Design, Modeling, And Control of a Single-Axis Self-Balancing Platform

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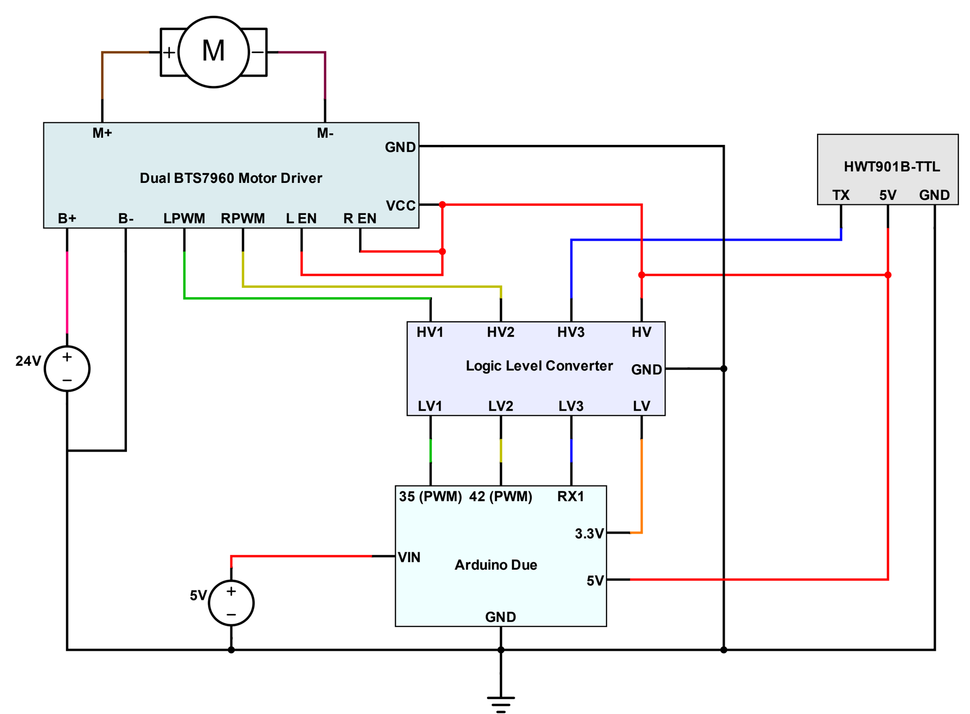
System Description



Circuit diagram for system

Disturbance mass: 200g
Platform mass: 558 g
Platform length: 12 in

Platform and disturbance mass

Plant:

Transfer Function from voltage u to angle θ
Characterized by motor current-to-torque, armature voltage, and load torque relationships, as well as $\theta = \dot{\omega}$
Armature inductance and dynamic friction approximated as zero
Parameters found from motor performance curves

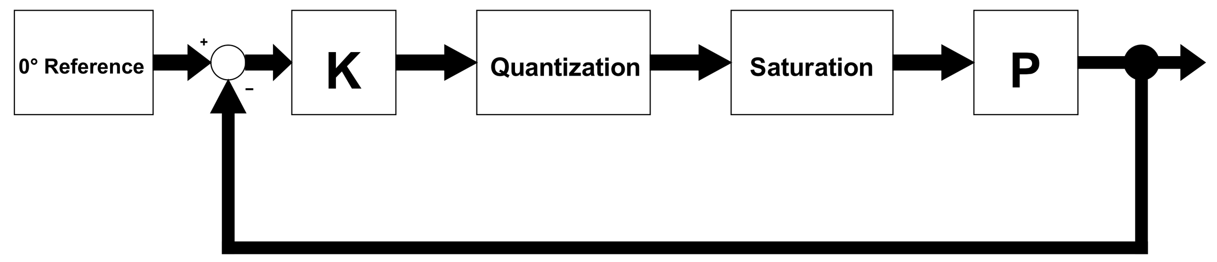
$$\frac{\theta}{u} = \frac{\frac{K_t}{R_a}}{Is^2 + K_e\frac{K_t}{R_a}s}$$

