METR6203: Control System Implementation Assignment 1

Control of a gyro-actuated inverted pendulum

Synopsis

You will work in groups of three to implement an inverted pendulum control system. You will be assessed by documentation, a presentation and a demonstration using the assignment Rubric.

Learning outcomes

This assignment develops and tests your understanding of the following learning objectives

LO1.Develop and Analyse Dynamic System Models - Construct and analyse state space models for linear and nonlinear, continuous and discrete systems across a range of domains. Use analytical and numerical methods, simulation tools (e.g., MATLAB/Simulink), and techniques such as linearisation and sampling to assess system behaviour and stability.

LO2. Design and Implement State-Feedback Controllers - Design and implement state-feedback controllers for linear systems, including MIMO configurations, considering reachability, observability, integral action, and performance trade-offs.

LO5. Collaborate in Engineering Teams - Work effectively in teams to solve control problems by defining roles, managing tasks, and addressing technical and interpersonal challenges collaboratively.

Introduction

Figure 1 shows a schematic for a balance system that has become something of a benchmark problem for control: a pendulum is attached to a cart. The idea is to apply force to the cart in such as way as to maintain the pendulum upright. The problem gets even more interesting when the pendulum is made to self-erect.

There are many Internet resources related to the problem of controlling this device including videos on youtube. These, no doubt, will serve an excellent resource for this assignment. As a starting point, see for example

http://en.wikipedia.org/wiki/Inverted_pendulum

http://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling

http://csd.newcastle.edu.au/simulations/pend_sim.html

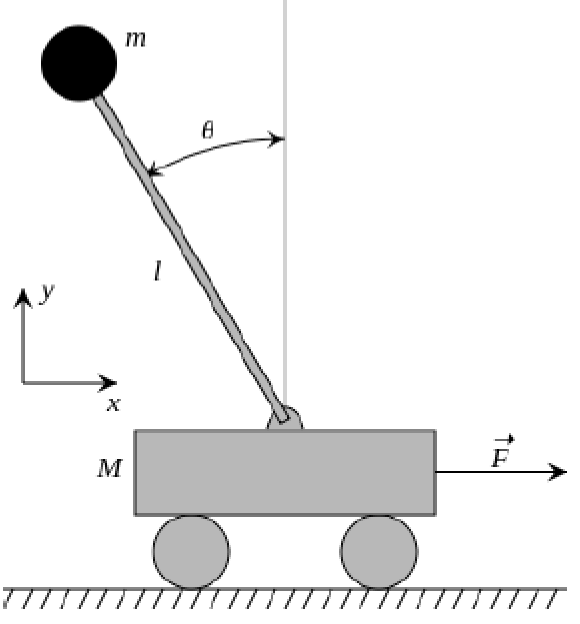

Figure 1. Cart and pendulum system.

Your task in this assignment is to develop a control system for the variant of the cart-and-pendulum system shown in Figure 2 called a gyro-actuated pendulum.

A gyro-actuated pendulum refers to a mechanical system where a gyroscope is used to actively control and manipulate the motion of a pendulum.

The gyroscope's rotational motion and angular momentum are harnessed to exert torques or forces on the attached pendulum, influencing its behavior. By carefully manipulating the gyroscope's rotation, orientation, and angular velocity, it becomes possible to control the pendulum's position, stability, and even perform specific tasks. This type of system can be challenging to control due to the complex interactions between the gyroscope and the pendulum, but it provides valuable insights into control theory and practical applications.

Figure 2. Gyro-actuated pendulum in inverted closed loop control.

How will your team do this?

This task is a hands-on learning experience designed to encourage your exploration of the interconnectedness between theory and practice. It also provides you with a chance to showcase your creative abilities as a control systems engineer. While the concepts introduced tie back to the course materials covered in lectures and tutorials, this task will also require you to cultivate practical skills and proficiencies beyond what is explicitly addressed in lectures. Throughout the journey, we will incorporate dedicated sessions on specialized topics to provide you with guidance and assistance.

