Mail Bot

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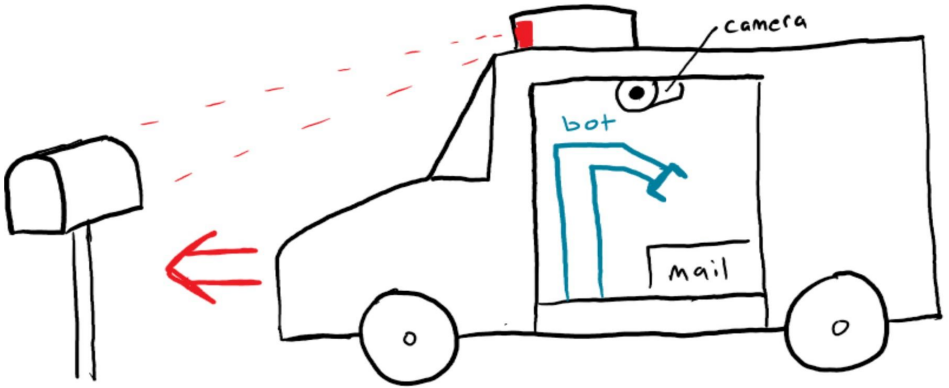
High Level Goals

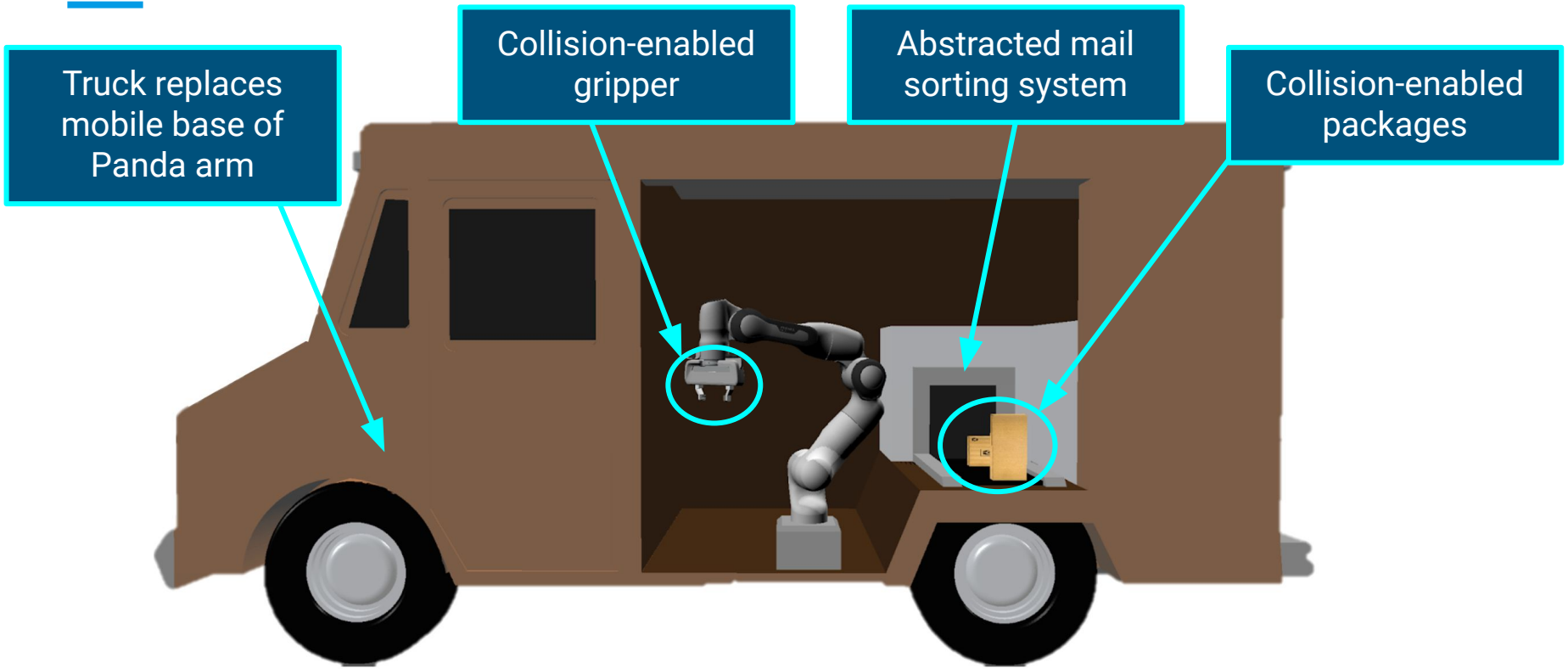
- **Goal:** Combine robotic manipulation with driverless car technology to achieve fully autonomous mail delivery.

