CLOSED-LOOP PALLET ENGAGEMENT IN AN UNSTRUCTURED ENVIRONMENT

Sertac Karaman, **Matthew Walter**, Emilio Frazzoli, & Seth Teller
CSAIL, LIDS
Massachusetts Institute of Technology

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JOINT WORK WITH

Sertac Karaman
(MIT/LIDS)

Emilio Frazzoli
(MIT/LIDS)

Seth Teller
(MIT/CSAIL)

CSAIL

AUTONOMOUS PALLET MANIPULATION

I. Palletized Cargo Manipulation: An Overview

II. LP Formulation for Fast, Closest Edge Detection

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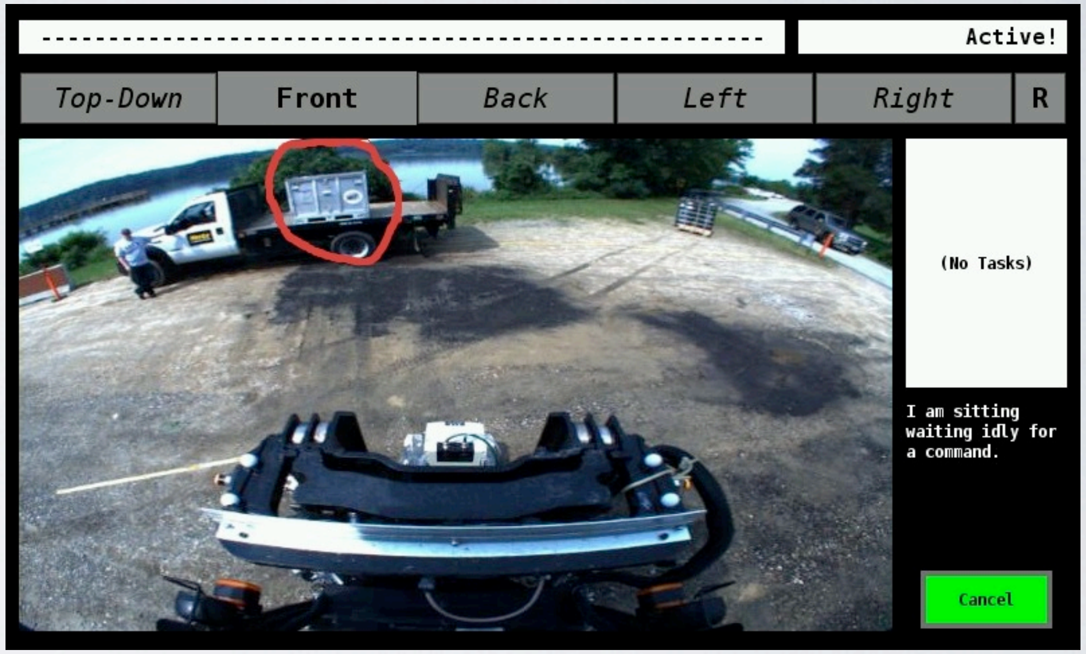
FLEXIBLE IN-SITU WAREHOUSE AUTOMATION

Goal: Autonomous palletized material handling in short-term outdoor warehouses

- Environment: Dynamic, forward-operating storage facilities
  - Disaster relief (Red Cross, FEMA), Military
  - Little reliable structure
  - Rapid, temporary deployment
  - Uneven terrain
  - Dynamic (people, vehicles)

HUMAN-DIRECTED MANIPULATION

- Hand-held tablet command interface
- Supervisor circles pallets to be picked up
- Supervisor circles desired destinations
- Manipulation is autonomous
  - Detect pallet and truck bed
  - Safely engage and place pallets



HUMAN-DIRECTED PALLET MANIPULATION

Autonomously pickup pallets from ground and from unknown truck beds

[Video: 2009_11_30_agile_short.mp4]

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Autonomously place pallets onto ground and onto unknown truck beds