Some terminology

The rigs will be configured for you before commencing any work, so you won't have to invest too much effort in getting started. Please be aware that the rigs are delicate, so handle them with care.

The pendulum will maintain its balance through the generation of a gyroscopic moment. The gyroscope responsible for actuating the pendulum is depicted in Figure 3 and possesses four degrees of freedom.

- Axis 1 spins up the flywheel. As a guide, this needs to spin at around 400RPM to generate appropriate gyroscopic torques to produce angular momentum about Axis 1 which results in motion of the gyroscope.

• Axis 2 is a gimbal1 axis. A velocity on this axis enable the generation of a gyroscopic torque causing motion about Axis 4.

• Axis 3 is also a gimbal axis but you will lock up this axis so that motion about it does not occur. The gyroscope has a built in brake that can be activated by a clearly labeled toggle switch on the ECP control box. **You must have this brake on at all times you are trying to control the pendulum.**

• Axis 4 is the third gimbal axis. This axis can also be braked by a clearly labeled toggle switch on the ECP control box. You should leave this brake **off** while controlling the system so that the assembly can rotate about the base axis.

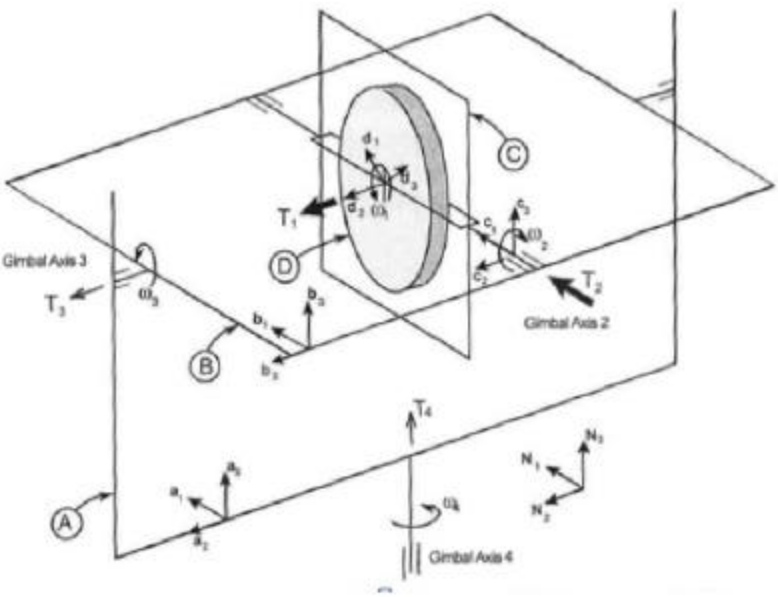

Figure 3. The gyroscopic system.

Principles of actuation

The mechanism for actuating the pendulum is based on the concept of a gyroscopic couple. With reference to Figure 4 (note the gratuitous change of notation so that Axis 4 from the previous section is now rebadged as Axis 1. Hopefully this won't confuse you too much), if the flywheel is spun up, its angular momentum is represented by $\boldsymbol{H}$. If gimbal[1] axis 2 is rotated at speed $\boldsymbol{\omega_2}$ a gyroscopic torque $\boldsymbol{T_1}$ will be generated given by

$$\boldsymbol{T_1} = \boldsymbol{\omega_2} \times \boldsymbol{H}$$

[1] A gimbal is a mechanical arrangement often used for keeping an instrument such as a compass or chronometer horizontal in a moving vessel or aircraft, typically consisting of rings pivoted at right angles. When you look at the gyroscope used for this assignment you should easily identify the three gimbal axes. The word has its origins in Latin: ***gemellus***, the diminutive of ***geminus***. It came into English in the 16th century, denoting connecting parts in machinery. Sometimes you still find reference to *gemels, which are* twin, hinged rings. When you look at the experimental rig you should appreciate the presence of twin hinge rings in the design.

