1 Introduction

I had the pleasure of teaching a new class called "Flexible Robotics" while on sabbatical at Bilkent University in Ankara, Turkey this Fall. The class was a 13 person, senior-level elective course that covered some of the same concepts as my graduate-level "Foldable Robotics" class that I have taught at ASU since 2016, but introduced about 75% new material, based on the needs of undergraduates in their senior year.

This course could not have been possible without the help and support of Onur Ozcan, who helped me get the course on the books in the first 24 hours I was in the country. The idea is that he will take on teaching responsibilities for this course at Bilkent in future years. His advice and guidance on getting the course set up in a different system than I am used to was critical. Thanks Onur!

1.1 What is *Flexbile Robotics*?

Flexible Robotics is a microcosm of some of the robotics research I do, and teaches a somewhat simplified version of the engineering approaches we use in my lab to design robots. It focuses on how to design robotic systems that are ultimately limited by the physics of the parts and materials they are constructed with. To find good designs, we have to know all about soft and flexible materials, motors and how they work, how to model non-ideal components using both first-principles and more realistic representations, and then the best practices for prototyping and validating the performance of our designs.

Flexible Robotics is also a class taught on a budget. I am of the belief that anyone should have access to robotics concepts, and so I have designed this course to use off-the shelf parts and materials that almost anyone can obtain. I teach using open-source software tools such as Python, so that anyone can run the code we use on any platform. And I teach experiment design and data collection using more accessible approaches that I believe **serve as a proxy** for the modern robotics lab. Not all undergraduates have access to high-speed motion capture systems, but everyone has a cell-phone. Not every department has a universal testing machine sitting in the student lab, but anyone can make a (relatively) standardized weight. When we focus on the concepts of how to create good experiments, and the tradeoffs between approaches, the ultimate resolution of the tool matters less.

Here's a summary of the high-level concepts baked into the course:

- I taught with a palette of low-cost parts and tools that are easily obtainable but didn't sacrifice or simplify the associated engineering challenges.
- I provided interactive coding experiences built into class time using Jupyter Notebook and Python.
- I reinforced the kinematics content students should already have had (3D vector operations, rotation matrices, and quaternions), but from a different perspective.
- I added MuJoCo for teaching many concepts in the second half of the course in order to simplify and streamline the number of different tools students had to pick up.
- The course focused on how flexible and compliant materials impact the modeling and design process, and which representations of compliance work best for modeling.
- I used the concepts of biomechanics, specifically terrestrial locomotion, as a way to focus design goals, observe and measure behavior, and talk about performance.

1.2 Course Highlights

Below is a list of the things I focused on when developing this course.

