Inverted Pendulum: Swing-up, Balance, Catching

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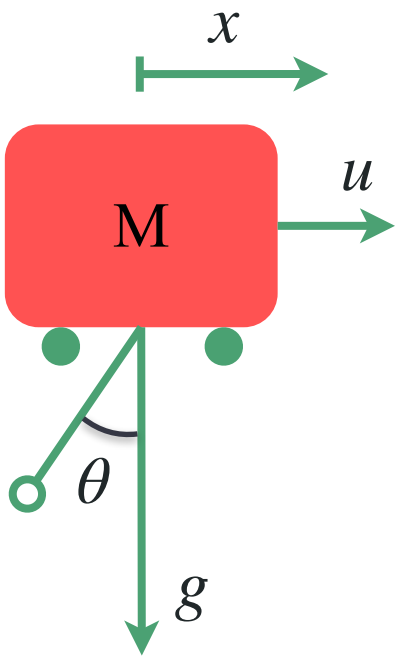
System Description

- Asymmetric metal rod with end pinned to cart
- Encoder for angle of rod
- Single Motor to drive cart
- Encoder for position of cart

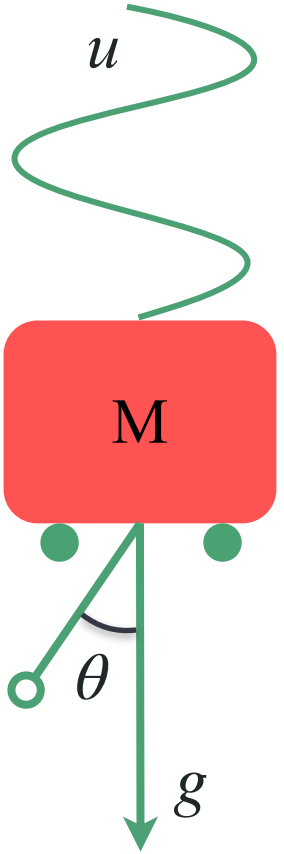


System Objectives

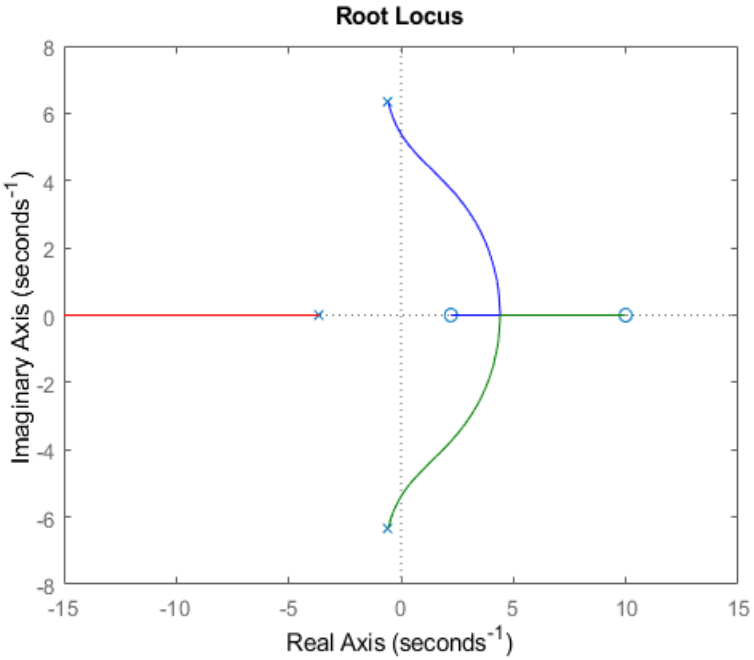
- Stabilize downward equilibrium (for faster catching)
- Stabilize upward equilibrium
- State transition between equilibria

