
  - Do everything right and can explain why → A
  - Do things wrong but can explain how it's wrong → B
  - DO NOT: Do things wrong but pretend it's right

- We grade on a 5-pt scale. In order to fail, you have to get lower than a 1/5
- To decrease stress, I will replace your lowest lab grade with your final project

Tips for writing lab reports

1. If you have questions, complaints, confusions, ASK! Don’t be frustrated in silence.
2. Examples posted on Canvas
3. Write the pre-lab as if you were writing the Methods section of the report
4. Start your experiments with a plan. Why are you doing this test? What will new information will it give you? If there is no more information you want to know, stop doing tests!
5. Write the report as you go
6. It is okay to be wrong if you demonstrate good debugging practice

Final Project Proposals due 11/16

Syllabus:

- Open-ended project relevant to course material
- Up to 4 people (more results will be expected of larger groups)
- Equivalent in effort to 1/2 per person

Final Project Proposals due 11/16

Options:

- **Implementation and evaluation** of a method or procedure we learned in class but did not use in lab. This option should have a substantial evaluation and analysis leading to conclusions of when the method works or does not work
- **Literature review** on recent results in an area discussed in class. I would expect you to read and synthesis ≥10 papers.
- **Research project** on a open-ended robotics problem. This is ambitious. I suggest you couple this with a small lit review so you have something to report.

Final Project Proposals due 11/16

Great topics you have brought up during class:

- Apply what we’ve learned to another robot (your choice)
- Alternate representations/procedures for FK/IK that are not D-H
- FK/IK of the parallel manipulator
- Other trajectory planners we haven’t seen in class
- Integrating sensing and online computation into planners
- Kinodynamic planning
- Planning in the presence of noise

Final Project Proposals due 11/16

Possible topics related to future material:

- Extensions of concepts to mobile/aerial/underwater vehicles
- Improve the accuracy of the Lynx controller
- Adaptive or robust control
- Underactuated manipulator arms

Final Project Proposals due 11/16

Q: What do I put in my project proposal?

Your project proposal should have the following information:

- **Goal**: Summarize in 2-3 sentences what you want to accomplish
- **Approach**: Describe in 2-3 sentences what techniques you plan to use
- **Relation to the course**: Explain the relevance to the course material

The project proposal is a completion grade worth 5 pts on Canvas.

Final Project Proposals due 11/16

Q: When is the final project due?

The final project report is officially due on 12/10 (last day of class). Officially, according to university policy, we cannot make it due any later than that. You will all be given a no penalty extension if you wish to submit your final report “late” by 12/12. After that, the standard late penalty of 25%/day applies.

Final Project Proposals due 11/16

Q: How will the grading work?

The final project report is worth 50 pts. The rubric is the same as for labs, but scaled by 2.

The report is limited to 12 pages, single-spaced, Times New Roman 11pt, with 1-in margins, not including references. It is okay to submit <12 pages. If you submit >12 pages, I will only read the first 12.

Completeness Was the project of appropriate scope? Did it address all relevant questions with no obvious holes?	/10
Method Was the approach technically sound and reproducible? Was it complete and free of error or bias?	/10
Evaluation Were all relevant results reported? Are the cases chosen sufficient to demonstrate advantages and limitations?	/10
Analysis Was the analysis complete, free of error, and based on data/observations?	/10
Clarity Was the report clear and organized?	/10

Final Project Proposals due 11/16

Q: I'm taking senior design / MEAM 543 / MEAM 510 / working in X lab. I think it would be cool to take Y concept and apply it to Z robot/device that I'm already working on. Is this okay?

Yes! I support doing a project related to your work outside of MEAM 520. You may want to check in with your other professor/advisor. Drs. Kothmann, Kumar, Posa, Wabiszewski, and Yim are already aware of and support this course of action.

Final Project Proposals due 11/16

Q: But… aren't we using the Lynx for all of our MEAM 520 projects?

The Lynx will be available to you for final projects, but you do **not** have to use it. The Lynx is a convenient platform for us to learn the material in class. If you want to continue to use it, that's great! If you would like to explore how the same concepts can be applied to other platforms, that's a great project, too.

Final Project Proposals due 11/16

Q: Do we have to do the project in a group?

I encourage you to do the project in a group so that you have someone to talk to about the project, but it is not necessary. Obviously, I will expect a project with a larger scope from a pair than from an individual.

Your partner does not have to be in the class, but in this case, your report should highlight the work that **you did** for the project.

Final Project Proposals due 11/16

Q: I have this really cool idea, but I'm afraid it won't work…

Your project is not required to "succeed." The goal here is for you to use the knowledge gained through this course to learn something that you are interested in. Similarly to labs, you should describe what you tried, **evaluate** and **analyze** your results, and draw conclusions based on your data and observations.

Final reports that report "failure" but characterize how and why they failed are as valuable as projects that succeed.

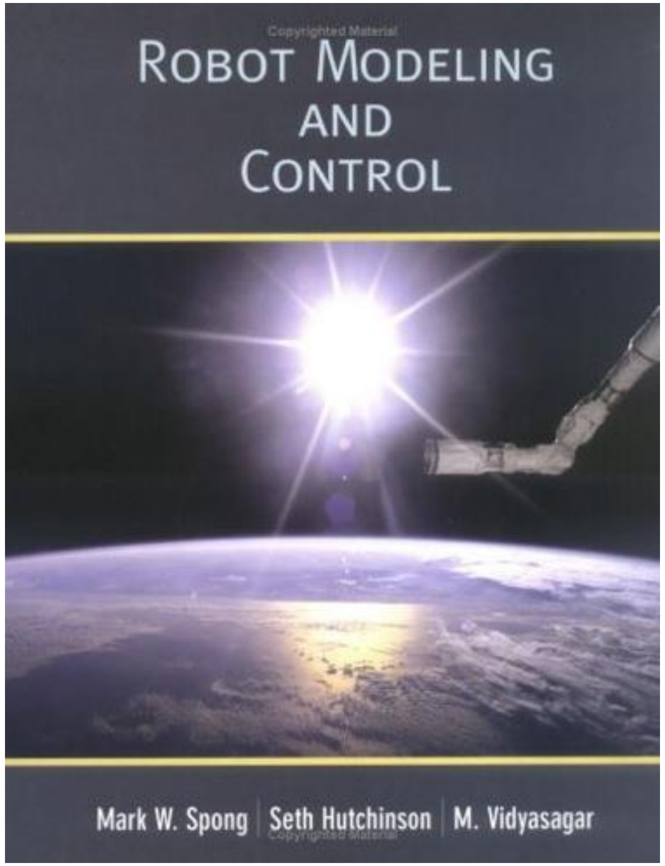
Final Project Proposals due 11/16

Q: Can I talk to you about my proposal?

Of course! Feel free to create a post on Piazza, drop by office hours, or make an appointment.

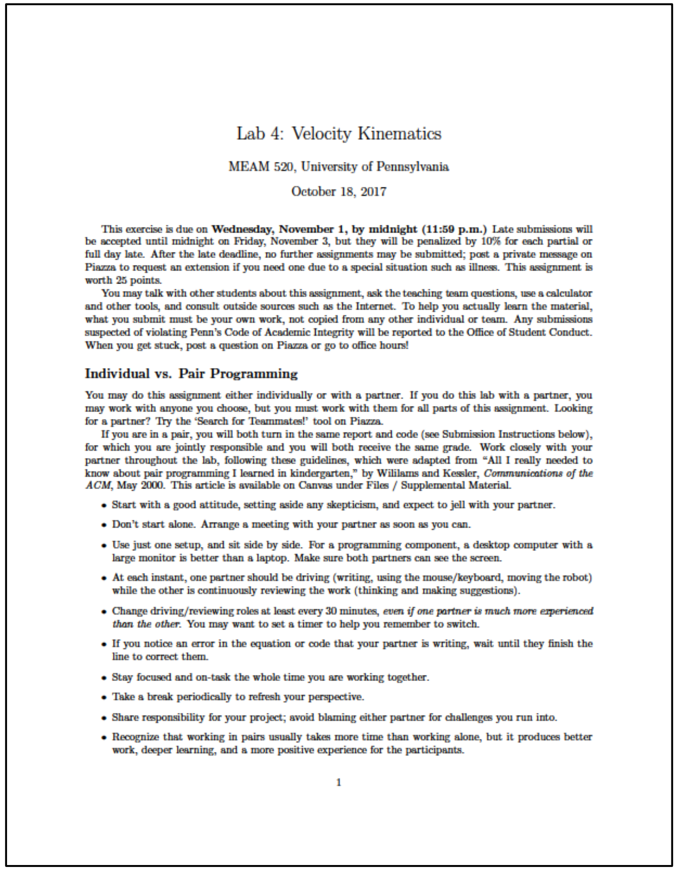
I will open up appointment slots next week until 11/16 (link to be posted).

Today: Jacobians and Forces



Ch 4: Velocity Kinematics – The Jacobian

- Read 4.8-4.13



Lab 4: Velocity Kinematics

MEAM 520, University of Pennsylvania

October 18, 2017

This exercise is due on **Wednesday, November 1, by midnight (11:59 p.m.)** Late submissions will be accepted until midnight on Friday, November 3, but they will be penalized by 10% for each partial or full day late. After the late deadline, no further assignments may be submitted; post a private message on Piazza to request an extension if you need one due to a special situation such as illness. This assignment is worth 25 points.

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 submit 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. When 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 lab with a partner, you may work with anyone you choose, but you must work with them for all parts of this assignment. Looking for a partner? Try the 'Search for Teammates!' tool on Piazza.

If you are in a pair, you will both turn in the same report and code (see Submission Instructions below), for which you are jointly responsible and you will both receive the same grade. Work closely with your partner throughout the lab, following these guidelines, which were adapted from "All I really needed to know about pair programming I learned in kindergarten," by Wililams and Kessler, *Communications of the ACM*, May 2000. This article is available on Canvas under Files / Supplemental Material.