K_t is the motor torque constant
K_e is the motor back-EMF constant
R_a is the armature resistance
I is the platform (unloaded) moment of inertia

Sensor considerations:

Converting angle reading from upside down sensor to true angle
UART interference due to computer serial port
Allowing time for serial data to clean out before initializing
Low sensor noise, but implementation of LPF anyway

Controller Design



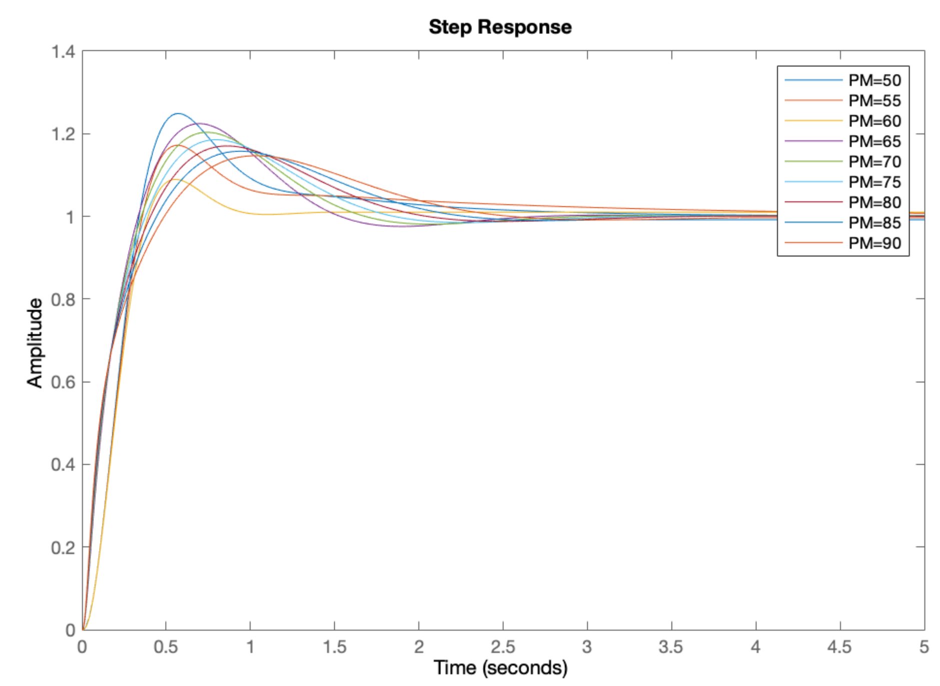
Block diagram for control system

Controller Design Methods:

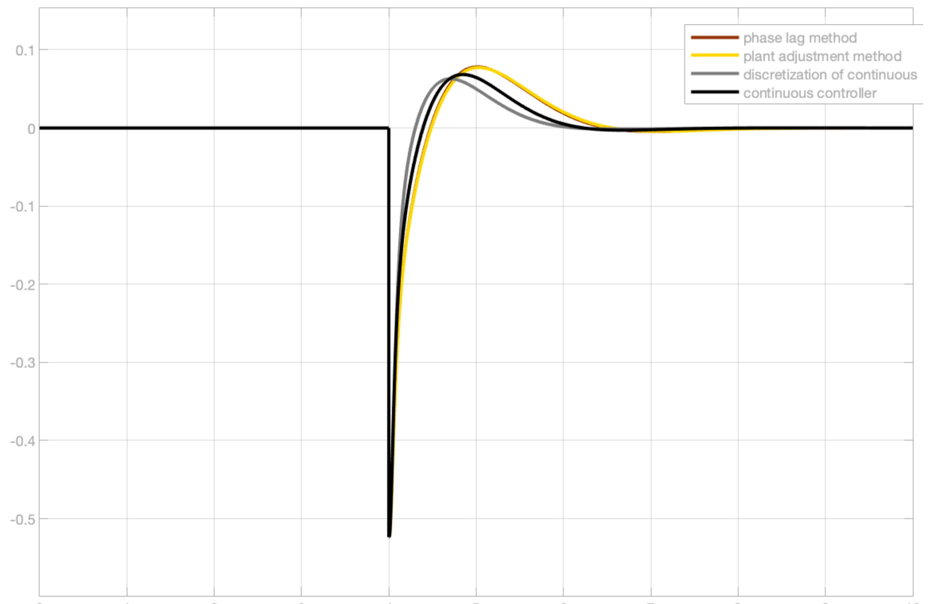
Design CT controller for BW and PM; discretize with ZOH
Discretize plant with ZOH, convert to CT with Tustin, design CT controller, then discretize with ZOH.
Design CT controller for BW and PM with ZOH lag accounted for in PM-based calculations
Design CT controller for pole placement & step response, discretize with ZOH