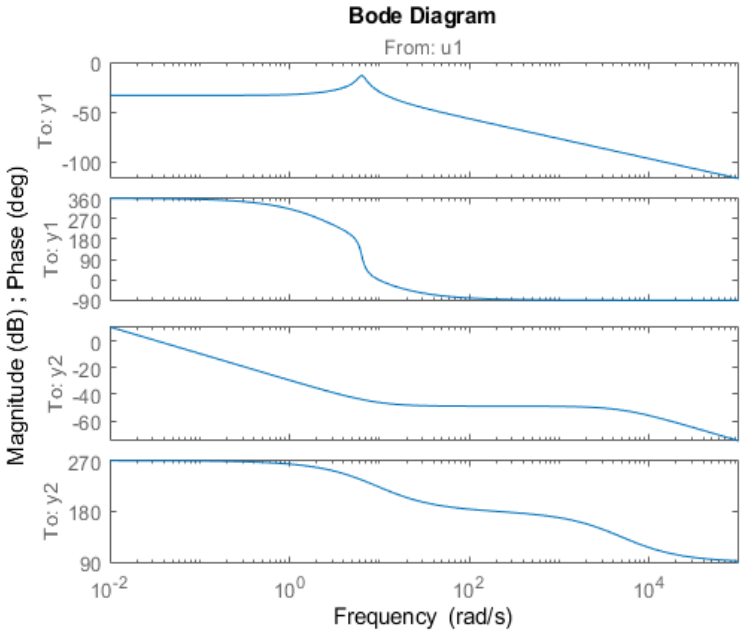
Model Identification

- Logarithmic Sine sweep ($f \in [0.3, 3]$ Hz)
- Tfest on 30 experiments to estimate linear model
- Assumed integrator for cart, fit Voltage to Velocity model
- Used 2 poles, 1 zero for cart, 3 poles 2 zeros for pendulum