- Start with a good attitude, setting aside any skepticism, and expect to jell with your partner.
- Don't start alone. Arrange a meeting with your partner as soon as you can.
- Use just one setup, and sit side by side. For a programming component, a desktop computer with a large monitor is better than a laptop. Make sure both partners can see the screen.
- At each instant, one partner should be driving (writing, using the mouse/keyboard, moving the robot) while the other is continuously reviewing the work (thinking and making suggestions).
- Change driving/reviewing roles at least every 30 minutes, *even if one partner is much more experienced than the other*. You may want to set a timer to help you remember to switch.
- If you notice an error in the equation or code that your partner is writing, wait until they finish the line to correct them.
- Stay focused and on-task the whole time you are working together.
- Take a break periodically to refresh your perspective.
- Share responsibility for your project; avoid blaming either partner for challenges you run into.
- Recognize that working in pairs usually takes more time than working alone, but it produces better work, deeper learning, and a more positive experience for the participants.

1

Lab 4 due tomorrow

Last Time: Manipulator Jacobian

(3 x n) linear velocity Jacobian

$$J = \begin{bmatrix} J_v \\ J_\omega \end{bmatrix}$$

(3 x n) angular velocity Jacobian

(6 x n) Jacobian
a.k.a. manipulator Jacobian
a.k.a. geometric Jacobian

$$J_v(\vec{q}) = \begin{bmatrix} \frac{\partial x}{\partial q_1} & \frac{\partial x}{\partial q_2} & \cdots & \frac{\partial x}{\partial q_n} \\ \frac{\partial y}{\partial q_1} & \frac{\partial y}{\partial q_2} & \cdots & \frac{\partial y}{\partial q_n} \\ \frac{\partial z}{\partial q_1} & \frac{\partial z}{\partial q_2} & \cdots & \frac{\partial z}{\partial q_n} \end{bmatrix}$$

$$J_\omega = [\rho_1 \hat{\mathbf{z}} \quad \rho_2 \mathbf{R}_1^0 \hat{\mathbf{z}} \quad \rho_3 \mathbf{R}_2^0 \hat{\mathbf{z}} \quad \cdots \quad \rho_n \mathbf{R}_{n-1}^0 \hat{\mathbf{z}}]$$

$\rho_i =$ 0 for prismatic
1 for revolute

forward velocity kinematics

$$\xi = J(q)\dot{q}$$

(6 x 1) body velocity

(6 x n) Jacobian

(n x 1) joint velocities

inverse velocity kinematics

$$\dot{q} = J^{-1}\xi$$

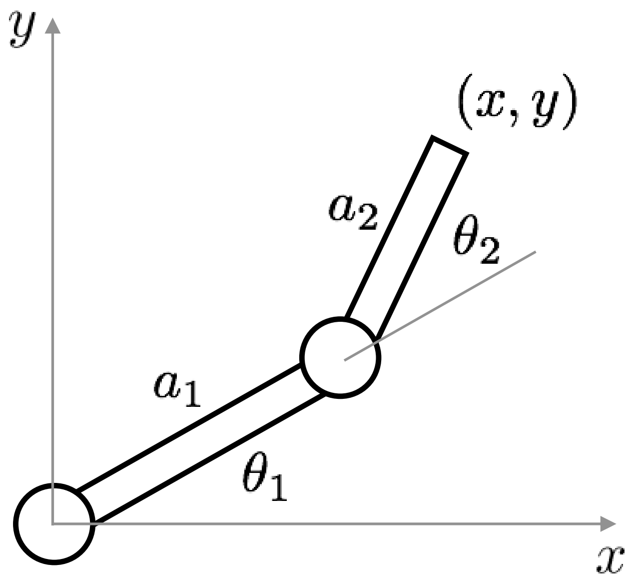
Last Time: Singularities

$$J_{v,\text{planar}}(\vec{q}) = \begin{bmatrix} -a_1 s_1 - a_2 s_{12} & -a_2 s_{12} \\ a_1 c_1 + a_2 c_{12} & a_2 c_{12} \end{bmatrix}$$

$$\det(J_{v,\text{planar}}(\vec{q})) = a_1 a_2 (c_1 s_{12} - s_1 c_{12})$$

$$\det(\mathbf{J}) = 0 \text{ when } \theta_2 = \ldots, -2\pi, -\pi, 0, \pi, 2\pi, \ldots$$

$$\det(\mathbf{J}) = 0 \text{ when } a_1 = 0 \text{ or } a_2 = 0 \; z_3 \text{ can become } || \; z_5$$



$$J_{planar}(q) = \begin{bmatrix} -a_1 s_1 - a_2 s_{12} & -a_2 s_{12} \\ a_1 c_1 + a_2 c_{12} & a_2 c_{12} \\ 0 & 0 \end{bmatrix}$$

rank(J) = 2

Manipulability (SHV 4.12)

For a specific configuration, the Jacobian scales the input (joint velocities) to the output (body velocity)

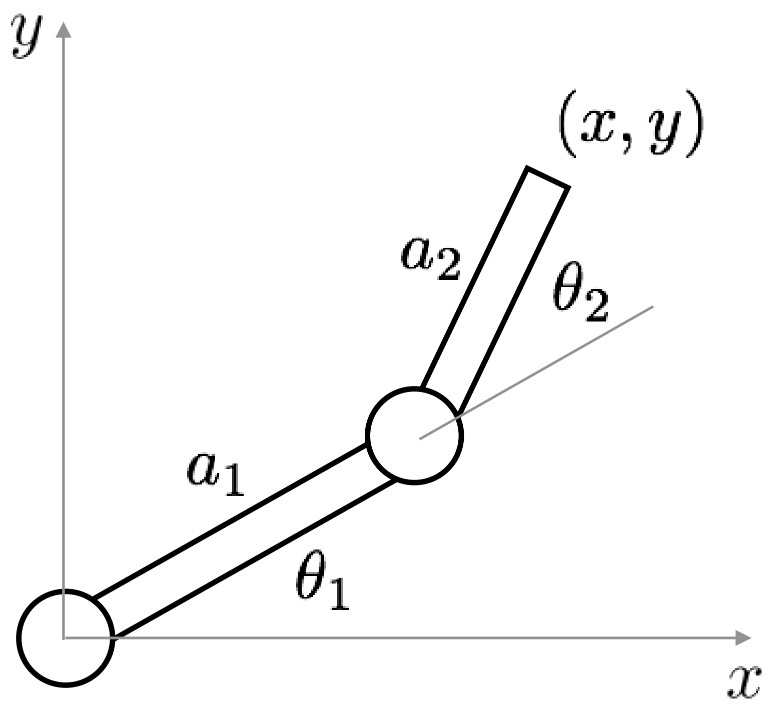
$$\xi = J(q)\dot{q}$$

If you put in a joint velocity vector with unit norm, you can calculate in which direction and how fast the robot's end-effector will translate and rotate.

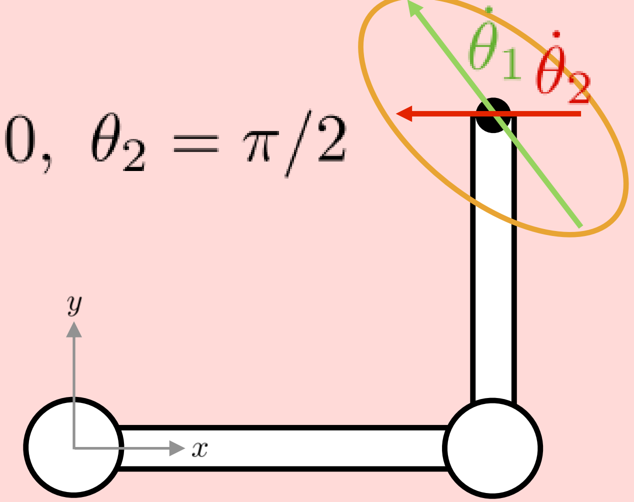
This approach allows you to calculate and plot the manipulability ellipsoid – a geometrical representation of all the possible tip velocities for a normalized joint velocity input.

A 6D ellipsoid is hard to visualize, but 2D and 3D ellipsoids are lovely and useful.

What does the manipulability ellipsoid look like for the planar RR robot?

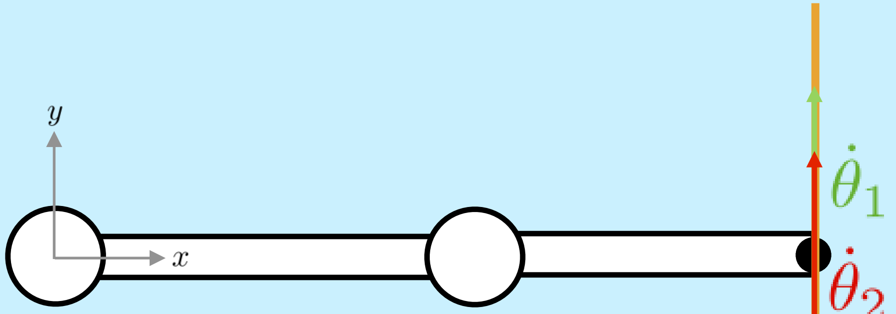


$$\theta_1 = 0,\ \theta_2 = \pi/2$$



$$J_v([0 \quad \pi/2]^T) = \begin{bmatrix} -a_2 & -a_2 \\ a_1 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\theta_1 = 0,\ \theta_2 = 0$$