- **Project Goals / Scope:**
  - Truck brings robot to mailbox
  - Robot tasks
    - Open mailbox
    - Grab mail
    - Place mail in mailbox
    - Close mailbox



Concept

Modeling - Mail Bot



Modeling - Other “Robots”

Mailbox

- Revolute hinge
- Revolute handle to maintain gripper orientation
- Collision-enabled handle
- Collision-enabled container

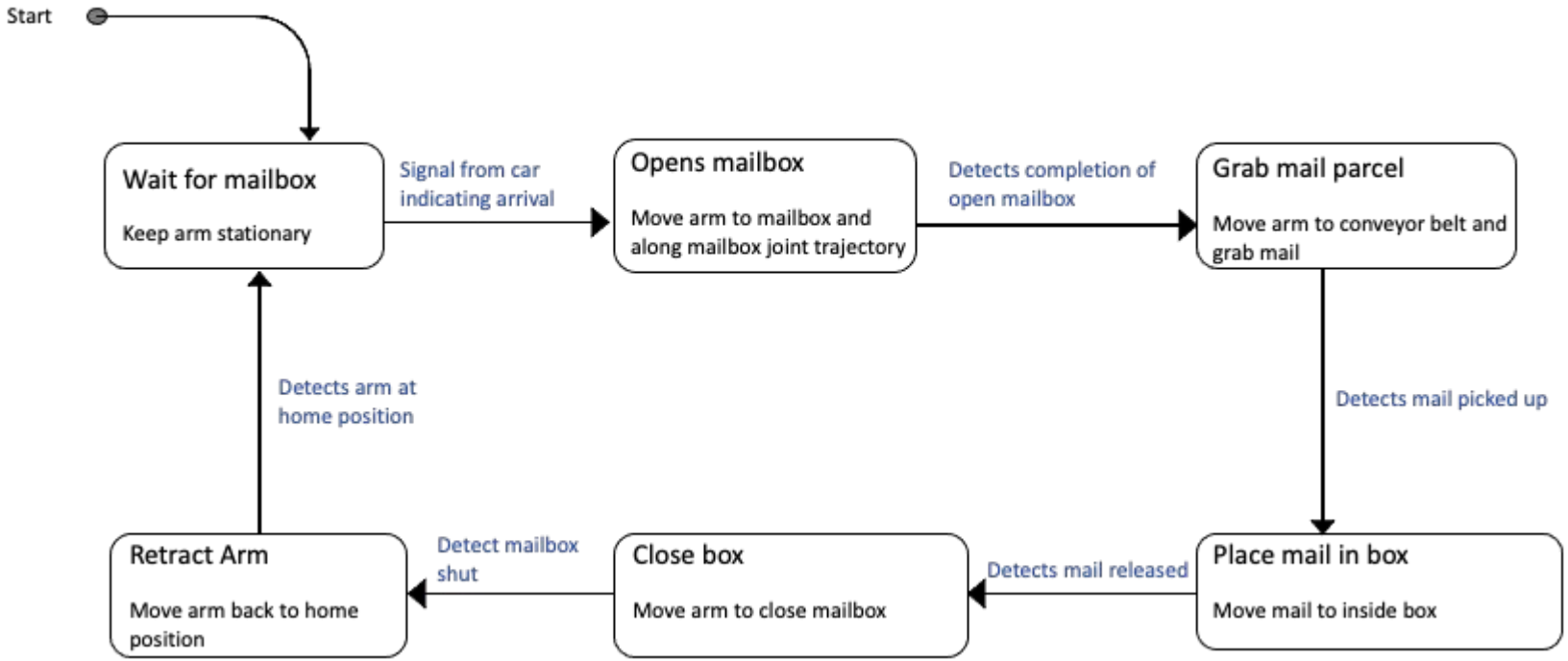
Package

- 6-joint free object
- Collision-enabled
- 3 different sizes modeled

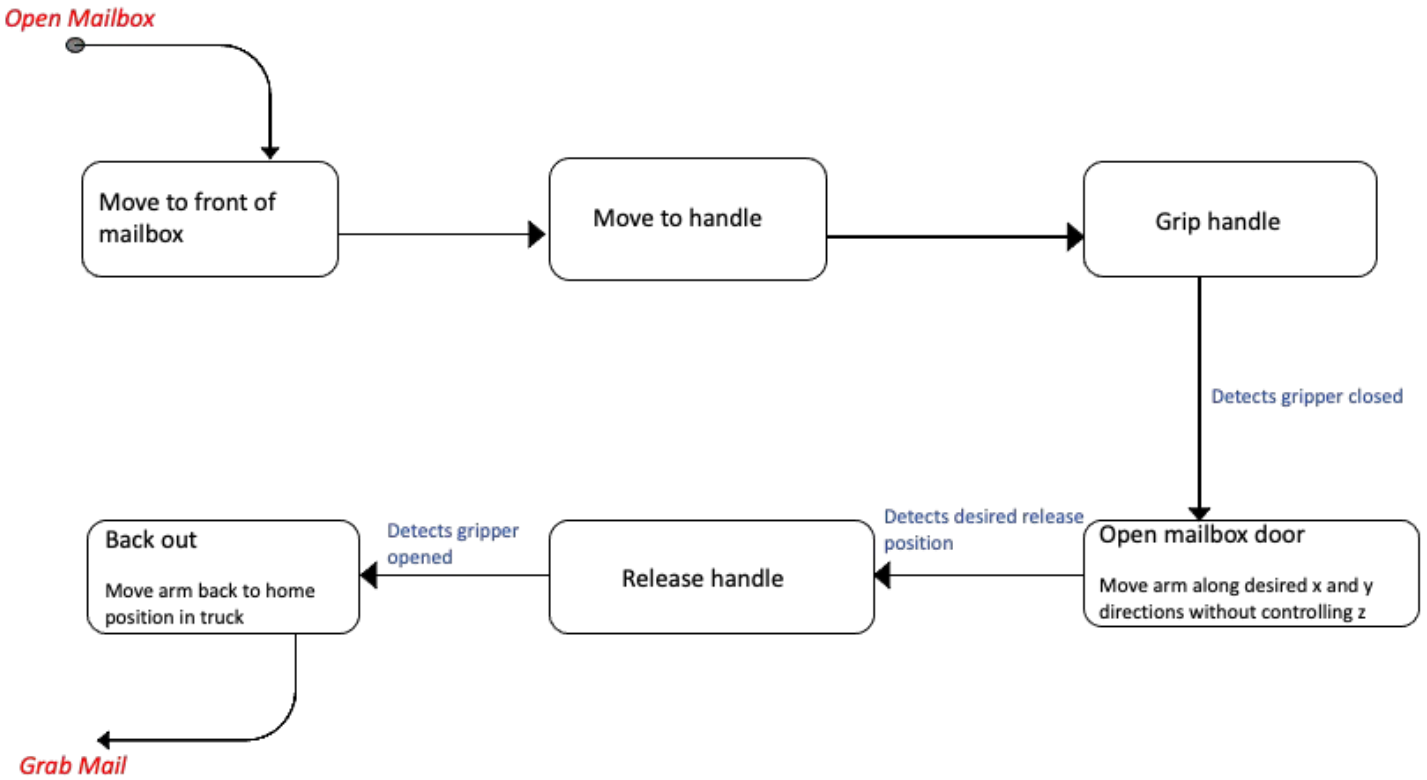
Modeling - Environment

- Suburban Environment
  - Houses
  - Trees
  - Cats everywhere
- Linear travel only