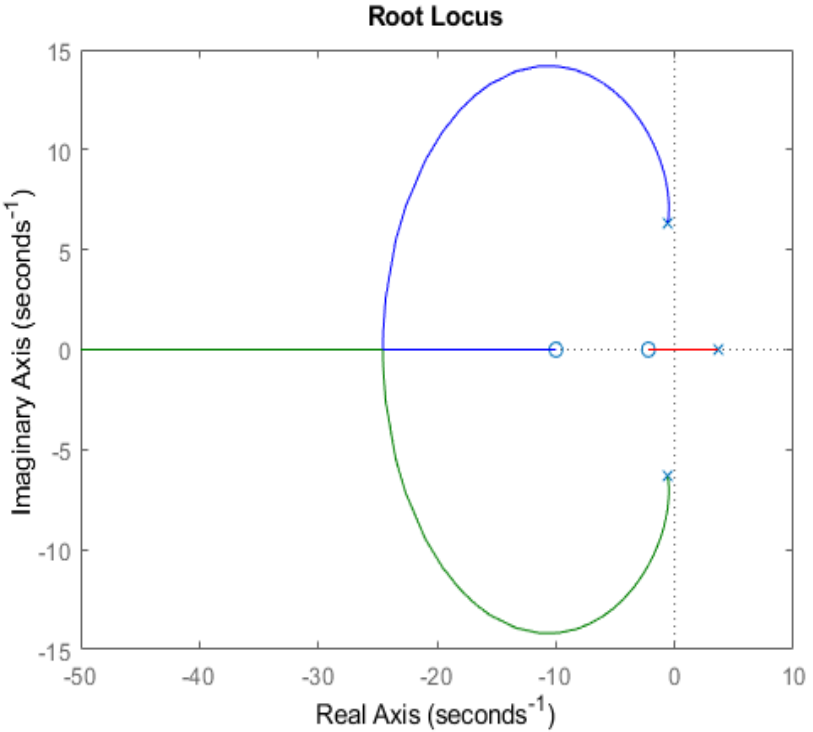


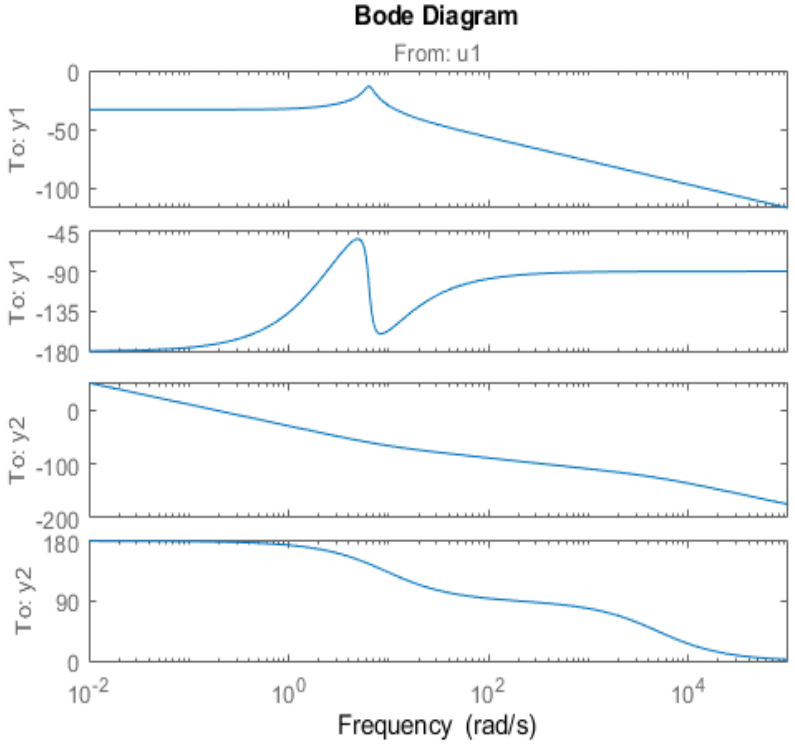
Identification of the stable equilibrium