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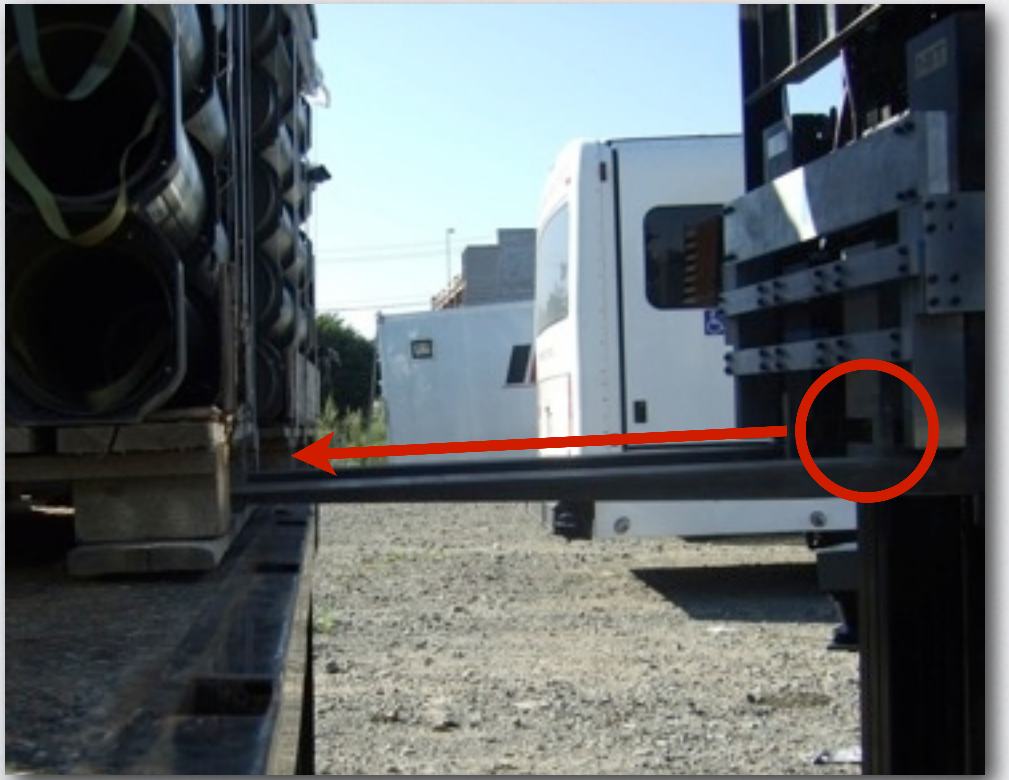
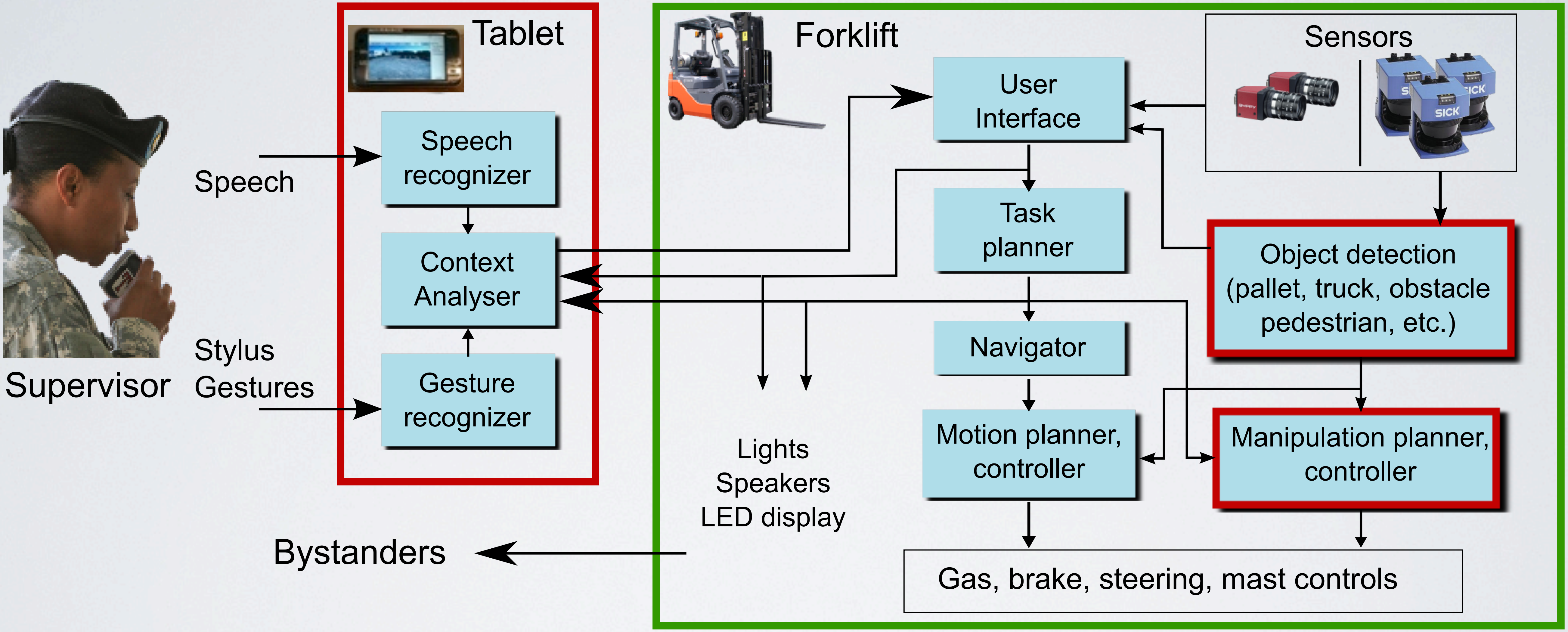
THE ROBOT: SENSING