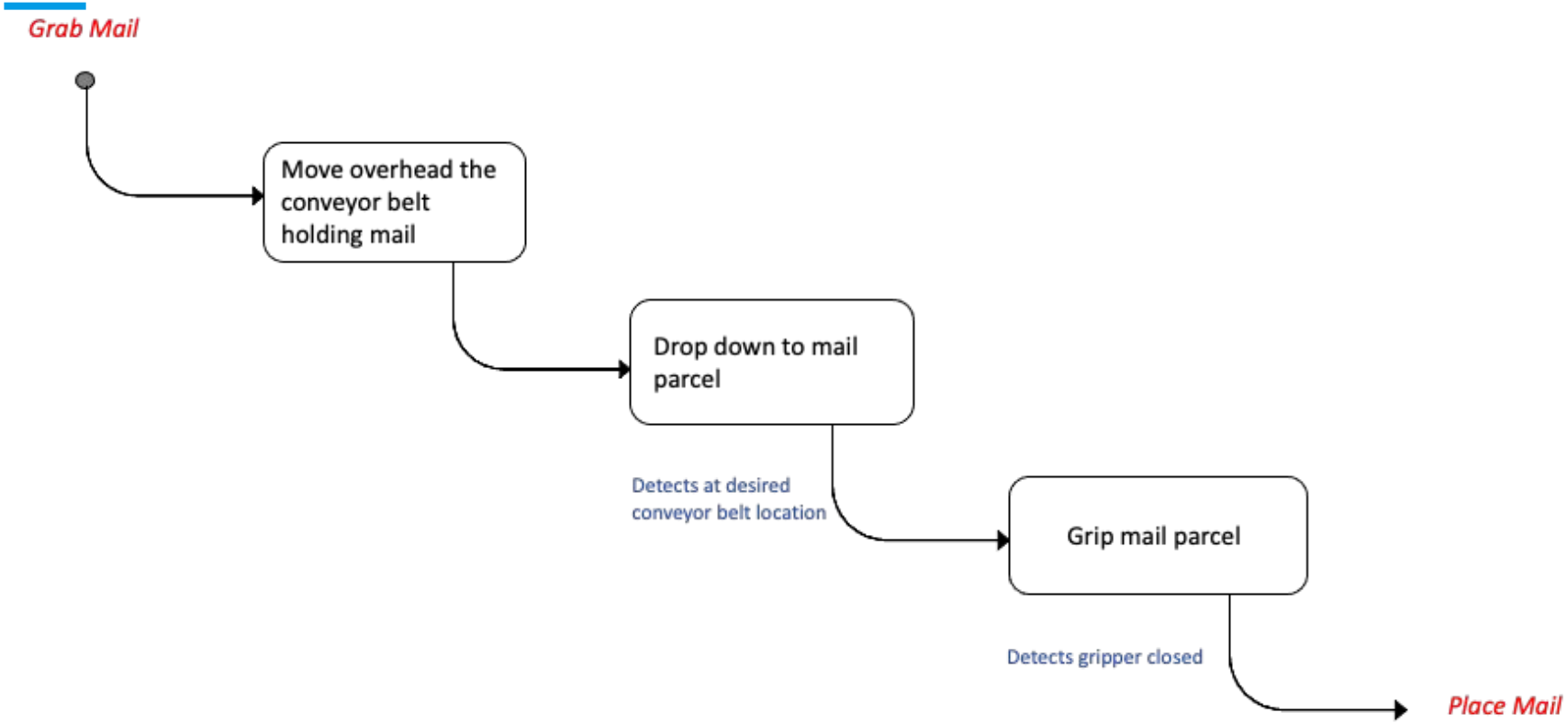
State machine diagram



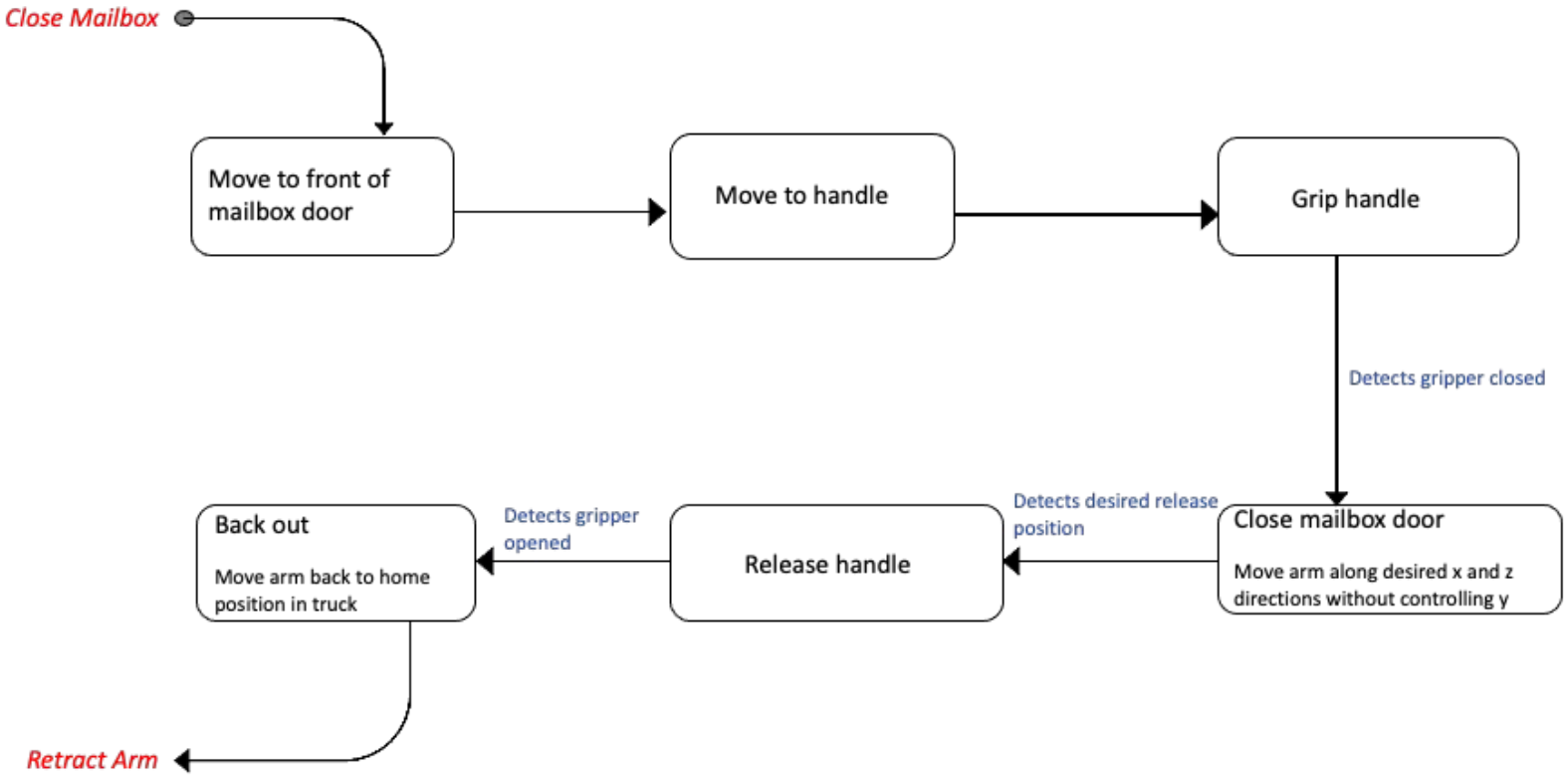
Sub-state machine - Open mailbox



Sub-state machine - Grab mail



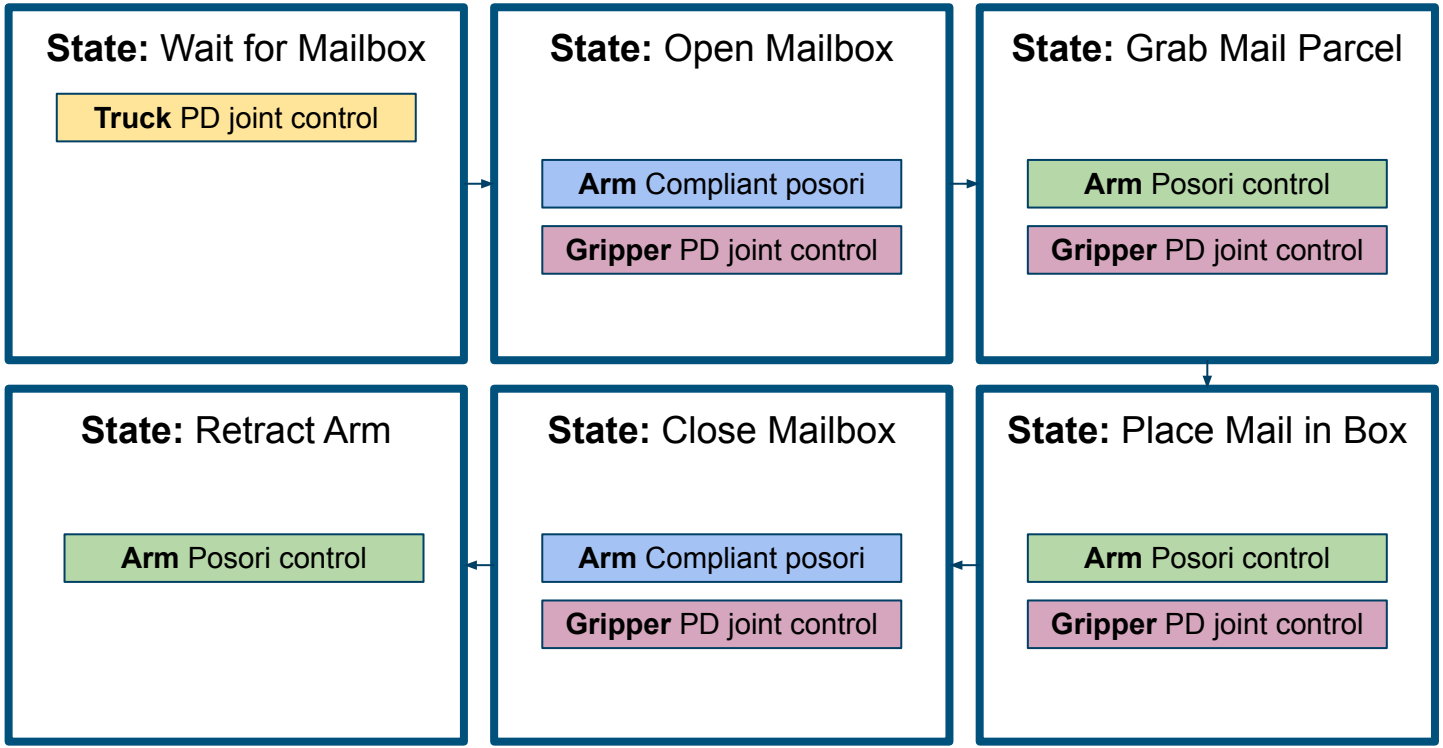
Sub-state machine - Close mailbox



Controller - High-level

Controllers

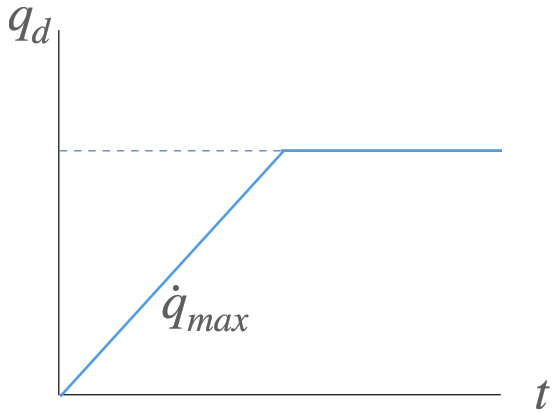
- **Truck** PD joint control
- **Arm** Posori control
- **Arm** Compliant posori