Design for Bandwidth and Phase Margin: PI(D):

Choose a bandwidth and create a family of controllers for a range of phase margins
Some require two poles to generate sufficient phase. These are PID.
Two-pole controllers have more aggressive initial response, which is ideal for preventing an object from falling



Family of step responses for continuous PI(D) controllers with bandwidth ≈ 5 rad/s



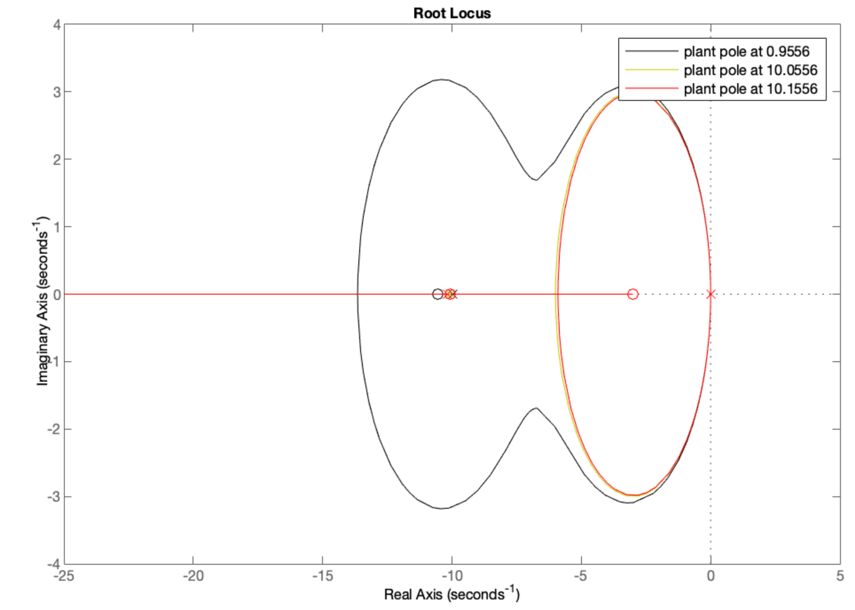
Comparison of disturbance response for different BW/PM methods (BW = 5; PM = 90°)

Controller:

Discrete Controller
Low-Pass Filter ($\omega_g = 100$)
Output Quantized to ±10000 steps due to PWM
Output Limited to ±24V
No prefilter needed because of unchanging setpoint (controller designed for disturbance rejection)

Pole Cancellation Considerations:

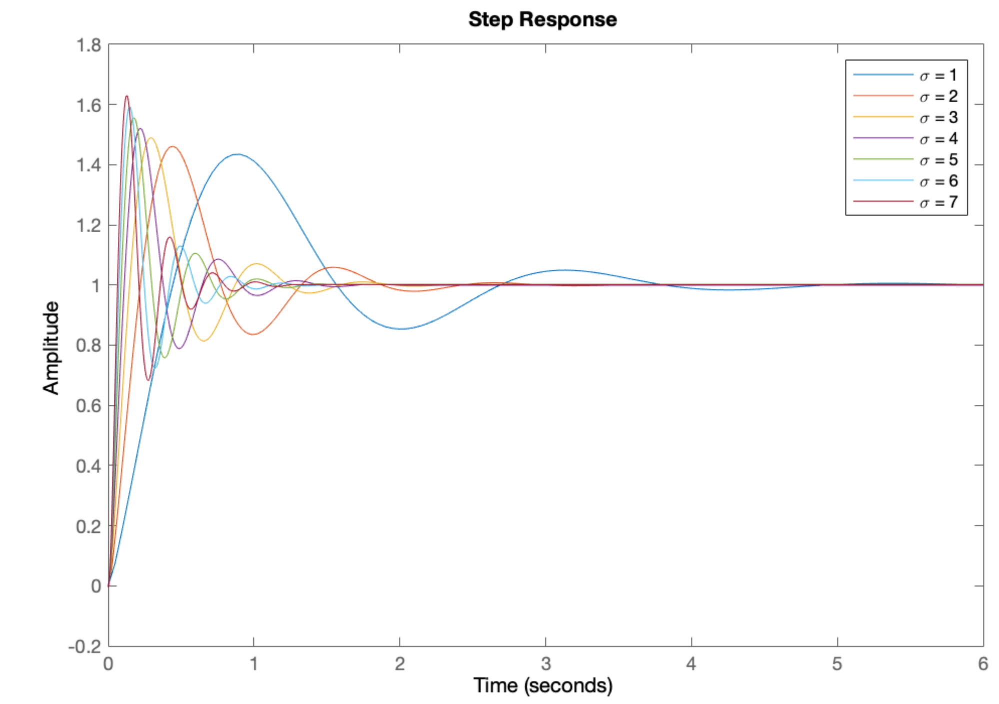
Little danger in overestimating pole
Underestimating pole could lead to deformations in root locus
These deformations are less significant for smaller polar angle and gain



Root locus plot describing effects of cancelling an incorrectly modeled pole

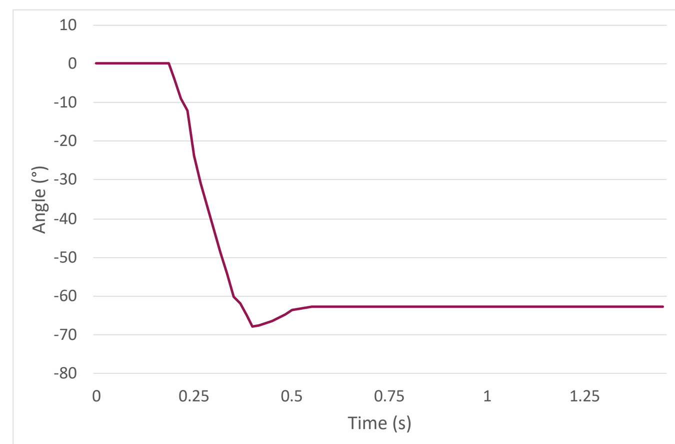
Design for Pole Placement:

One zero at modeled plant fast pole
Choose a polar angle and create a family of controllers for a range of sigmas
θ corresponds with overshoot, σ is inversely proportional to settling time
If implementing, discretize with ZOH
Overshoots differ because of the inclusion of the LPF