- LIDARs directed along tines for pallet detection and servoing during fork insertion
- LIDARs with vertical FOV mounted to carriage for truck detection

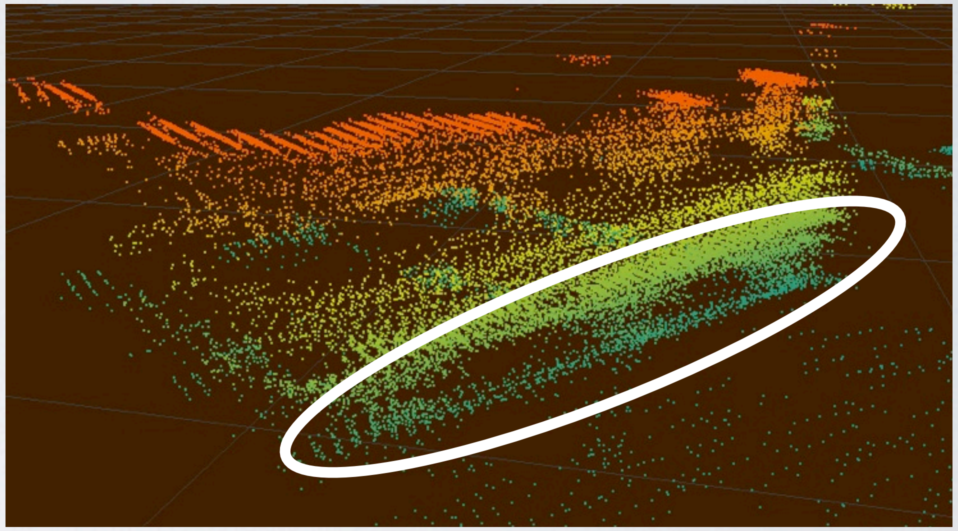


SYSTEM ARCHITECTURE



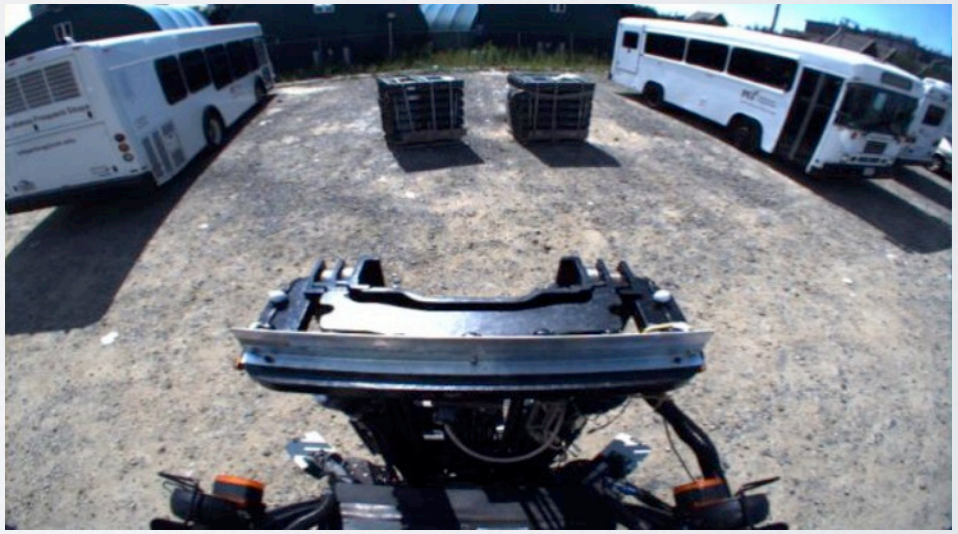
WHY IS THIS HARD?