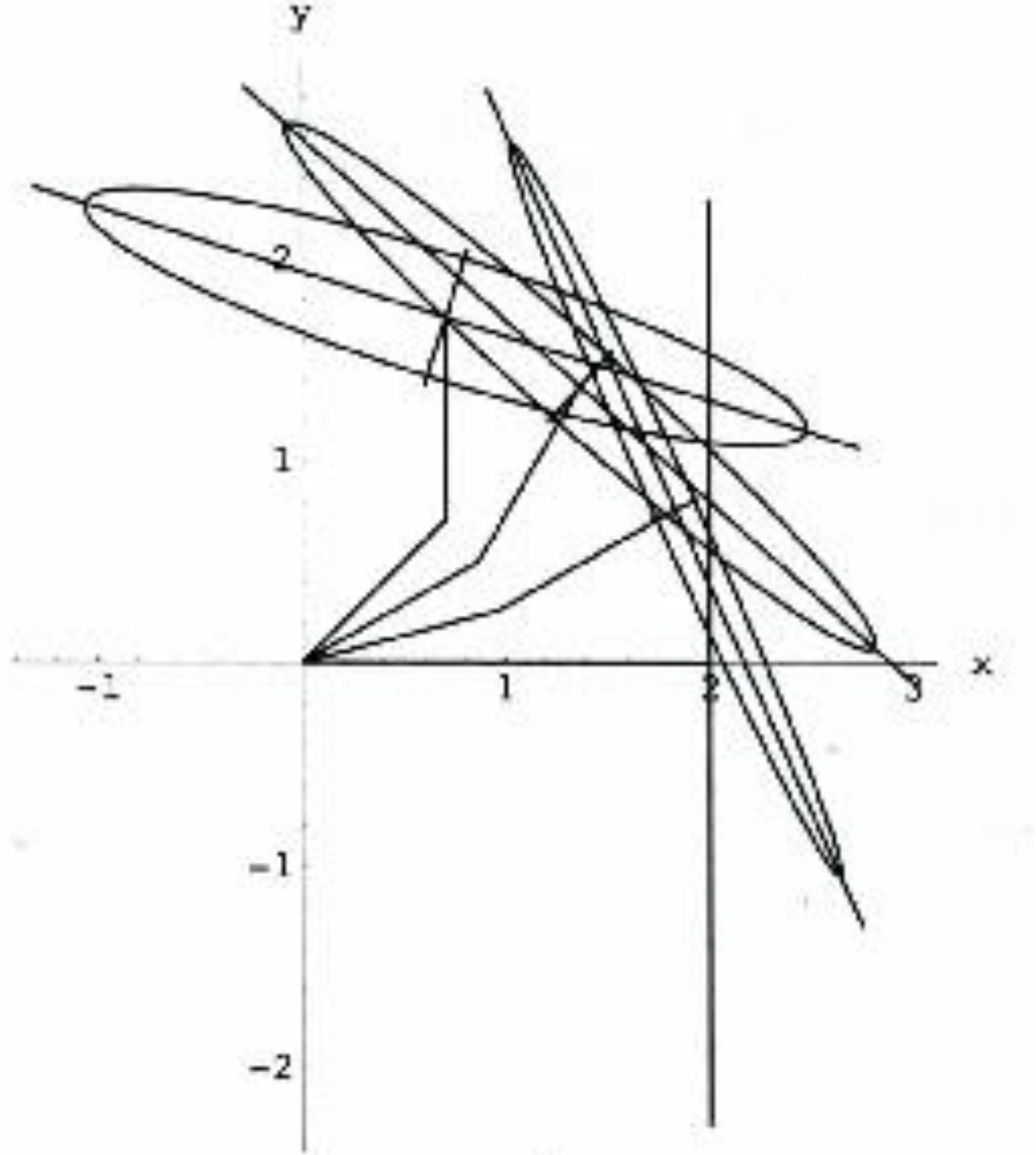
$$J_v([0 \quad 0]^T) = \begin{bmatrix} 0 & 0 \\ a_1 + a_2 & a_2 \\ 0 & 0 \end{bmatrix}$$

$$\dot{\vec{p}} = J_v(\vec{q})\,\dot{\vec{q}}$$

$$\begin{bmatrix} \dot x \\ \dot y \\ \dot z \end{bmatrix} = \begin{bmatrix} \boxed{-a_2\dot\theta_1}\boxed{-\ a_2\dot\theta_2} \\ \boxed{a_1\dot\theta_1} \\ 0 \end{bmatrix}$$

The robot's tip cannot move in the z direction, but it can move in both x and y directions...

$$\begin{bmatrix} \dot x \\ \dot y \\ \dot z \end{bmatrix} = \begin{bmatrix} 0 \\ \boxed{(a_1 + a_2)\dot\theta_1}\boxed{+\ a_2\dot\theta_2} \\ 0 \end{bmatrix}$$



Manipulability

$$\mu = |\det(J)| = a_1 a_2 |\sin(\theta_2)|$$

Can be used to tell you where to perform certain tasks.

Also useful for deciding how to design a manipulator.

Static Force/Torque Relationships

The transpose of the Jacobian relates joint forces and torques
to Cartesian end-effector forces and torques

(n x 1)   (n x 6) (6 x 1)

$$\vec{\tau} = J^T(\vec{q})\vec{F}$$

joint forces and torques

endpoint forces and torques

Jacobian matrix transpose

Simplest to think about for a 3-DOF robot with all revolute joints.
We want to output a force at the tip.

(3 x 1)   (3 x 3) (3 x 1)

$$\vec{\tau} = J^T(\vec{q})\vec{F}$$

joint torques

endpoint forces

Jacobian matrix transpose

Static Force/Torque Relationships

$$\vec{\tau} = J_v^\top \vec{F}$$

This relationship stems from virtual work:
if we assume the arm has no frictional losses or compliance,
we can equate work done at the joints with work done at the
end-effector.

joints $\vec{\tau} \cdot d\vec{q} = \vec{F} \cdot d\vec{x}$ end-effector

$$\dot{\vec{x}} = J_v \dot{\vec{q}}$$

or equivalently

$$\vec{\tau}^\top d\vec{q} = \vec{F}^\top d\vec{x}$$

$$\frac{d\vec{x}}{dt} = J_v \frac{d\vec{q}}{dt}$$

$$\vec{\tau}^\top \cancel{d\vec{q}} = \vec{F}^\top J_v \cancel{d\vec{q}}$$

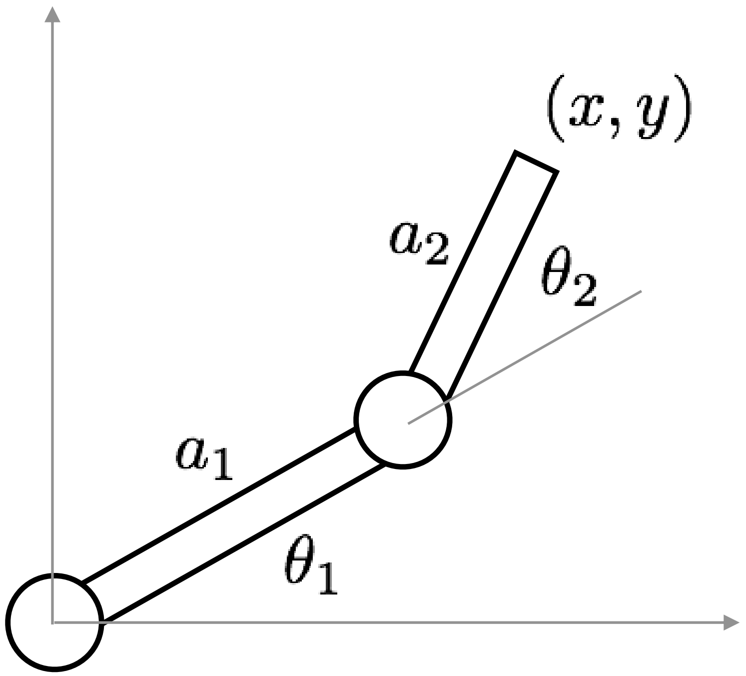
$$\left(\vec{\tau}^\top\right)^\top = \left(\vec{F}^\top J_v\right)^\top$$

$$d\vec{x} = J_v d\vec{q}$$

$$\vec{\tau}^\top = \vec{F}^\top J_v$$

$$\boxed{\vec{\tau} = J_v^\top \vec{F}}$$

Example: Planar RR



Beginning with the 2 x 2 linear velocity Jacobian

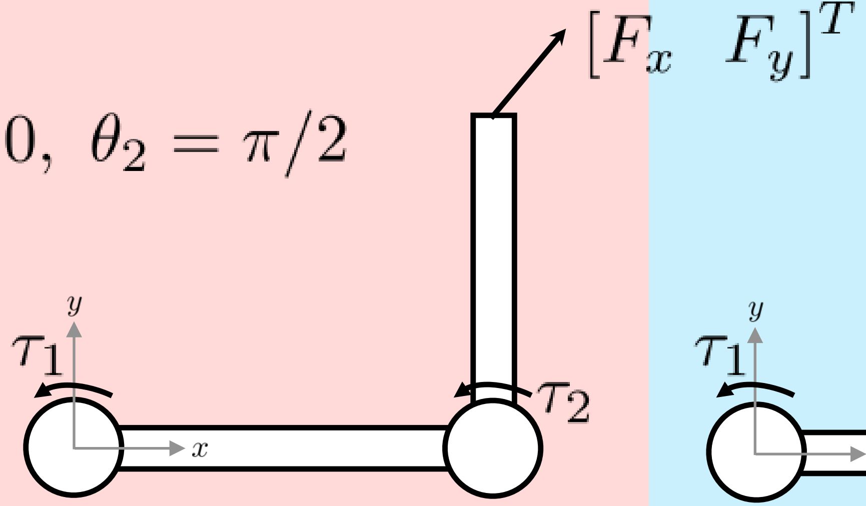
$$J_{v,\text{planar}}(\vec{q}) = \begin{bmatrix} -a_1 s_1 - a_2 s_{12} & -a_2 s_{12} \\ a_1 c_1 + a_2 c_{12} & a_2 c_{12} \end{bmatrix}$$

We can solve for the joint torques necessary to exert a desired force at the end-effector using the Jacobian transpose

$$\vec{\tau} = J_v^\top \vec{F}$$

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} -a_1 s_1 - a_2 s_{12} & a_1 c_1 + a_2 c_{12} \\ -a_2 s_{12} & a_2 c_{12} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix}$$

$$\theta_1 = 0,\ \ \theta_2 = \pi/2$$



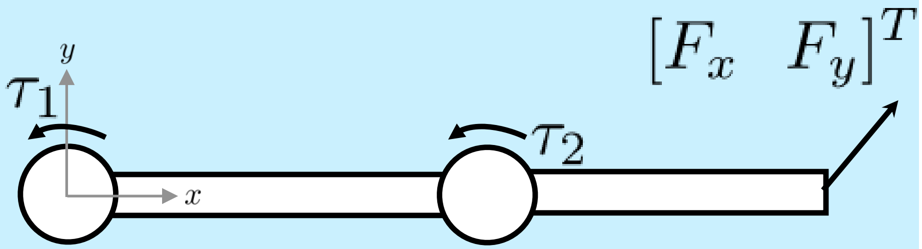
$$J_v([0 \quad \pi/2]^T) = \begin{bmatrix} -a_2 & -a_2 \\ a_1 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\tau_1 = -a_2 F_x + a_1 F_y$$

$$\tau_2 = -a_2 F_x$$

Can create forces in both x and y directions.

$$\theta_1 = 0,\ \theta_2 = 0$$



$$J_v([0 \quad 0]^T) = \begin{bmatrix} 0 & 0 \\ a_1 + a_2 & a_2 \\ 0 & 0 \end{bmatrix}$$

$$\tau_1 = (a_1 + a_2) F_y$$

$$\tau_2 = a_2 F_y$$

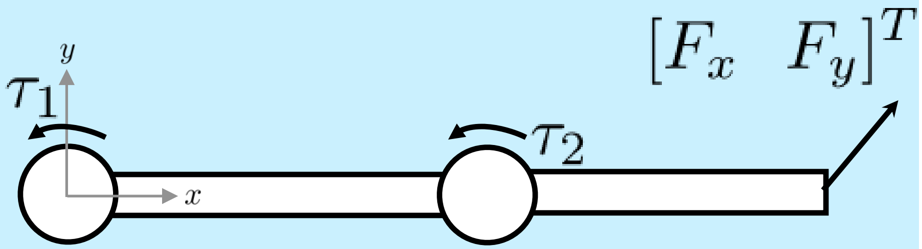
Can’t create forces in the x direction!