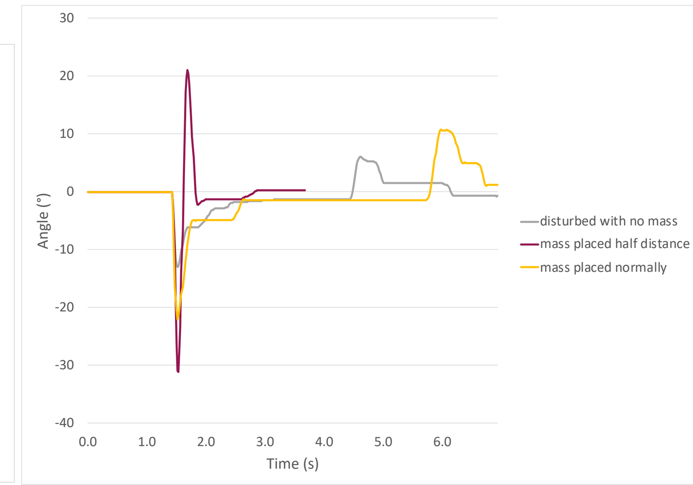


Family of step responses for continuous PI(D) controllers with θ ≈ 20°

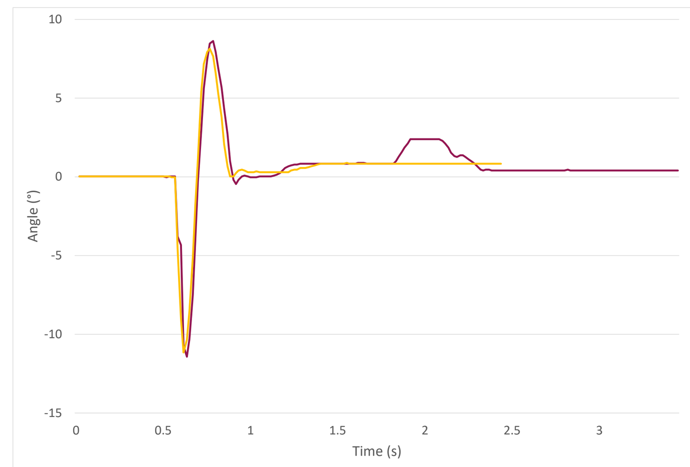
Results



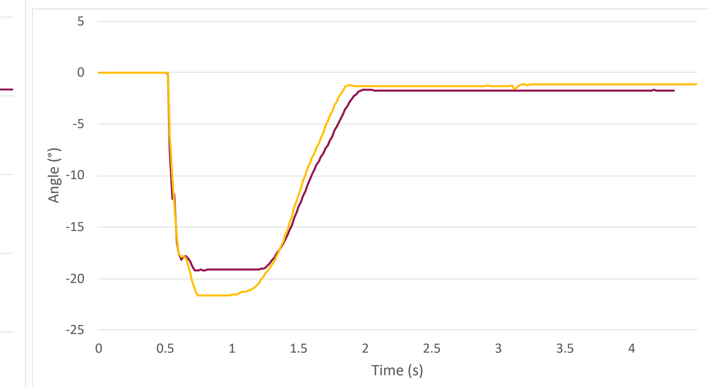
Response to mass when motor is unpowered



Measured responses of a suboptimal controller



Response with controller θ = 20°, σ = 7



Response with controller BW = 5, PM = 90°

Observations:

For the purpose of catching a falling mass, a more aggressive transient response is desirable. This can't be increased infinitely because of the limit to voltage supplied.
Controllers designed for BW and PM did not response similarly to their simulations, but had high enough stability margins to still function

Nonlinearities:

While there was little dynamic friction, static friction is significant
With the mass on the end, it would take 5–6 volts for movement to begin
Makes it difficult for the system to settle into a steady state gently
Torque due to addition of mass
Controllers were able to stabilize for this, but not able to design for this

Next Steps:

Apply knowledge of software handling of this particular sensor to the controlled ascent of a rocket
Apply knowledge of software handling of discrete control system (state recording, interrupt timing)
Use a different motor or find ways to account for static friction in rocket controller design
Actuating fins will likely be a lower torque system, especially due to not having to work against gravity, but aerodynamic forces will still cause torques
System will need to be much faster, and overshoot may be less desired

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