- LIDAR range returns are noisy
- Variable pallet geometry and structure
- Pallet and truck poses unknown *a priori*
- Sparse pallet and truck structure yields limited LIDAR returns
- Pallet load is variable and unknown



Assumptions

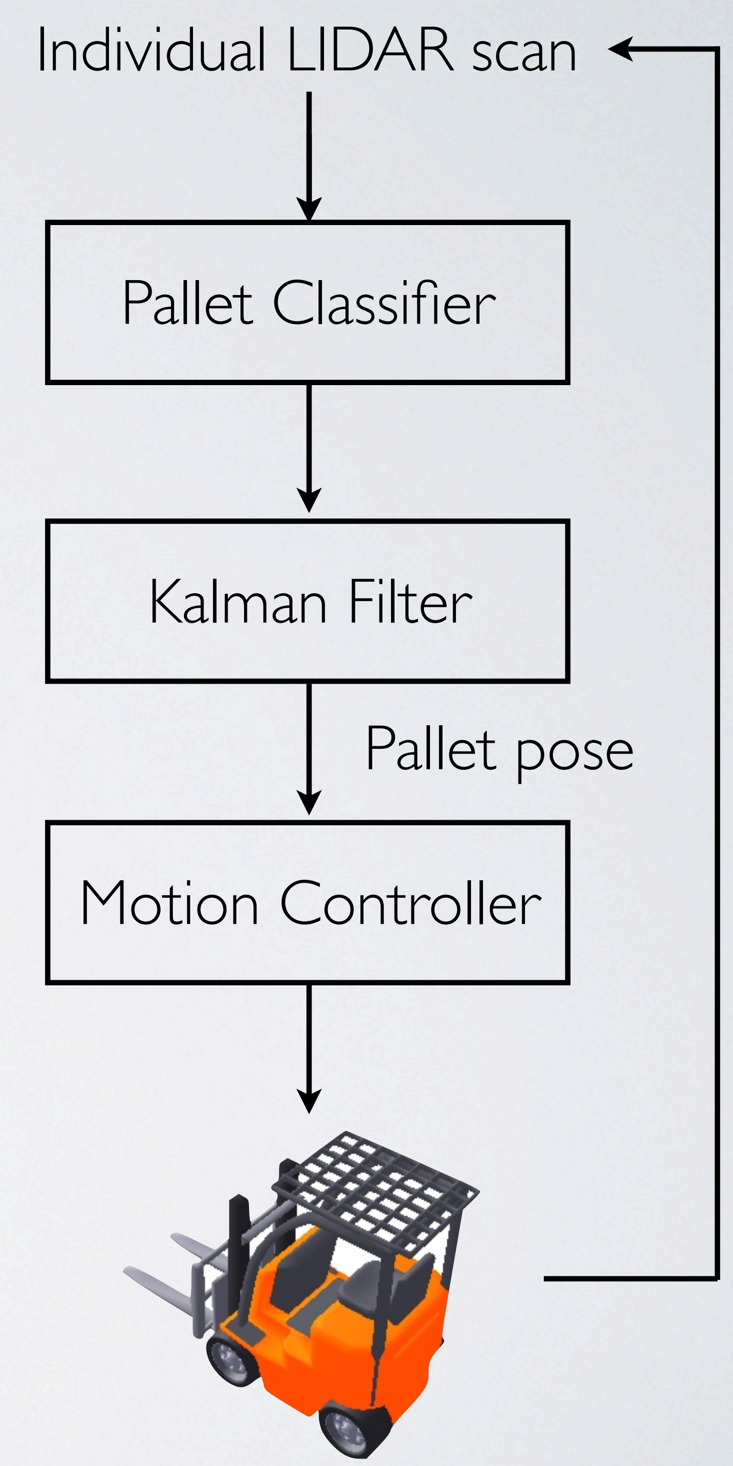
- Pallet initially in LIDAR FOV (i.e., in front of robot)
- Pallet is not occluded
- No obstacles between robot and pallet or truck