At singularities, the manipulator is unable to move in certain directions.

Near singularities, the manipulator can only **actively** apply forces in certain directions.

Q: Can the manipulator apply forces in other directions?

$$\theta_1 = 0,\ \theta_2 = 0$$



$$J_v([0 \quad 0]^T) = \begin{bmatrix} 0 & 0 \\ a_1 + a_2 & a_2 \\ 0 & 0 \end{bmatrix}$$

$$\tau_1 = (a_1 + a_2)F_y$$

$$\tau_2 = a_2 F_y$$

Can’t create forces in the x direction!

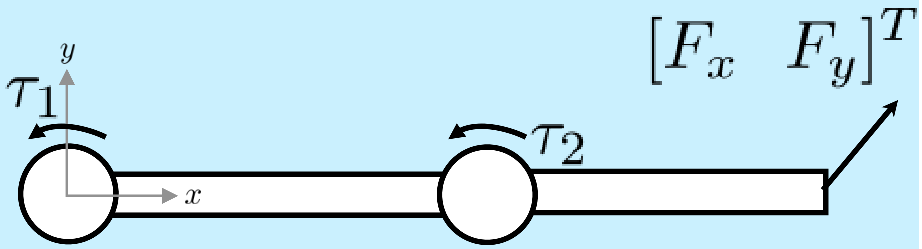
At singularities, the manipulator is unable to move in certain directions.

Near singularities, the manipulator can only **actively** apply forces in certain directions.

Q: Can the manipulator apply forces in other directions?

The robot can resist arbitrary externally applied forces/torques in Null(J^T) without moving.

$$\theta_1 = 0,\ \theta_2 = 0$$



$$J_v([0 \quad 0]^T) = \begin{bmatrix} 0 & 0 \\ a_1 + a_2 & a_2 \\ 0 & 0 \end{bmatrix}$$

$$\tau_1 = (a_1 + a_2)F_y$$

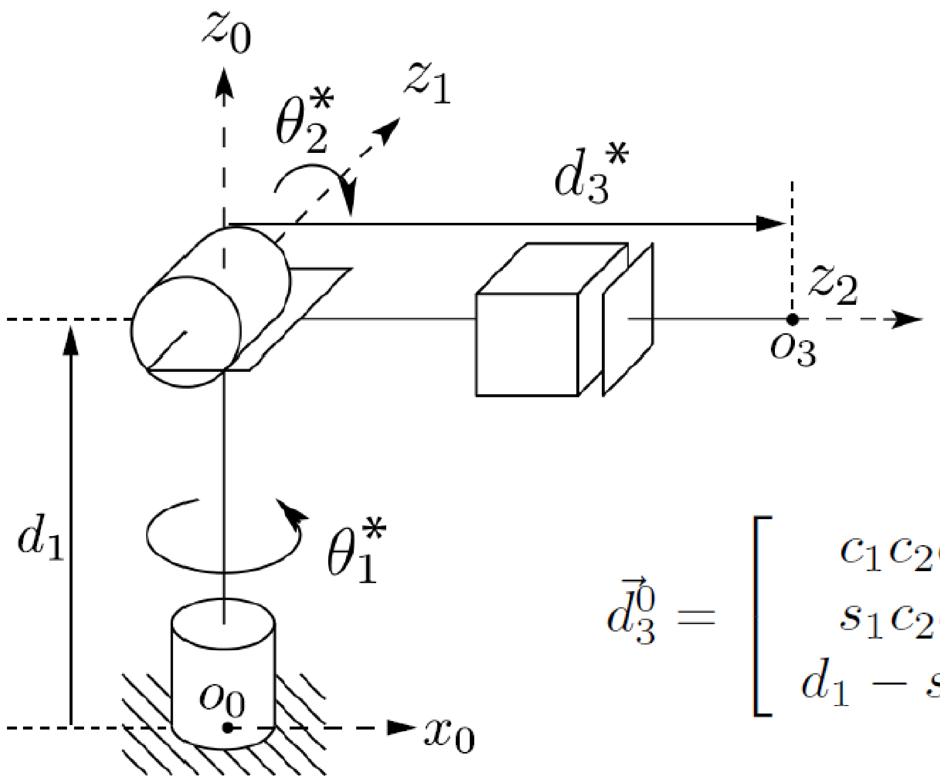
$$\tau_2 = a_2 F_y$$

Can't create forces in the x direction!

Practice: Spherical Manipulator

$$J_v(\vec{q}) = \begin{bmatrix} \frac{\partial x}{\partial q_1} & \frac{\partial x}{\partial q_2} & \cdots & \frac{\partial x}{\partial q_n} \\ \frac{\partial y}{\partial q_1} & \frac{\partial y}{\partial q_2} & \cdots & \frac{\partial y}{\partial q_n} \\ \frac{\partial z}{\partial q_1} & \frac{\partial z}{\partial q_2} & \cdots & \frac{\partial z}{\partial q_n} \end{bmatrix}$$

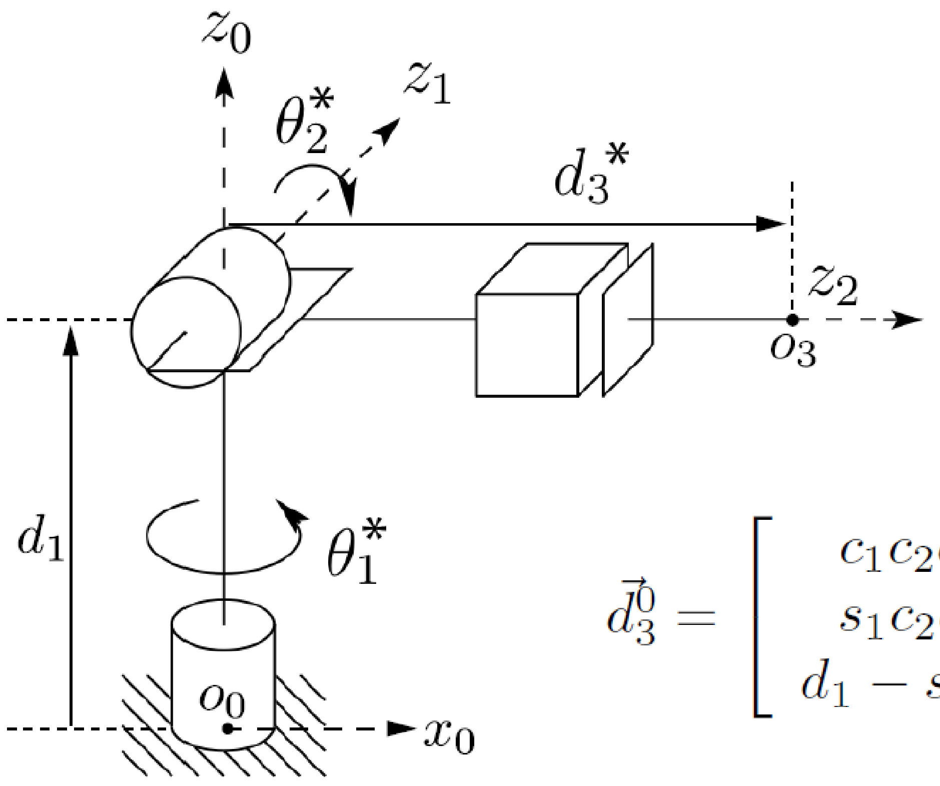
$$J_\omega = [\rho_1 \hat{\mathbf{z}} \quad \rho_2 \mathbf{R}_1^0 \hat{\mathbf{z}} \quad \rho_3 \mathbf{R}_2^0 \hat{\mathbf{z}} \quad \cdots \quad \rho_n \mathbf{R}_{n-1}^0 \hat{\mathbf{z}}]$$



$$\vec{d}_3^0 = \begin{bmatrix} c_1 c_2 d_3 \\ s_1 c_2 d_3 \\ d_1 - s_2 d_3 \end{bmatrix}$$

Practice: Spherical Manipulator

- Find the Jacobian.



$$\vec{d}_3^0 = \begin{bmatrix} c_1 c_2 d_3 \\ s_1 c_2 d_3 \\ d_1 - s_2 d_3 \end{bmatrix}$$