- **Gripper** PD joint control



Controller - Truck

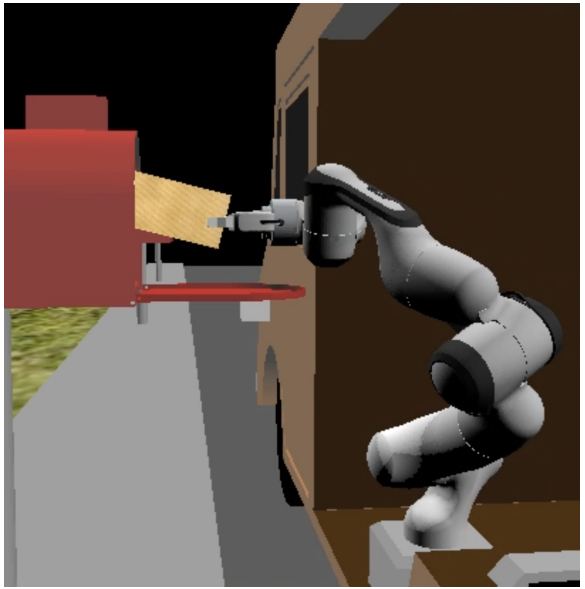
- PD joint-space control moves the truck to the mailbox and maintains position during mail delivery
  - Truck is limited to one DoF (forwards and backwards)
- Velocity saturation limits the truck speed
- A large mass helps stabilize the truck during other states

$$\Gamma = A(-k_p(q - q_d) - k_v\dot{q}) + b + g$$



Controller - Robust Arm Movement

- Position-orientation control for arm joints only
  - Posture controlled in the null-space using a task-dependent posture
    - Interior posture used for grabbing mail in the truck
    - Exterior posture used for opening/closing the mailbox and placing mail into the mailbox
  - Velocity saturation limits speed at the end effector
- Truck and gripper positions maintained with PD control