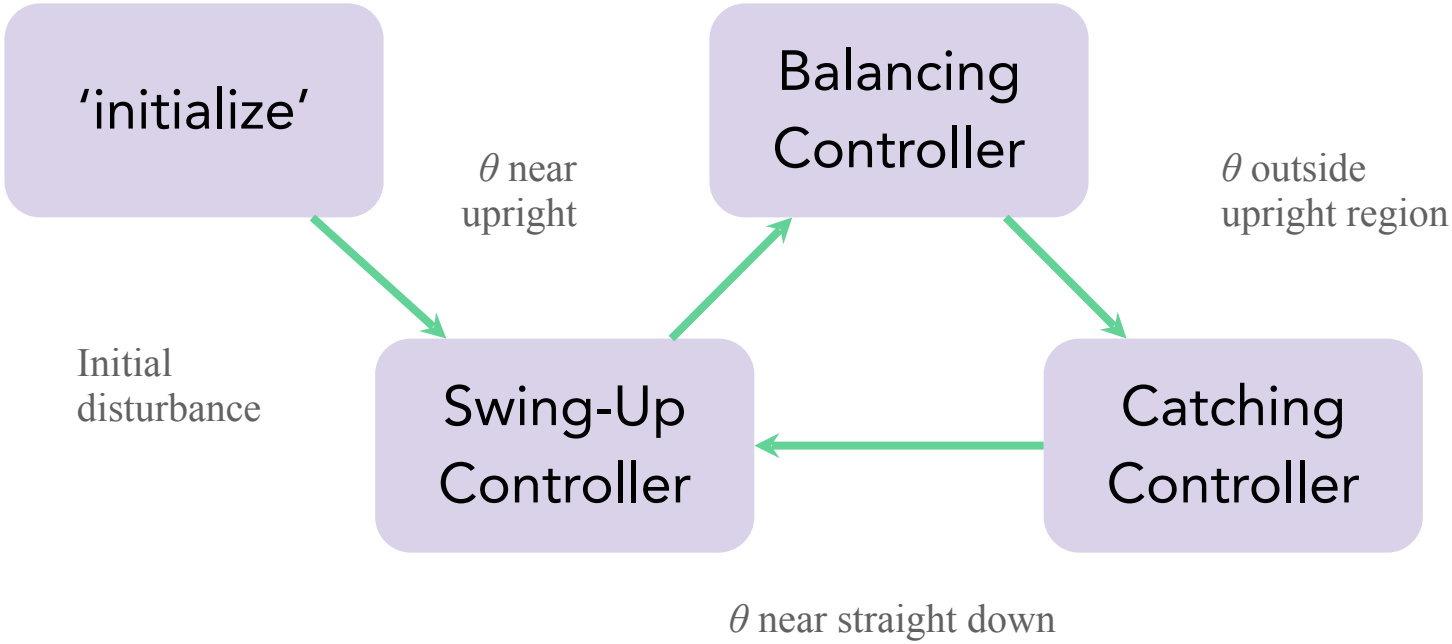


Modify for unstable equilibrium



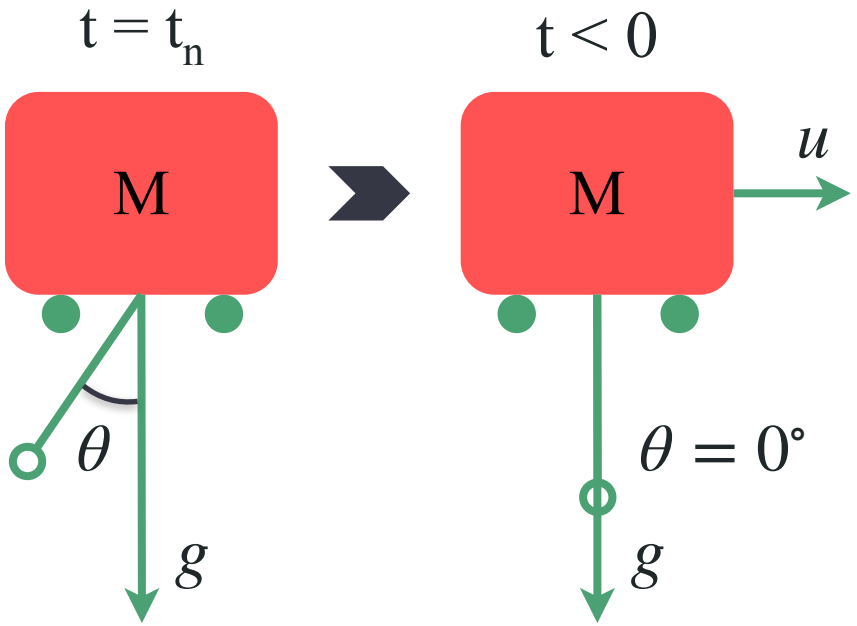


State Machine



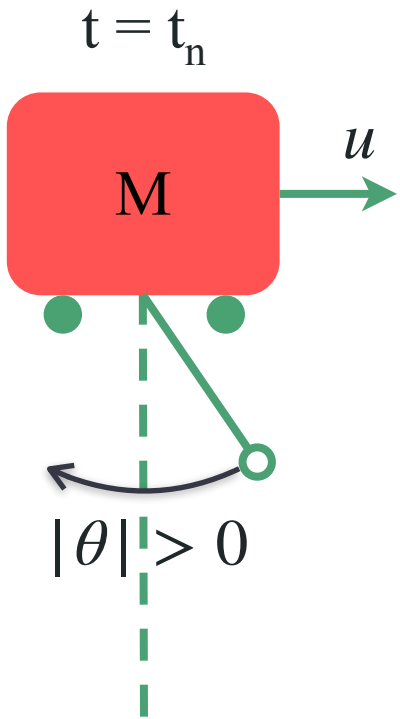
Initialization

- Accurate initial theta with gravity aligning the pendulum
- Important to have accurate reading for inverted upward position



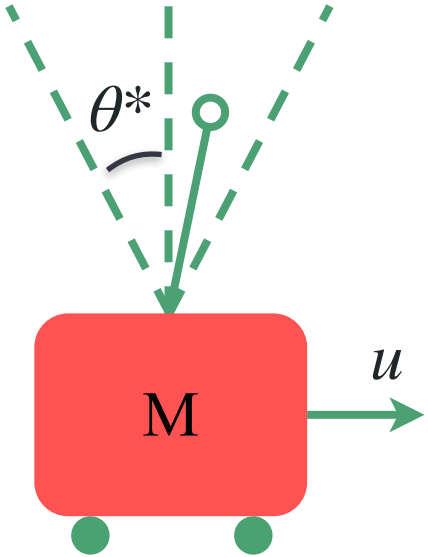
Swing Up Controller

- Energy addition method:
  - Around every zero crossing of θ, the cart moves in direction opposite to the direction of the velocity to increase the energy in the pendulum
  - Continues until pendulum is able to fully “swing up”
  - Simple proportional controller regulates cart position
- The activation is limited to a range $\theta \in [-30,30]°$ to try and reach inverted state with a small velocity