When the flywheel is spinning at constant speed and $\boldsymbol{\theta_3 = 0}$ (gimbal axis 3 fixed horizontal), and with small excursions in $\boldsymbol{\theta_2}$ about $\boldsymbol{\theta_2 = 0}$ (flywheel spinning so that $\boldsymbol{H}$ is aligned with gimbal axis 3), the generated torque is

$$\boldsymbol{T_1 = \omega_2 H}$$

The torque $\boldsymbol{T_1}$ will be generated around gimbal axis 1.

The principle of actuation is to spin up the flywheel with all axes orthogonal and gimbal Axis 3 locked and then make small change to $\boldsymbol{\theta_2}$ generating torques cause the gyroscope assembly to rotate about axis 4, now of course called Axis 1.

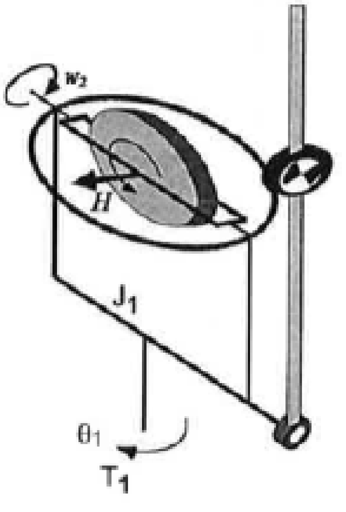

Figure 4.

Where should you start

Every control system initiation begins with the creation of a model. The initial step involves deriving equations of motion based on your mechanical understanding. During this process, you'll need to make decisions concerning the model's level of complexity and subsequently linearize it around its stable operational point. To illustrate, you'll be required to make choices regarding the inputs, which offer several options. To assist you in this endeavor, parameter values for the components constituting the pendulum can be found in MATLAB files accessible on the website. Additionally, the Blackboard site provides MATLAB files that can generate a linearized plant model – an option you can opt for. However, higher scores will be attainable if you choose to construct your own model. This alternative serves as a safety net, ensuring that regardless of your performance in the modeling task, you have the means to establish a functioning system.

From a pragmatic perspective, as an initial step, contemplate initiating speed regulation for the flywheel. Your objective should revolve around maintaining the flywheel's speed at 400 RPM. This opportunity not only facilitates the creation of a Single-Input Single-Output (SISO) control loop but also helps you acquaint yourself with the system.

The control system you are constructing is a hybrid blend of logic and feedback mechanisms. It is advisable to incorporate two distinct controllers: one responsible for swinging the pendulum to an upright stance (as covered in PBA2), and another dedicated to capturing and maintaining the system's equilibrium (outlined in PBA3). To seamlessly switch between these controllers, you can make use of Stateflow (PBA1).

Take it from there.

Where should you finish?

Through meticulous documentation of your model and a remarkable demonstration accompanied by a superb presentation, you have the opportunity to showcase the true potential of feedback control concepts. Ideally, your demonstration should offer an engaging perspective on the efficacy of these ideas. This can be achieved by developing a balancing system that autonomously rights the pendulum from a non-inverted to an inverted state, demonstrating its robust capability to handle disturbances. Your presentation will effectively illustrate the seamless integration of lecture concepts into practical problem-solving, highlighting the practical application of the knowledge acquired.

How will you get there?

With teamwork!

When Winston Churchill met with his Cabinet on May 13 1940 he told them that “I have nothing to offer but blood, toil, tears and sweat.” He liked the phasing so much that he repeated it in a speech to the House of Commons on the same day in seeking a vote of confidence for his all-party government.

There is not denying that Winston could turn a phrase and in his honour I anticipate you will bring some blood, toil, tears and sweat to this project as a constructive member of your team. Of course, you will need to convince me that you are working as a team and that you have distributed work equally among team members. No cowboys! Hero’s not required! No passengers! Think Dora the Explorer: “When we work together as a team, *there's nothing we can't do*, 'cause being on a team means you help me and I help you."