Controller - Robust Arm Movement

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{15} & m_{16} & m_{17} & m_{18} & m_{19} & m_{1,10} & m_{1,11} & m_{1,12} \\ m_{21} & m_{22} & m_{23} & m_{24} & m_{25} & m_{26} & m_{27} & m_{28} & m_{29} & m_{2,10} & m_{2,11} & m_{2,12} \\ m_{31} & m_{32} & m_{33} & m_{34} & m_{35} & m_{36} & m_{37} & m_{38} & m_{39} & m_{3,10} & m_{3,11} & m_{3,12} \\ m_{41} & m_{42} & m_{43} & m_{44} & m_{45} & m_{46} & m_{47} & m_{48} & m_{49} & m_{4,10} & m_{4,11} & m_{4,12} \\ m_{51} & m_{52} & m_{53} & m_{54} & m_{55} & m_{56} & m_{57} & m_{58} & m_{59} & m_{5,10} & m_{5,11} & m_{5,12} \\ m_{61} & m_{62} & m_{63} & m_{64} & m_{65} & m_{66} & m_{67} & m_{68} & m_{69} & m_{6,10} & m_{6,11} & m_{6,12} \\ m_{71} & m_{72} & m_{73} & m_{74} & m_{75} & m_{76} & m_{77} & m_{78} & m_{79} & m_{7,10} & m_{7,11} & m_{7,12} \\ m_{81} & m_{82} & m_{83} & m_{84} & m_{85} & m_{86} & m_{87} & m_{88} & m_{89} & m_{8,10} & m_{8,11} & m_{8,12} \\ m_{91} & m_{92} & m_{93} & m_{94} & m_{95} & m_{96} & m_{97} & m_{98} & m_{99} & m_{9,10} & m_{9,11} & m_{9,12} \\ m_{10,1} & m_{10,2} & m_{10,3} & m_{10,4} & m_{10,5} & m_{10,6} & m_{10,7} & m_{10,8} & m_{10,9} & m_{10,10} & m_{10,11} & m_{10,12} \\ m_{11,1} & m_{11,2} & m_{11,3} & m_{11,4} & m_{11,5} & m_{11,6} & m_{11,7} & m_{11,8} & m_{11,9} & m_{11,10} & m_{11,11} & m_{11,12} \\ m_{12,1} & m_{12,2} & m_{12,3} & m_{12,4} & m_{12,5} & m_{12,6} & m_{12,7} & m_{12,8} & m_{12,9} & m_{12,10} & m_{12,11} & m_{12,12} \end{bmatrix}$$

M_{truck} M_{arm} $M_{gripper}$

$$J = \begin{bmatrix} J_{11} & J_{12} & J_{13} & J_{14} & J_{15} & J_{16} & J_{17} & J_{18} & J_{19} & J_{1,10} & J_{1,11} & J_{1,12} \\ J_{21} & J_{22} & J_{23} & J_{24} & J_{25} & J_{26} & J_{27} & J_{28} & J_{29} & J_{2,10} & J_{2,11} & J_{2,12} \\ J_{31} & J_{32} & J_{33} & J_{34} & J_{35} & J_{36} & J_{37} & J_{38} & J_{39} & J_{3,10} & J_{3,11} & J_{3,12} \\ J_{41} & J_{42} & J_{43} & J_{44} & J_{45} & J_{46} & J_{47} & J_{48} & J_{49} & J_{4,10} & J_{4,11} & J_{4,12} \\ J_{51} & J_{52} & J_{53} & J_{54} & J_{55} & J_{56} & J_{57} & J_{58} & J_{59} & J_{5,10} & J_{5,11} & J_{5,12} \\ J_{61} & J_{62} & J_{63} & J_{64} & J_{65} & J_{66} & J_{67} & J_{68} & J_{69} & J_{6,10} & J_{6,11} & J_{6,12} \end{bmatrix}$$