Balancing Controller

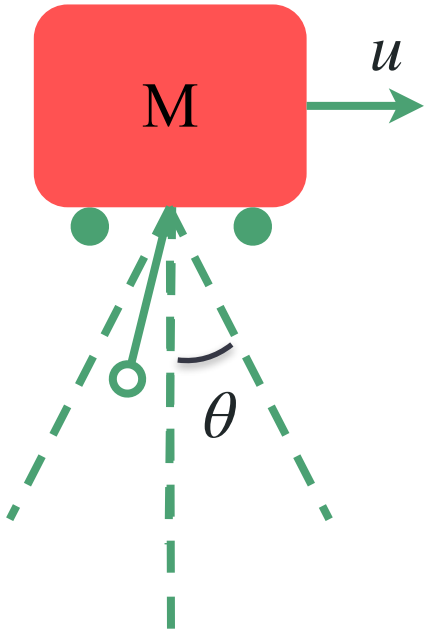
- Activates upon state entering:
  - $\theta^* \in [-23,23]°$
  - Swing Up getting ‘close’
- Stabilizes unstable equilibrium
- Utilizes LQR/LQG with the model identified earlier to regulate both cart position and pendulum angle
- Carefully tuned parameters to be as robust as possible



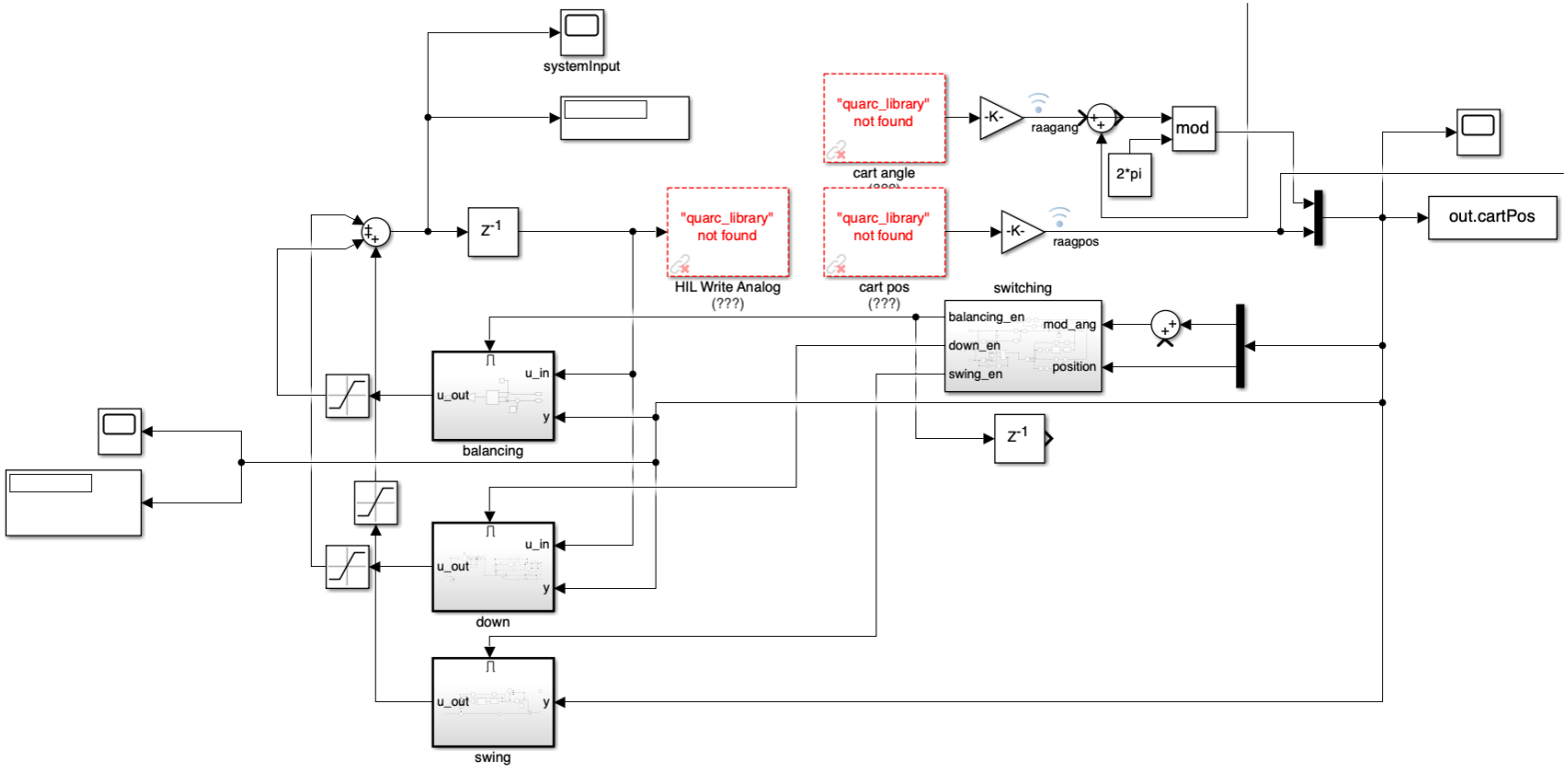
Note: $\theta^* = \theta \bmod(2\pi) - \pi$