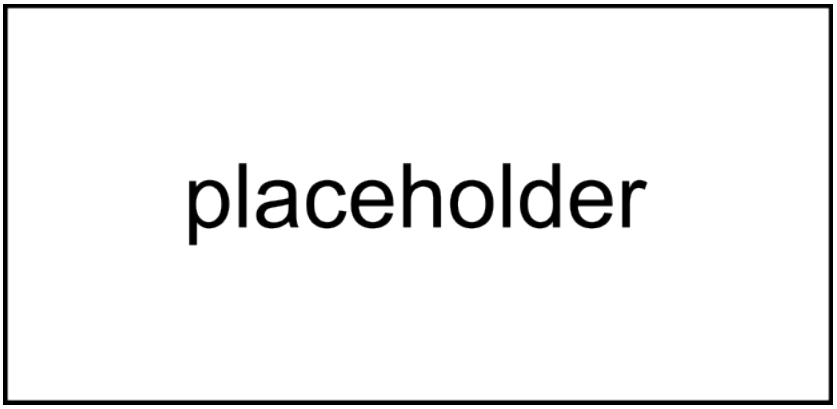


Figure 1: Team 3's horse-inspired design

1.2.1 MuJoCo

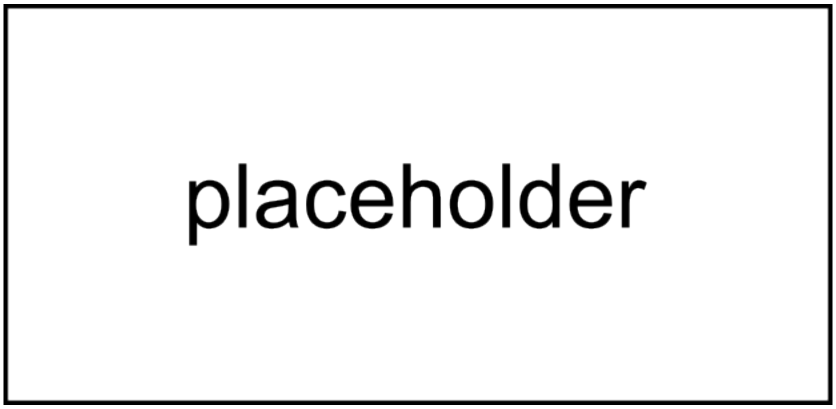
For the first time, I taught using MuJoCo as a design, modeling, and validation tool instead of my own Python dynamics package that I have previously taught with. I liked this shift because it made students more aware of the current challenges in simulation using a popular and powerful tool that is easier to learn than my own package. MuJoCo has much more thorough documentation, with more examples from the community, so I was not always "on call" supporting my own code. It also permitted the class to explore the role that contact and friction play at a deeper level than I had been able to take a class before. On the flip side, the tradeoffs of contact, friction, and "soft solvers" is complex and required more discussion than I gave it, without a satisfying or straightforward "answer" for how to apply it correctly.

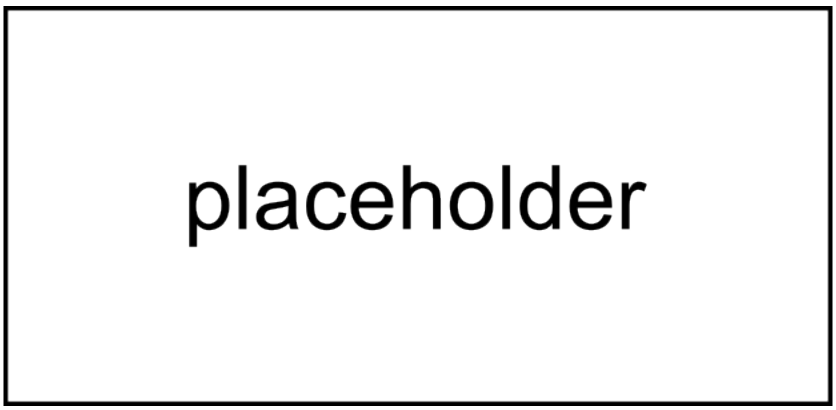
1.2.2 Mechanisms and Kinematics

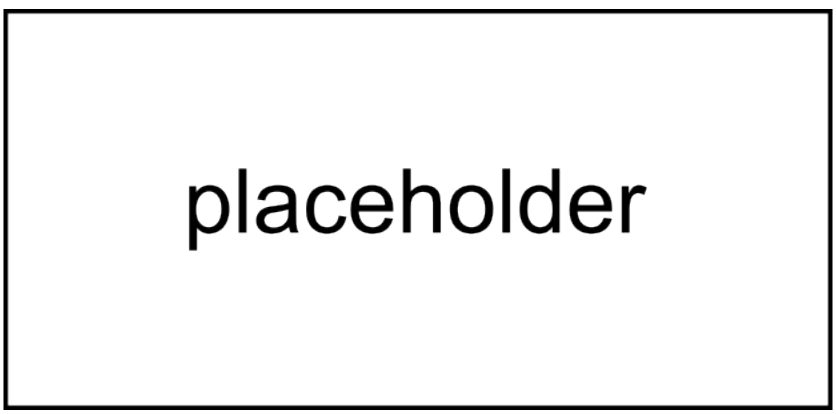
In contrast to the graduate class I teach, the senior-level *Flexible Robotics* spends more time reinforcing fundamental concepts in vectors, kinematics, and transformations, but uses the framework of flexible, foldable, and compliant systems to teach from a different perspective. For example, we defined spherical parallel mechanisms using quaternions instead of rotation matrices or DH parameters, and used the fundamental properties of vectors to define closed-loop constraint equations that we then solved numerically. Other approaches are often important in foldable systems, where kinematics are often defined from flat-foldable sheets of material rather than from rigid serial chains, and require efficient representations for faster solutions.

1.3 Compliant Materials

It has been difficult introducing compliant material systems, even in the graduate level course I teach, without getting into some complex topics and not feeling like there is enough time to do the topic justice. In this course, we focused on a few basic concepts of compliant material systems, while leaving others just to discussion:







1.3.1 Exams

To satisfy University requirements, I added a midterm and final exam to the course. Typically I have lumped more points into assignments and projects, but this helped get the course accepted by the provost on the first pass. It also required that I spend more class time focusing on fundamentals, but in the end I believe this was time well spent.