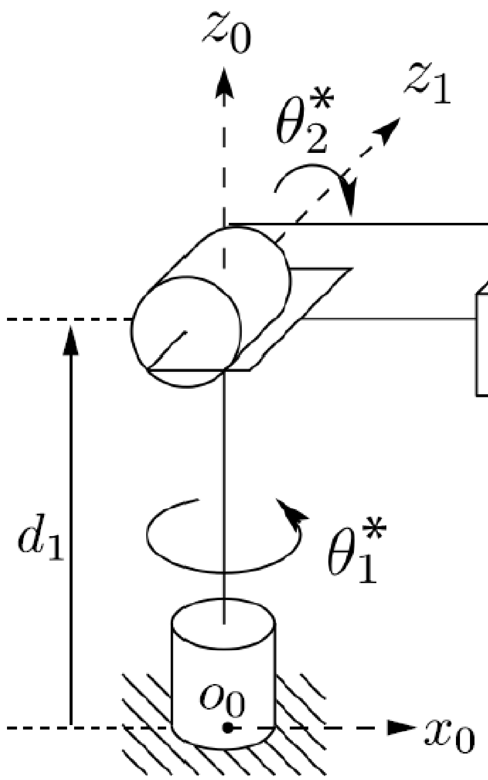
$$J_v(\vec{q}) = \begin{bmatrix} \frac{\partial x}{\partial q_1} & \frac{\partial x}{\partial q_2} & \cdots & \frac{\partial x}{\partial q_n} \\ \frac{\partial y}{\partial q_1} & \frac{\partial y}{\partial q_2} & \cdots & \frac{\partial y}{\partial q_n} \\ \frac{\partial z}{\partial q_1} & \frac{\partial z}{\partial q_2} & \cdots & \frac{\partial z}{\partial q_n} \end{bmatrix}$$

$$= \begin{bmatrix} -s_1 c_2 d_3 & -c_1 s_2 d_3 & c_1 c_2 \\ c_1 c_2 d_3 & -s_1 s_2 d_3 & s_1 c_2 \\ 0 & -c_2 d_3 & -s_2 \end{bmatrix}$$

$$J_\omega = [\rho_1 \hat{\mathbf{z}} \quad \rho_2 \mathbf{R}_1^0 \hat{\mathbf{z}} \quad \rho_3 \mathbf{R}_2^0 \hat{\mathbf{z}} \quad \cdots \quad \rho_n \mathbf{R}_{n-1}^0 \hat{\mathbf{z}}] = \begin{bmatrix} 0 & -s_1 & 0 \\ 0 & c_1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

Practice: Spherical Manipulator

- Under what conditions is there no solution to the IK?
- Where are the singularities?



$$\vec{d}_3^0 = \begin{bmatrix} c_1 c_2 d_3 \\ s_1 c_2 d_3 \\ d_1 - s_2 d_3 \end{bmatrix}$$

$$d_3 = 0 \qquad or \qquad \theta_2 = \frac{\pi}{2} + k\pi \quad \text{with } k = ..., -2, -1, 0, 1, 2, ...$$

$$J_v = \begin{bmatrix} -s_1 c_2 d_3 & -c_1 s_2 d_3 & c_1 c_2 \\ c_1 c_2 d_3 & -s_1 s_2 d_3 & s_1 c_2 \\ 0 & -c_2 d_3 & -s_2 \end{bmatrix}$$

$$J_\omega = \begin{bmatrix} 0 & -s_1 & 0 \\ 0 & c_1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

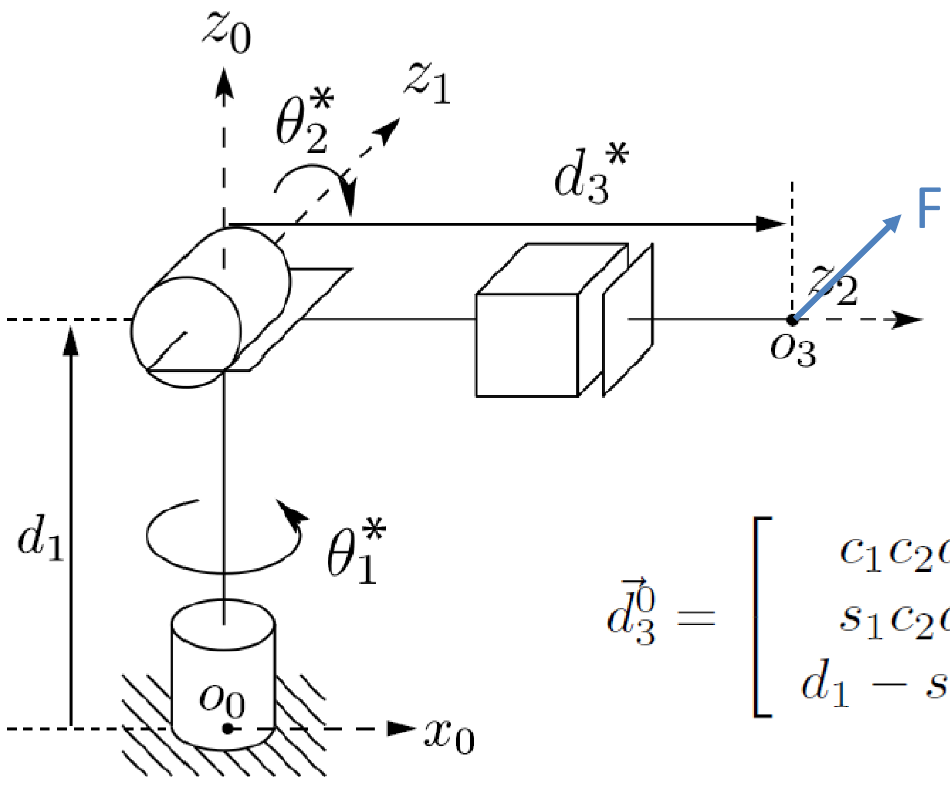
Practice: Spherical Manipulator

- If the robot has the following joint values, what joint torques to choose if the tip should apply [0 N, 2.0 N, 2.0 N]?
  $\theta_1 = \frac{\pi}{4}\,\text{rad}, \theta_2 = 0\,\text{rad}, d_3 = 1\text{m}$

$$\vec{\tau} = J_v^\top \vec{F}$$

$$J_v = \begin{bmatrix} -\sqrt{2}/2\ \text{m} & 0 & \sqrt{2}/2 \\ \sqrt{2}/2\ \text{m} & 0 & \sqrt{2}/2 \\ 0 & -1\ \text{m} & 0 \end{bmatrix}$$

$$\tau = [\sqrt{2}\ \text{N m} \quad -2\ \text{N m} \quad \sqrt{2}\ \text{N}]$$



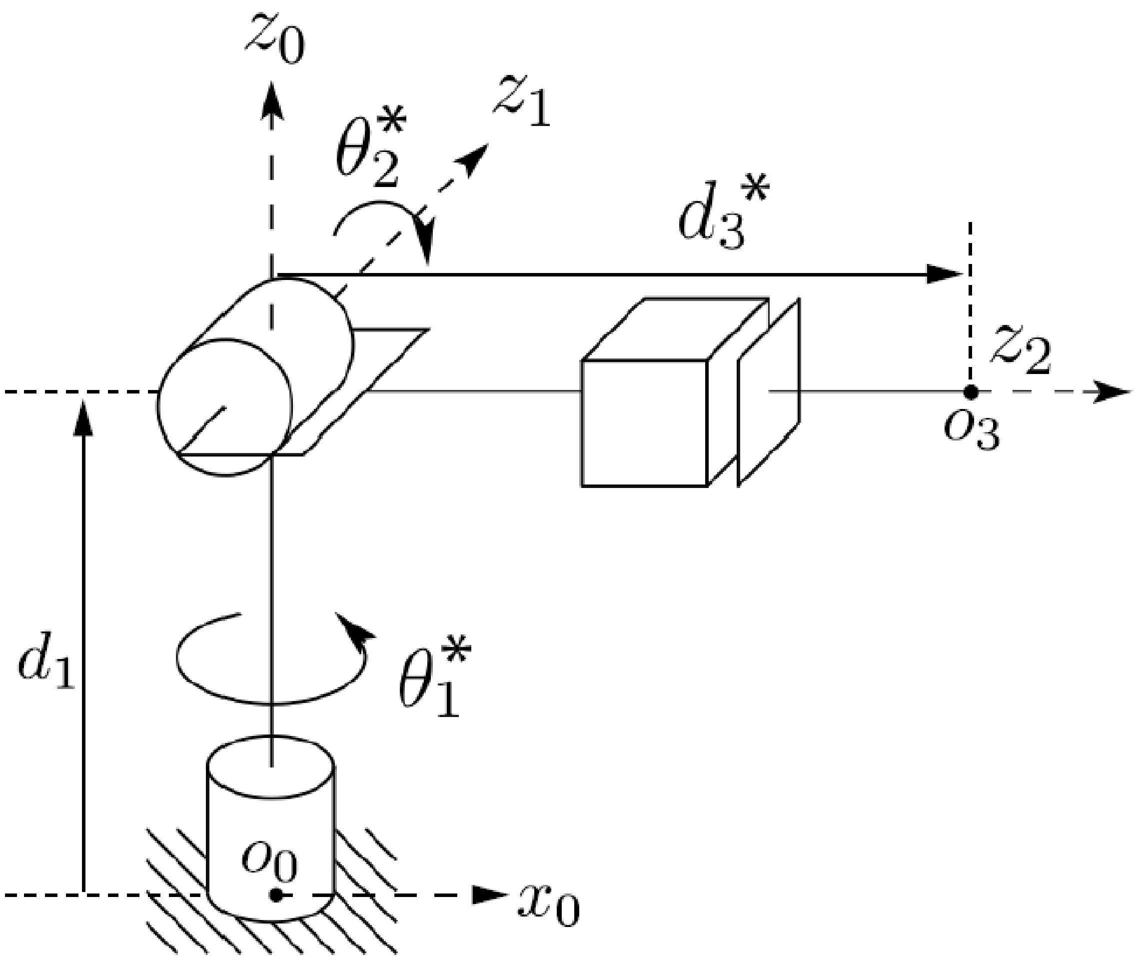
$$\vec{d}_3^0 = \begin{bmatrix} c_1 c_2 d_3 \\ s_1 c_2 d_3 \\ d_1 - s_2 d_3 \end{bmatrix}$$

$$\boxed{J_v = \begin{bmatrix} -s_1 c_2 d_3 & -c_1 s_2 d_3 & c_1 c_2 \\ c_1 c_2 d_3 & -s_1 s_2 d_3 & s_1 c_2 \\ 0 & -c_2 d_3 & -s_2 \end{bmatrix}}$$