PALLET ESTIMATION & MANIPULATION

Our approach: Closed-loop manipulation based on individual LIDAR scans

- Input: Individual scans from tine-mounted LIDAR
- Hierarchical classification of individual scans
- Filter over positive detections to estimate pallet pose
- Servo vehicle and tine poses to filter estimates via simple closed-loop controller



Key component: Fast, robust linear shape estimation

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CHALLENGES OF SERVOING APPROACH

Two primary challenges of perception for closed-loop servoing:

- **Noisy data**:
  Outliers in range data, particularly near pallet corners
- **Computational requirements**:
  Each LIDAR produces 1000 range and bearing returns at 40Hz

Our approach:

- Formulate a linear program (LP) that accounts for noise and outliers
- Exploit the structure of the LP to solve it in real-time

LP FORMULATION

- **Simple problem:**

  Given an orientation, find the line farthest from the origin that separates all range returns

- **A simple algorithm (but not robust):**
  - Find distance of closest point along known orientation
  - Efficient (linear time) but not robust to outliers

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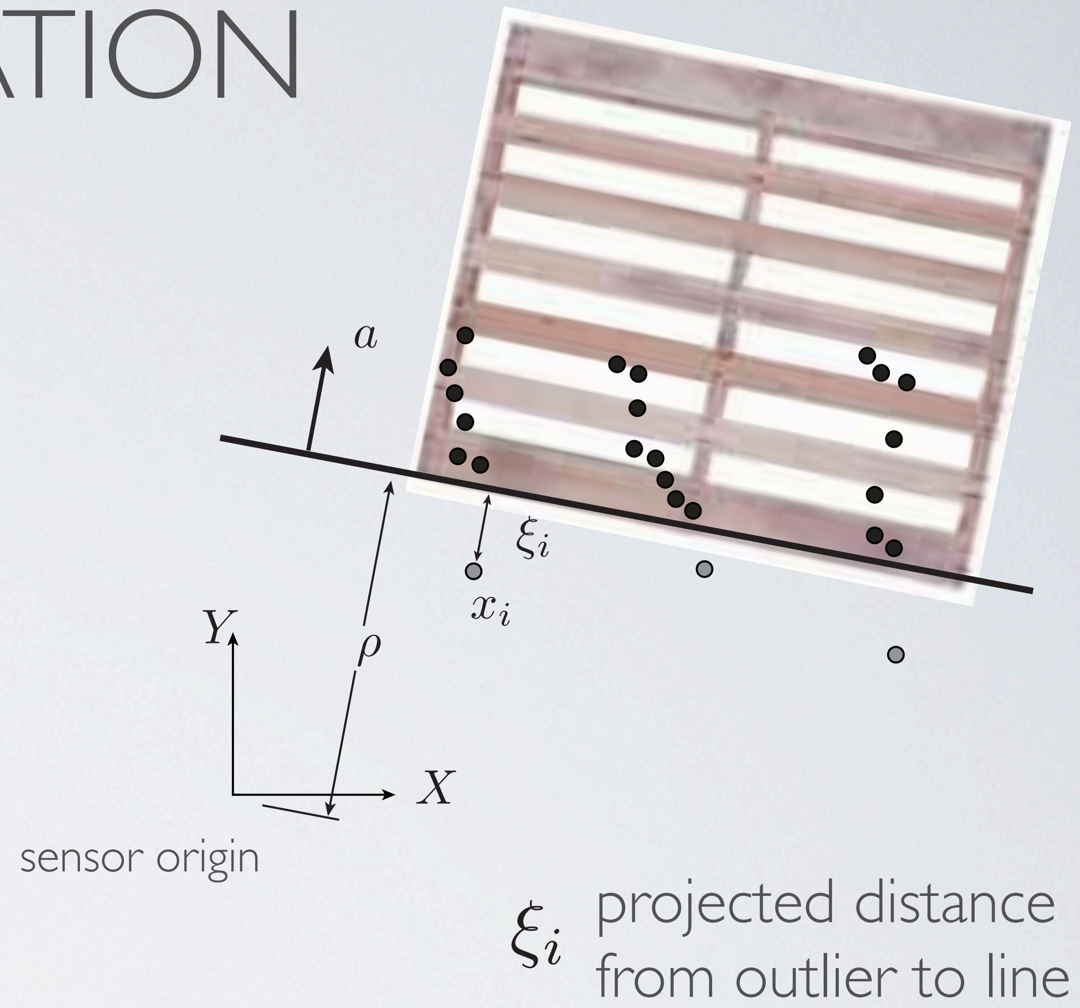