Catching Controller

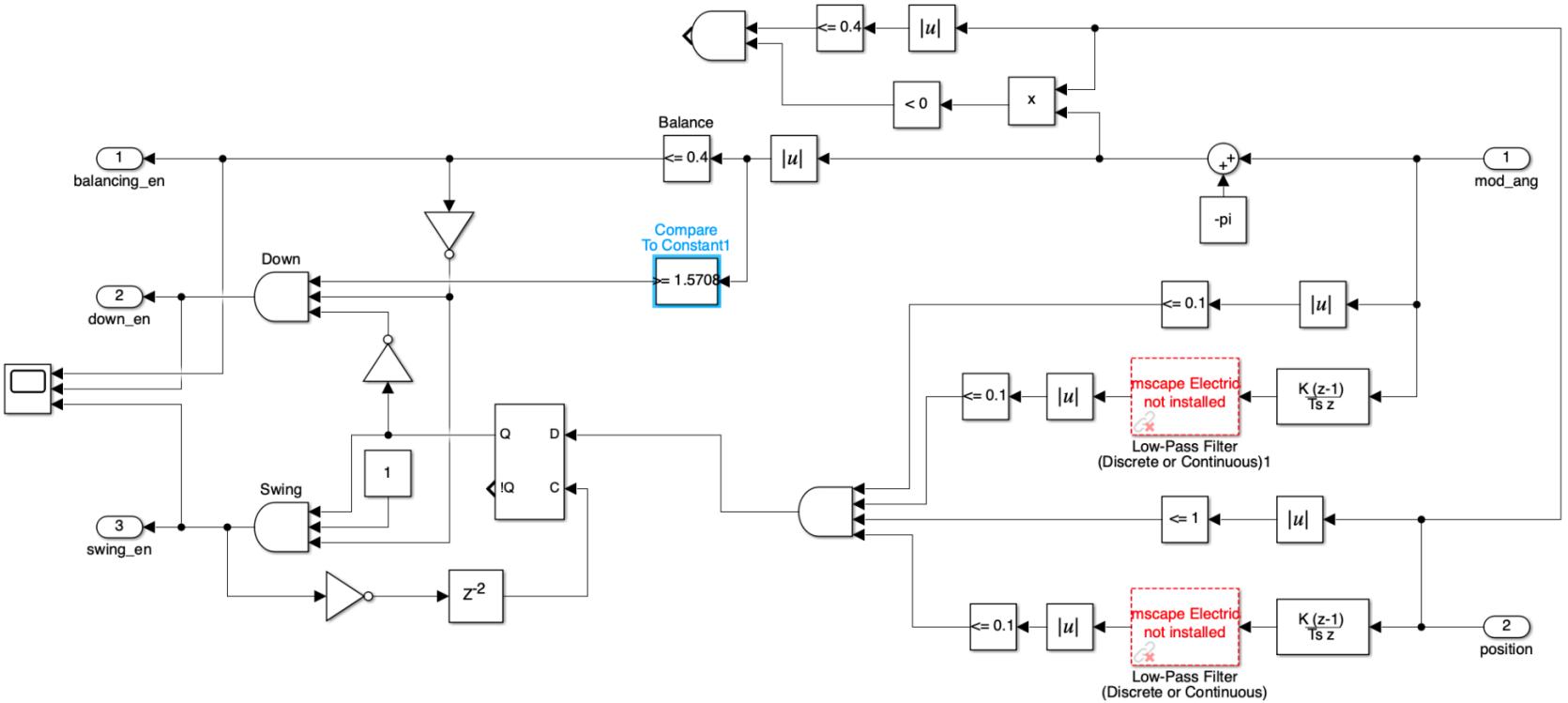
- Activates upon state entering:
  - $\theta \in [-90,90]°$
  - Pendulum Falls
- Also utilizes LQR/LQG, this time to return to the bottom stable position
- Brings pendulum back into predictable state to start Swing Up Controller