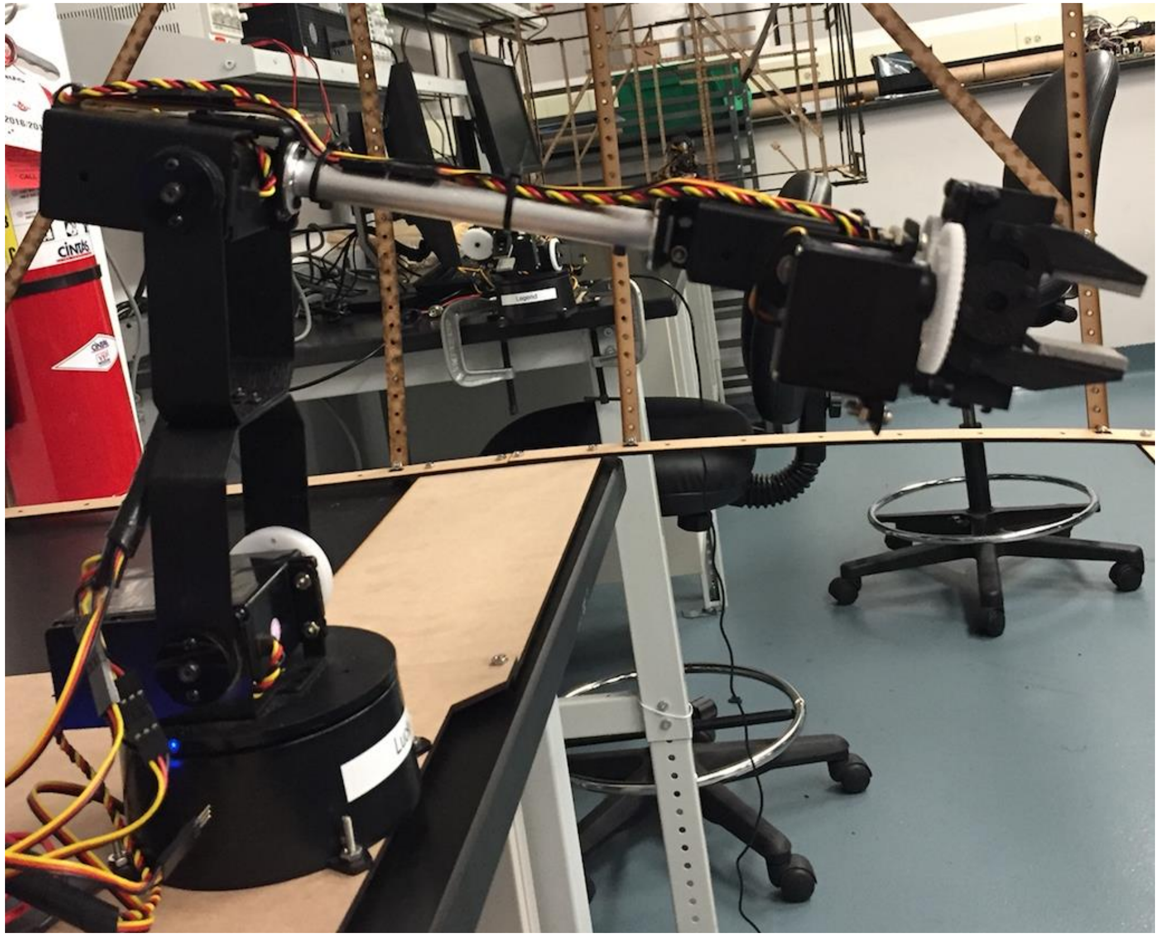
$$\boxed{J_\omega = \begin{bmatrix} 0 & -s_1 & 0 \\ 0 & c_1 & 0 \\ 1 & 0 & 0 \end{bmatrix}}$$

Practice: Spherical Manipulator

- What does the manipulability ellipsoid look like in the zero configuration?



Application: Gravity Compensation



Strategy:

Determine expected form for gravitational force/torque and cancel out using statics analysis

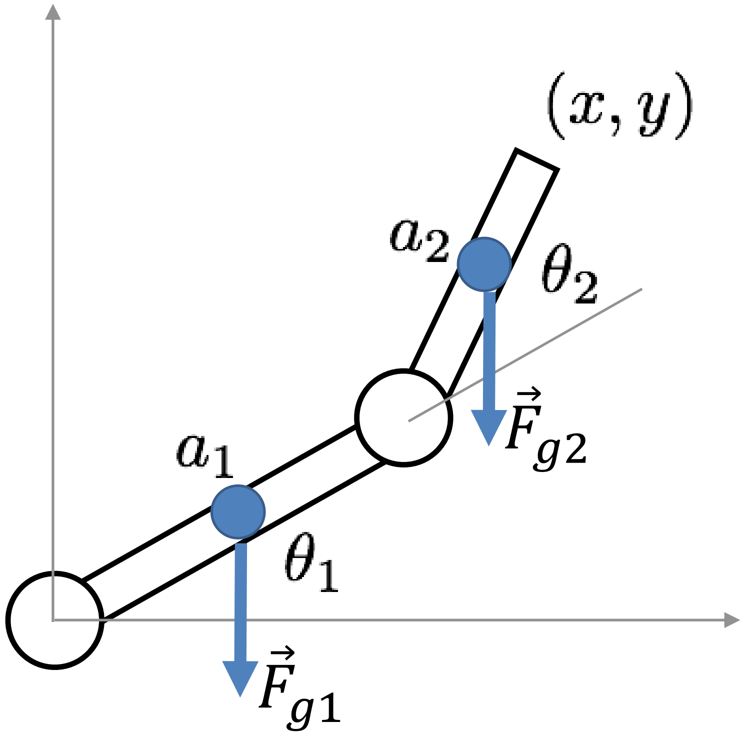
Gravitational Force/Torque

$$\vec{\tau}^\top d\vec{q} = \vec{F}^\top d\vec{x}$$

$$\vec{\tau}^\top d\vec{q} = \sum_{i=1}^{n} \vec{F}_{gi}^\top d\vec{x}_i$$

$$\vec{\tau}^\top d\vec{q} = \sum_{i=1}^{n} \vec{F}_{gi}^\top J_i d\vec{q}$$

$$\vec{\tau} = \sum_{i=1}^{n} J_i^\top \vec{F}_{gi}$$

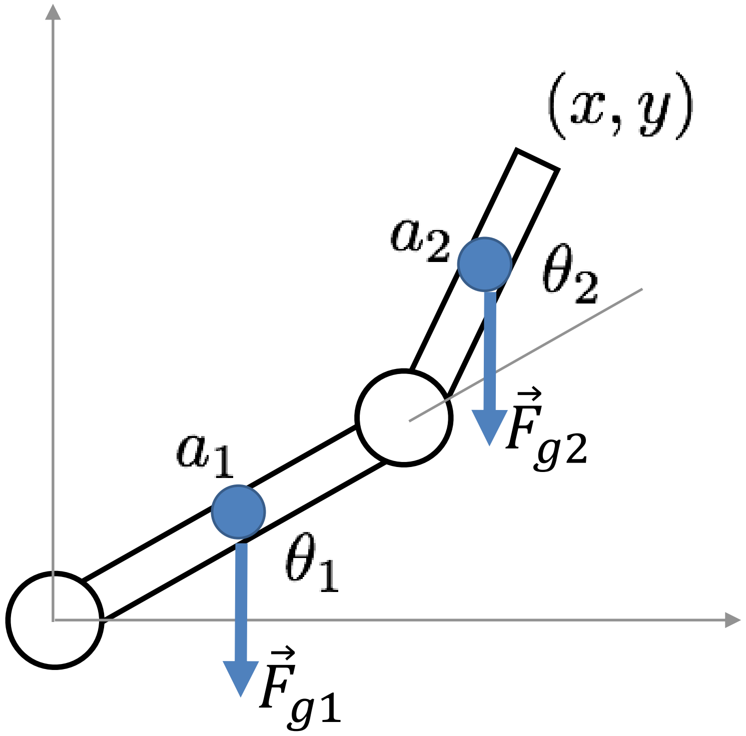


Example: Planar RR

$$\vec{\tau} = \sum_{i=1}^{n} J_i^\top \vec{F}_{gi} \qquad \vec{F}_{gi} = -m_i g \hat{y}$$

$$COM_1 = \begin{bmatrix} (a_1/2)c_1 \\ (a_1/2)s_1 \\ 0 \end{bmatrix} \qquad COM_2 = \begin{bmatrix} (a_2/2)c_{12} + a_1 c_1 \\ (a_2/2)s_{12} + a_1 s_1 \\ 0 \end{bmatrix}$$

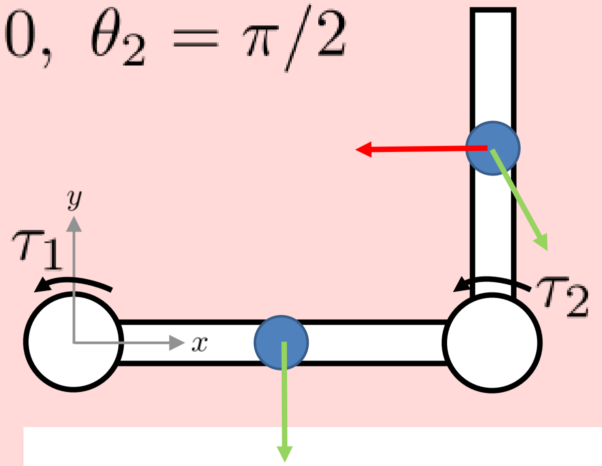
$$J_1 = \begin{bmatrix} -(a_1/2)s_1 & 0 \\ (a_1/2)c_1 & 0 \\ 0 & 0 \end{bmatrix} \qquad J_2 = \begin{bmatrix} -(a_2/2)s_{12} - a_1 s_1 & -(a_2/2)s_{12} \\ (a_2/2)c_{12} + a_1 c_1 & (a_2/2)c_{12} \\ 0 & 0 \end{bmatrix}$$