J_{arm}

$$\dot{x}_d = \frac{k_p}{k_v}(x_d - x)$$

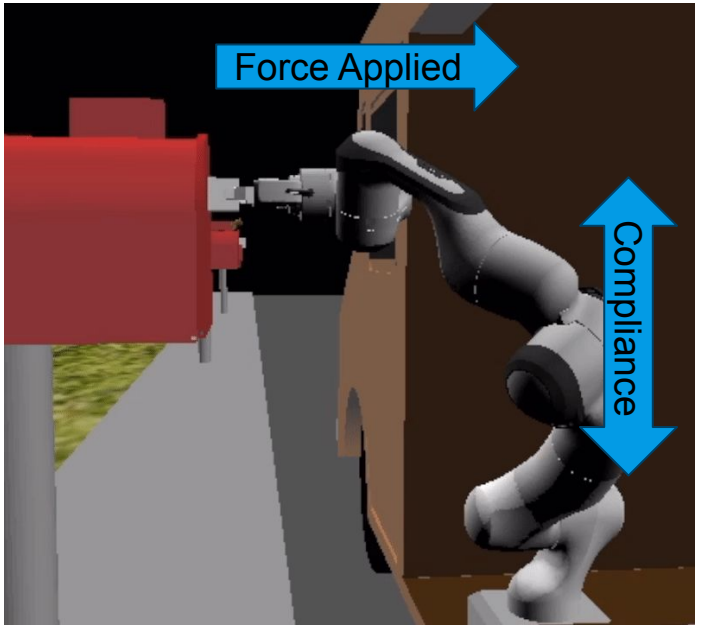
$$v = sat\left(\frac{V_{max}}{|\dot{x}_d|}\right)$$

$$F = \Lambda_0 \begin{bmatrix} \Sigma_F(-k_v)(\dot{x} - v\dot{x}_d) \\ -k_p(\partial\phi) - k_v\omega \end{bmatrix}$$

$$\Gamma = \begin{bmatrix} M_{truck}(-k_p(q_{truck} - q_{d_{truck}}) - k_v\dot{q}_{truck}) \\ J_{arm}^T F + N^T M_{arm}(-k_p(q_{arm} - q_{d_{arm}}) - k_v\dot{q}_{arm}) \\ M_{gripper}(-k_p(q_{gripper} - q_{d_{gripper}}) - k_v\dot{q}_{gripper}) \end{bmatrix} + g$$

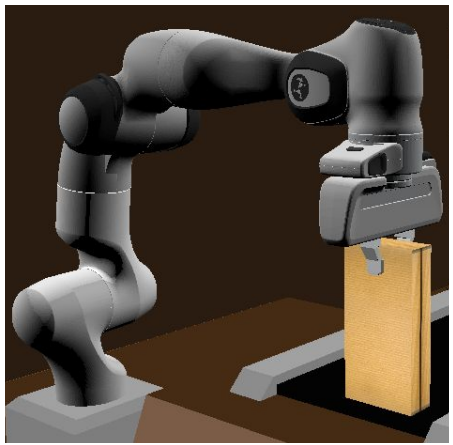
Controller - Compliant Open/Close

- Selection matrix applied to the arm movement controller, which zeroes out the compliant direction
  - During opening, the controller pulls back while maintaining vertical compliance
  - During closing, the controller pushes up while maintaining horizontal compliance



Controller - Gripper

- PD joint-space control is used to set and maintain the gripper position
  - Joint position set to full-closed position
  - After 1 second the parcel is considered “gripped” and the state changes
- Force feedback not implemented (no fragile packages, excluding cat)



$$\Gamma = A(-k_p(q - q_d) - k_v\dot{q}) + g$$

Challenges

- Separating joints
  - **Resolution:** Dissect Jacobian and Mass Matrix to execute operation space control for the arm. Combined operation space for the arm + joint space for the truck / gripper
- Carrying mail in the truck
  - **Resolution:** Mail parcels are locked relative to the truck joint until gripped. Dynamics are enabled after gripping.
- Compliant opening of mailbox
  - **Resolution:** A Selection matrix is used to zero torque in the compliant direction and a rotating collision mesh at the handle allows the handle to maintain orientation.

Future Extensions

- Gripping compliant objects with force feedback
- Handling a variety of mailboxes
- In a physical system, add computer vision
- Negative potential to avoid collisions (e.g. cat’s paw swiping)