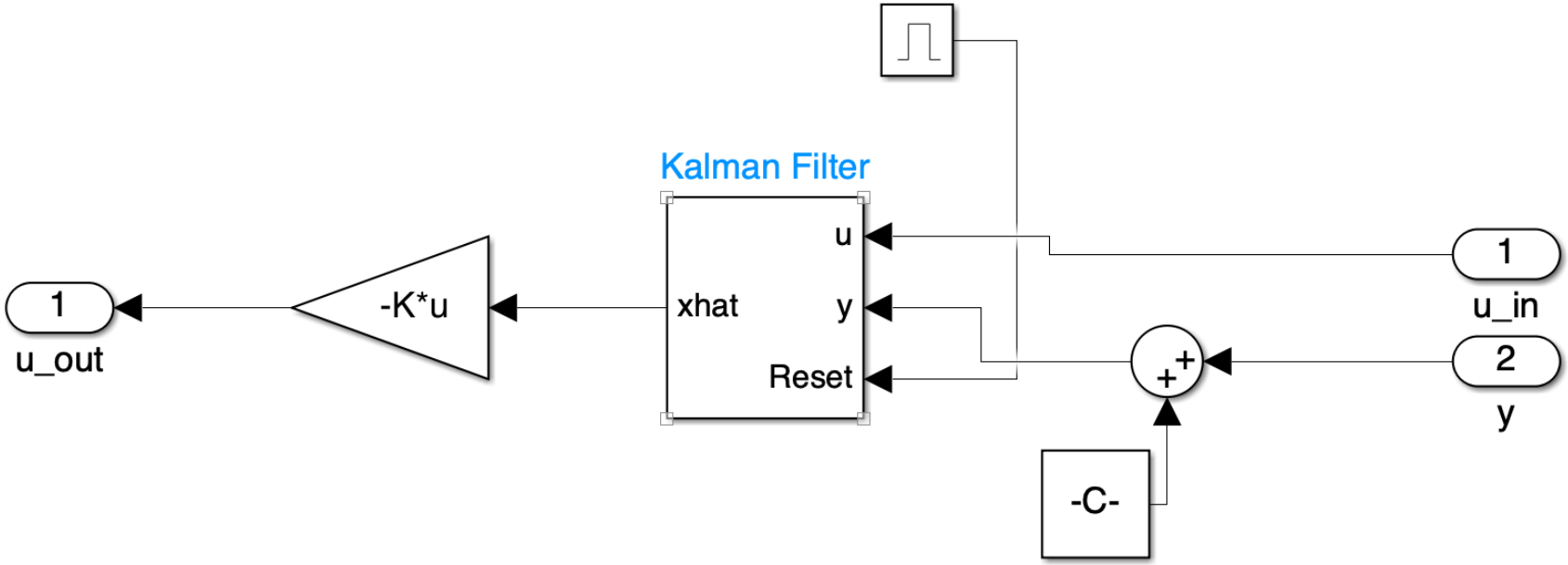
Full Controller



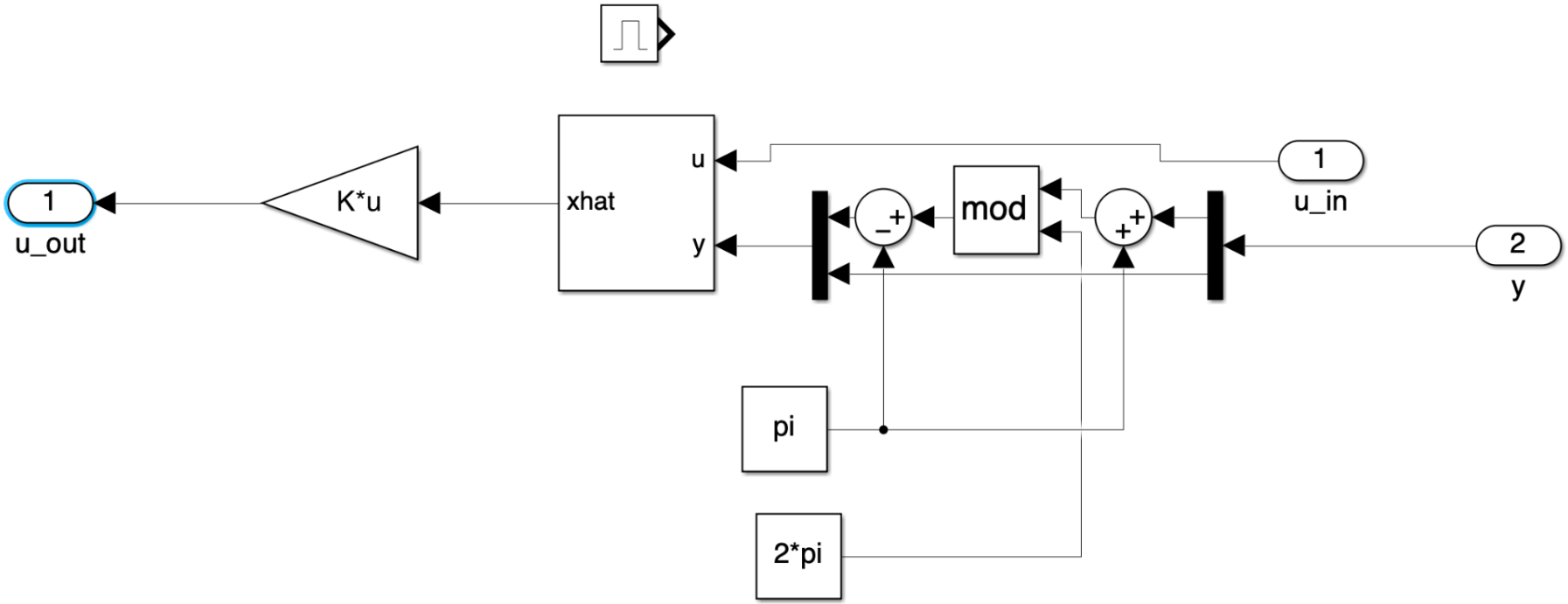
Switching


1
balancing_en
2
down_en
3
swing_en
Down
Swing
1
Q
D
!Q
C
Z-2
Balance
<= 0.4
|u|
< 0
x
Compare
To Constant1
>= 1.5708
-pi
1
mod_ang
<= 0.1
mscape Electric
not installed
K (z-1)
Ts z
Low-Pass Filter
(Discrete or Continuous)1
<= 1
2
position
Low-Pass Filter
(Discrete or Continuous)

Balancing



Catching



Demo:

see YouTube link on raaghavt.com

Future Work

- Introduce correction term to account for steady state error
- More robust failure logic

Acknowledgement

Zeki

Joao