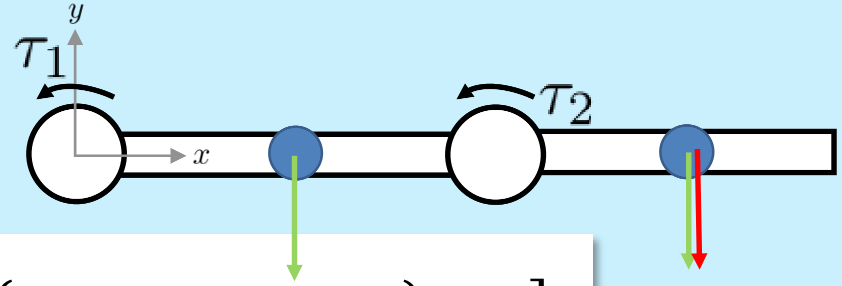
$$\vec{\tau} = J_1^\top \vec{F}_{g1} + J_2^\top \vec{F}_{g2}$$

$$\vec{\tau} = \begin{bmatrix} -(a_1/2)c_1 m_1 g \\ 0 \end{bmatrix} + \begin{bmatrix} -\big((a_2/2)c_{12} + a_1 c_1\big)m_2 g \\ -(a_2/2)c_{12} m_2 g \end{bmatrix}$$

$\theta_1 = 0,\ \theta_2 = \pi/2$



$\theta_1 = 0,\ \theta_2 = 0$

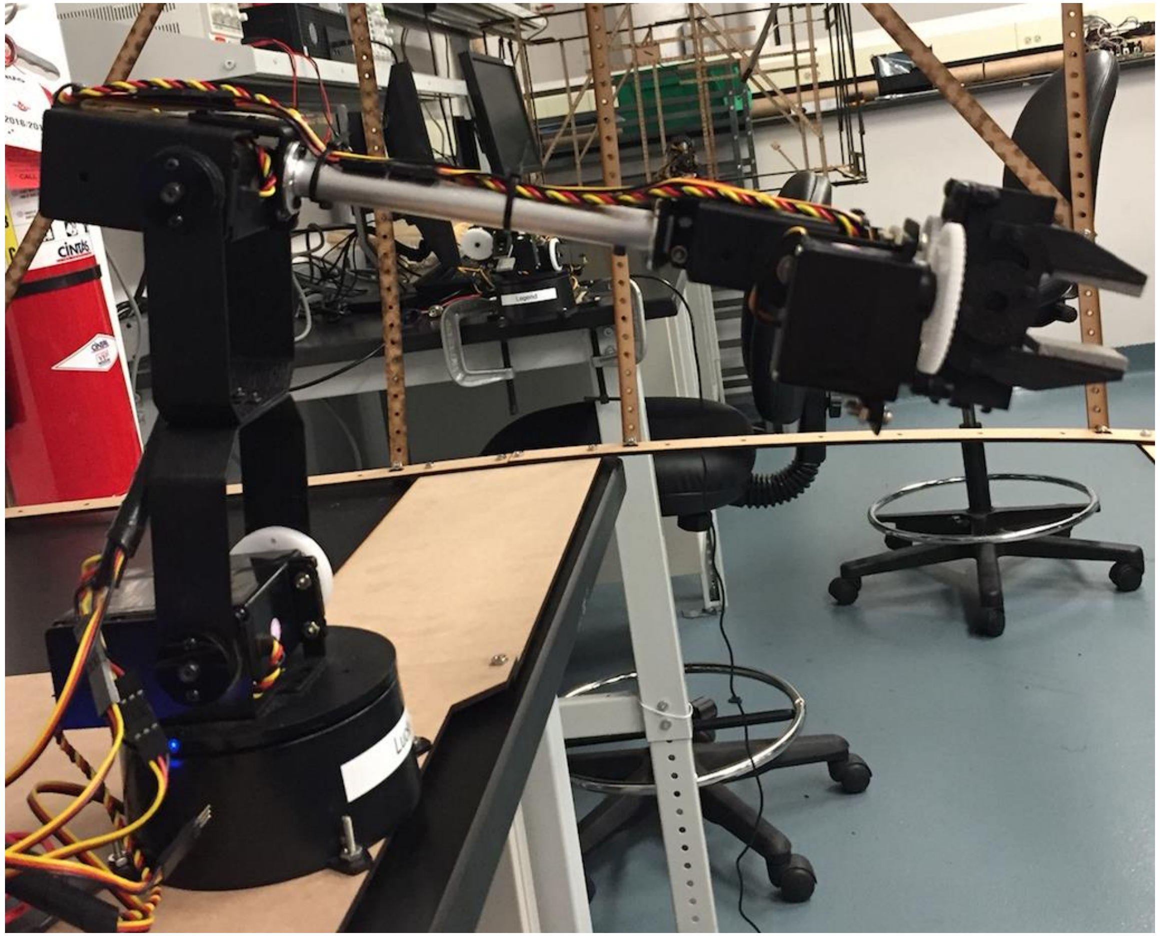


$$\vec{\tau} = \begin{bmatrix} -(a_1/2)c_1 m_1 g \\ 0 \end{bmatrix} + \begin{bmatrix} -((a_2/2)c_{12} + a_1 c_1)m_2 g \\ -(a_2/2)c_{12} m_2 g \end{bmatrix}$$

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} \boxed{-(a_1/2)m_1 g} \\ \boxed{0} \end{bmatrix} + \begin{bmatrix} \boxed{-a_1 m_2 g} \\ \boxed{0} \end{bmatrix}$$

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} \boxed{-(a_1/2)m_1 g} \\ \boxed{0} \end{bmatrix} + \begin{bmatrix} \boxed{-((a_2/2) + a_1)m_2 g} \\ \boxed{-(a_2/2)m_2 g} \end{bmatrix}$$

Application: Gravity Compensation

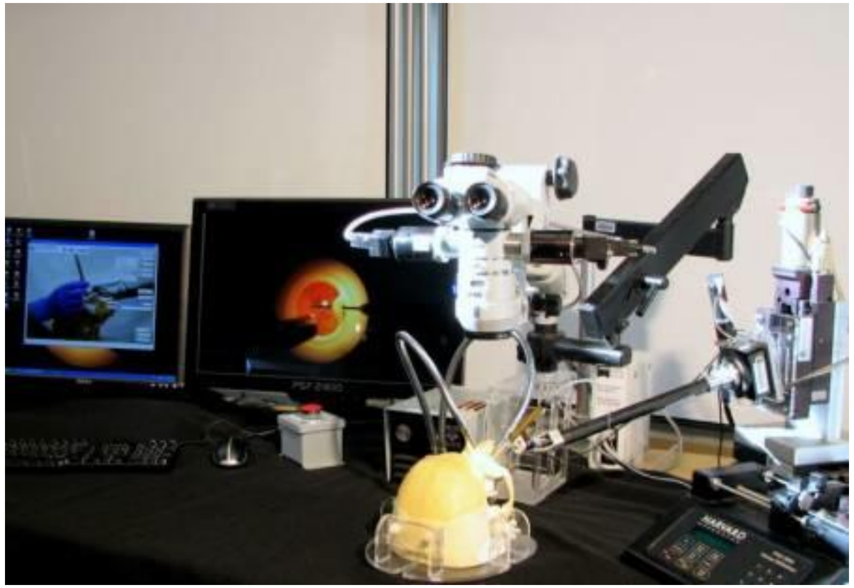


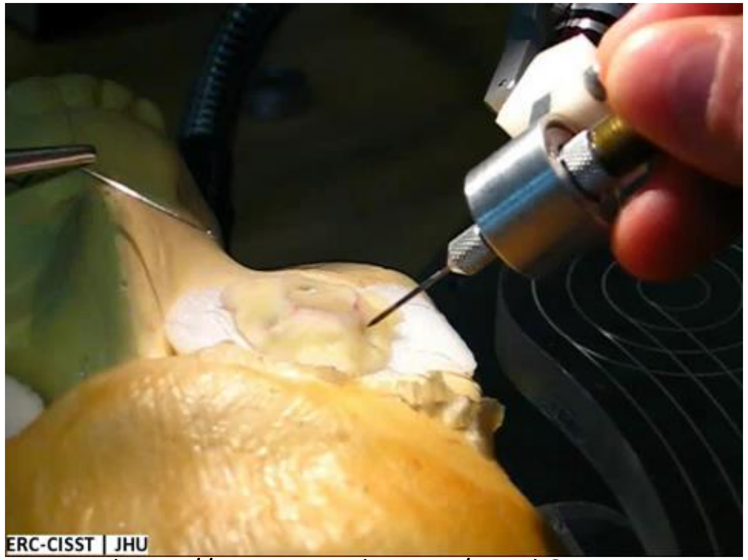
Strategy:

Determine expected form for gravitational force/torque and cancel out using statics analysis

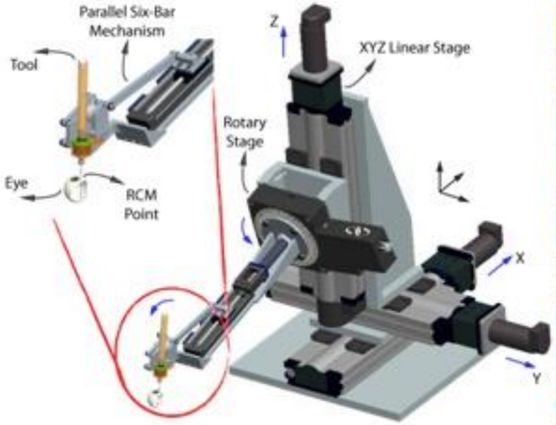
$$\vec{\tau}_{app} = -\sum_{i=1}^{n} J_i^{\top} \vec{F}_{gi}$$

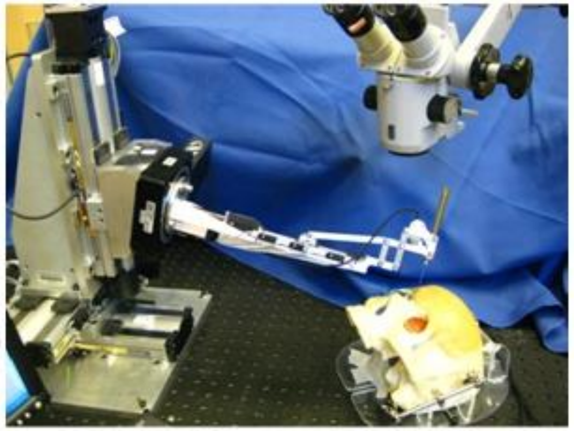
Real Example: JHU Steady-Hand Eye Robot

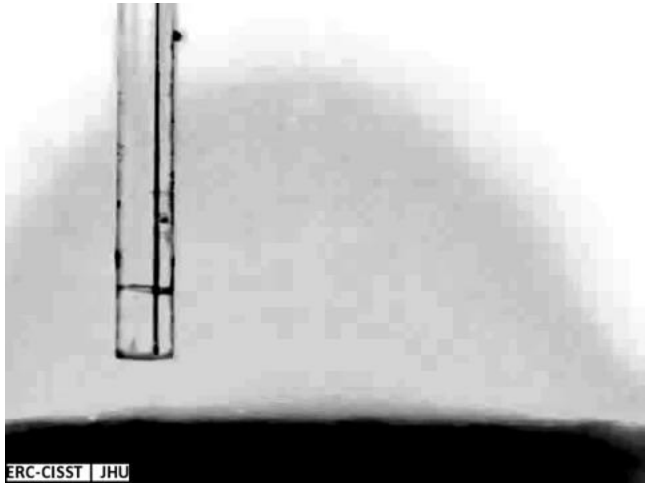




https://www.youtube.com/watch?v=WiK-CSr-FBs



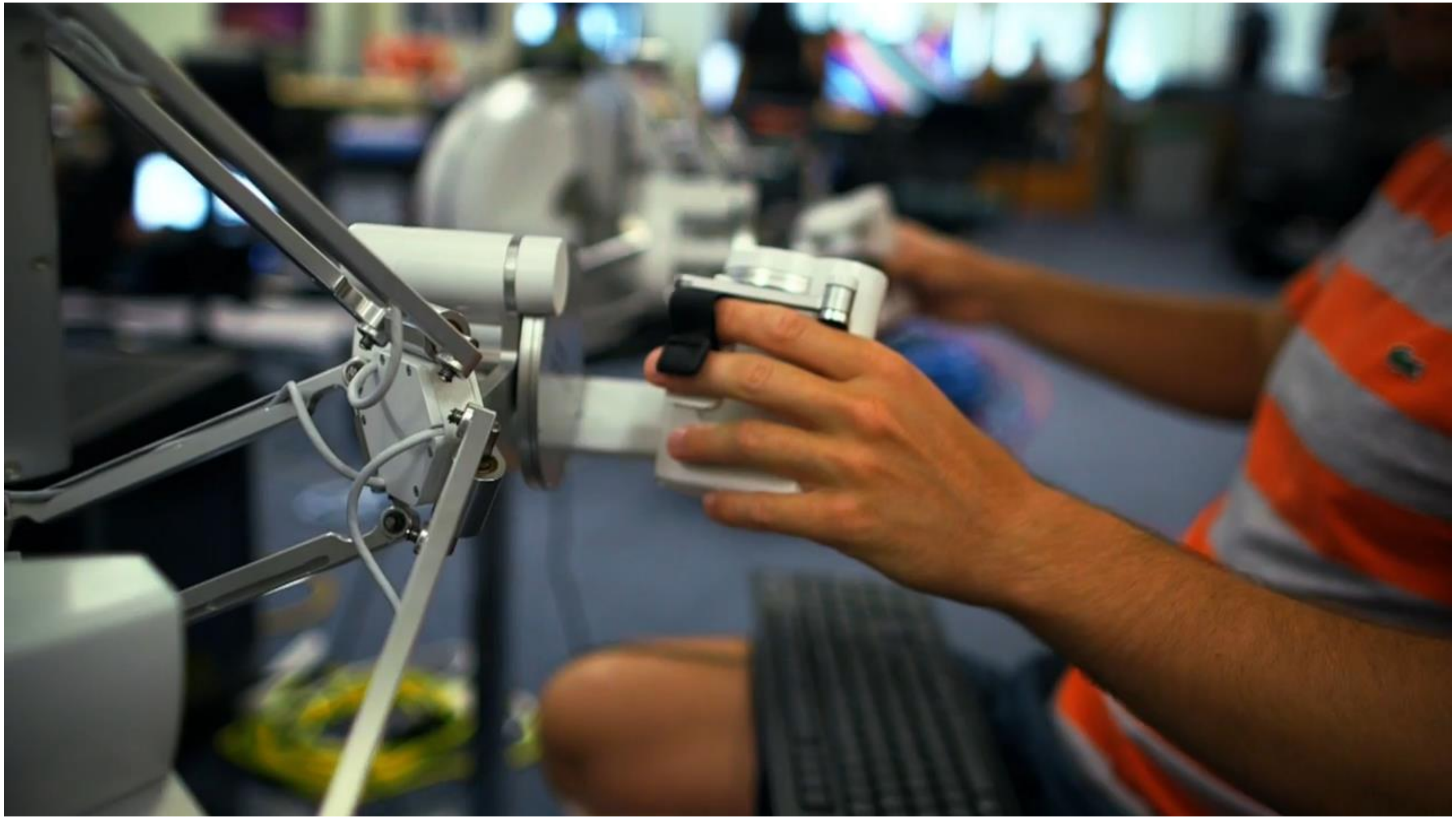




https://www.youtube.com/watch?v=ML45iQB2oU0

https://ciis.lcsr.jhu.edu/dokuwiki/doku.php?id=research.eyerobots

Teleop Example: Stanford Ocean One

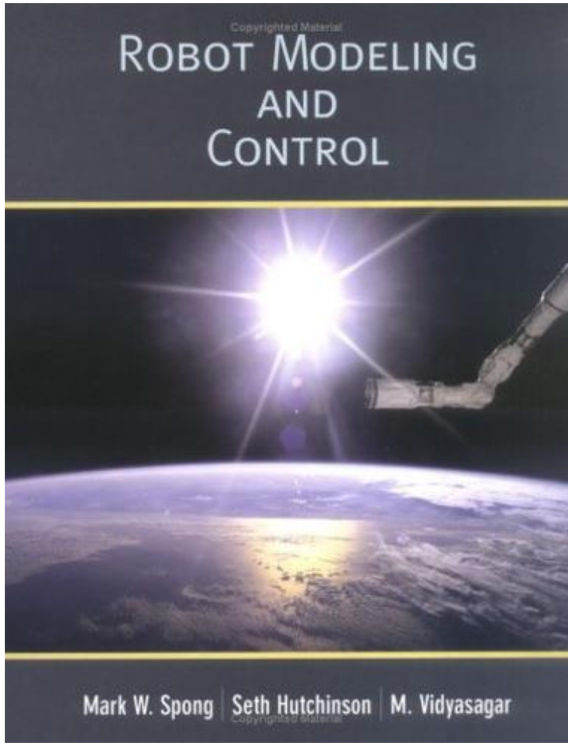


https://www.youtube.com/watch?v=p1HmgP9l4VY

Simulation Example: 3D CAD with Phantom Omni

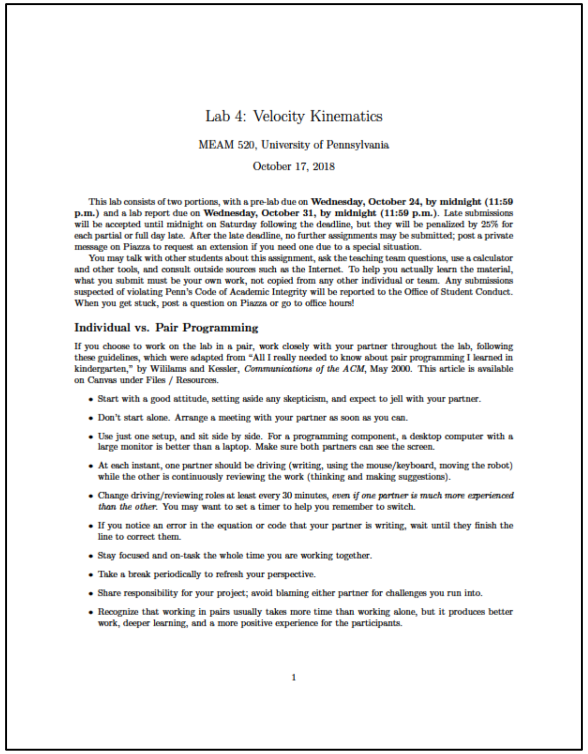
https://www.youtube.com/watch?v=REA97hRX0WQ

Next time: Potential Fields



Chapter 5: Trajectory Planning

- Read 5.2



Lab 4: Velocity Kinematics

MEAM 520, University of Pennsylvania

October 17, 2018

This lab consists of two portions, with a pre-lab due on **Wednesday, October 24, by midnight (11:59 p.m.)** and a lab report due on **Wednesday, October 31, by midnight (11:59 p.m.)**. Late submissions will be accepted until midnight on Saturday following the deadline, but they will be penalized by 25% for each partial or full day late. After the late deadline, no further assignments may be submitted; post a private message on Piazza to request an extension if you need one due to a special situation.

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 submit 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. When you get stuck, post a question on Piazza or go to office hours!

Individual vs. Pair Programming

If you choose to work on the lab in a pair, work closely with your partner throughout the lab, following these guidelines, which were adapted from "All I really needed to know about pair programming I learned in kindergarten," by Wililams and Kessler, *Communications of the ACM*, May 2000. This article is available on Canvas under Files / Resources.

- Start with a good attitude, setting aside any skepticism, and expect to jell with your partner.
- Don't start alone. Arrange a meeting with your partner as soon as you can.
- Use just one setup, and sit side by side. For a programming component, a desktop computer with a large monitor is better than a laptop. Make sure both partners can see the screen.
- At each instant, one partner should be driving (writing, using the mouse/keyboard, moving the robot) while the other is continuously reviewing the work (thinking and making suggestions).
- Change driving/reviewing roles at least every 30 minutes, *even if one partner is much more experienced than the other*. You may want to set a timer to help you remember to switch.
- If you notice an error in the equation or code that your partner is writing, wait until they finish the line to correct them.
- Stay focused and on-task the whole time you are working together.
- Take a break periodically to refresh your perspective.
- Share responsibility for your project; avoid blaming either partner for challenges you run into.
- Recognize that working in pairs usually takes more time than working alone, but it produces better work, deeper learning, and a more positive experience for the participants.

1

Lab 4: Velocity Kinematics

due tomorrow