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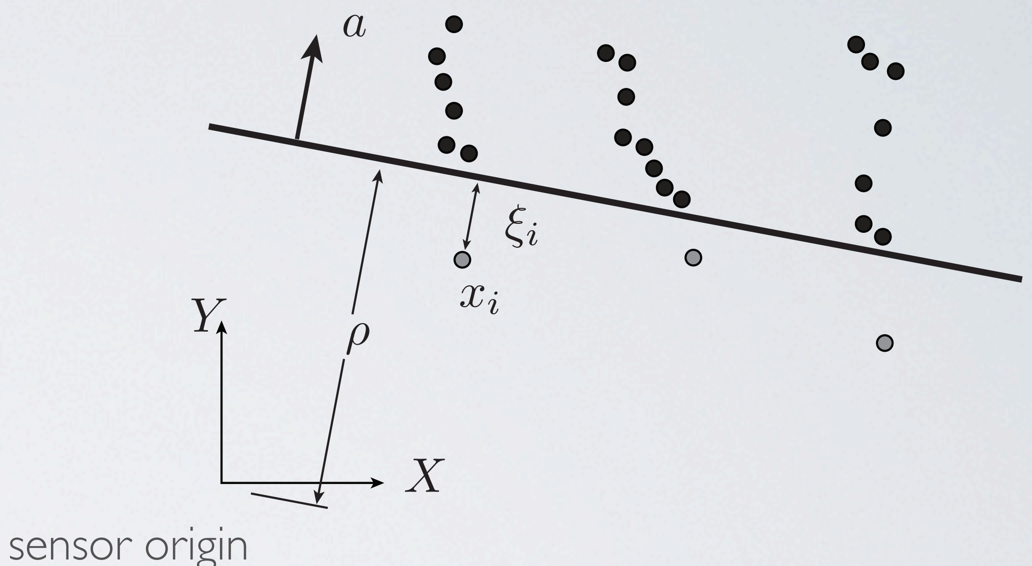

ξ_i projected distance from outlier to line

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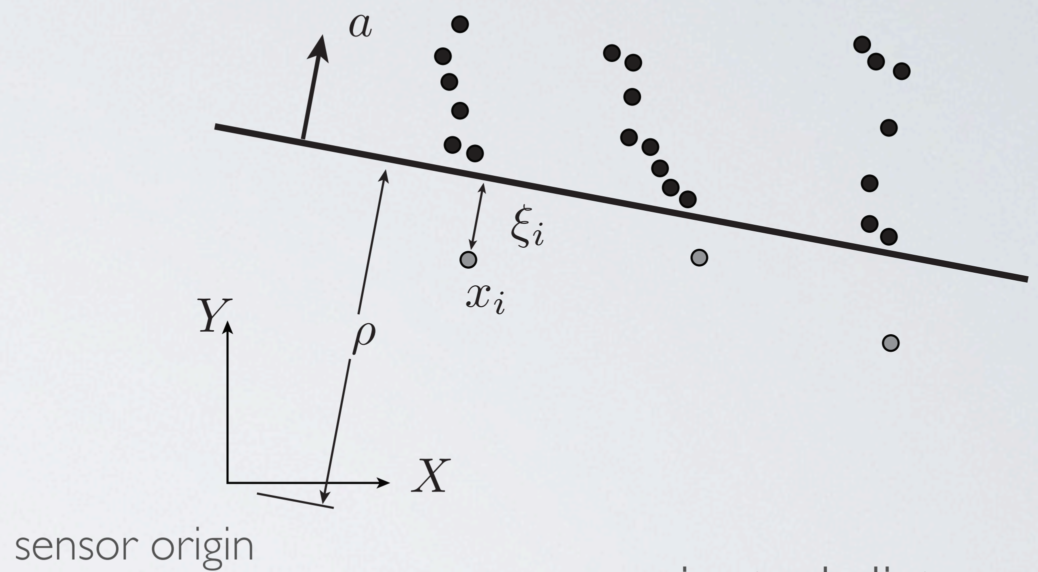

ξ_i projected distance from outlier to line

- **A more robust formulation:**
  - Express as LP that allows for, but penalizes, outliers
  - Exploit the structure of the dual to solve in $O(n \min\{\nu, \log n\})$
  - Allows for linear shape estimation and pallet detection in real-time

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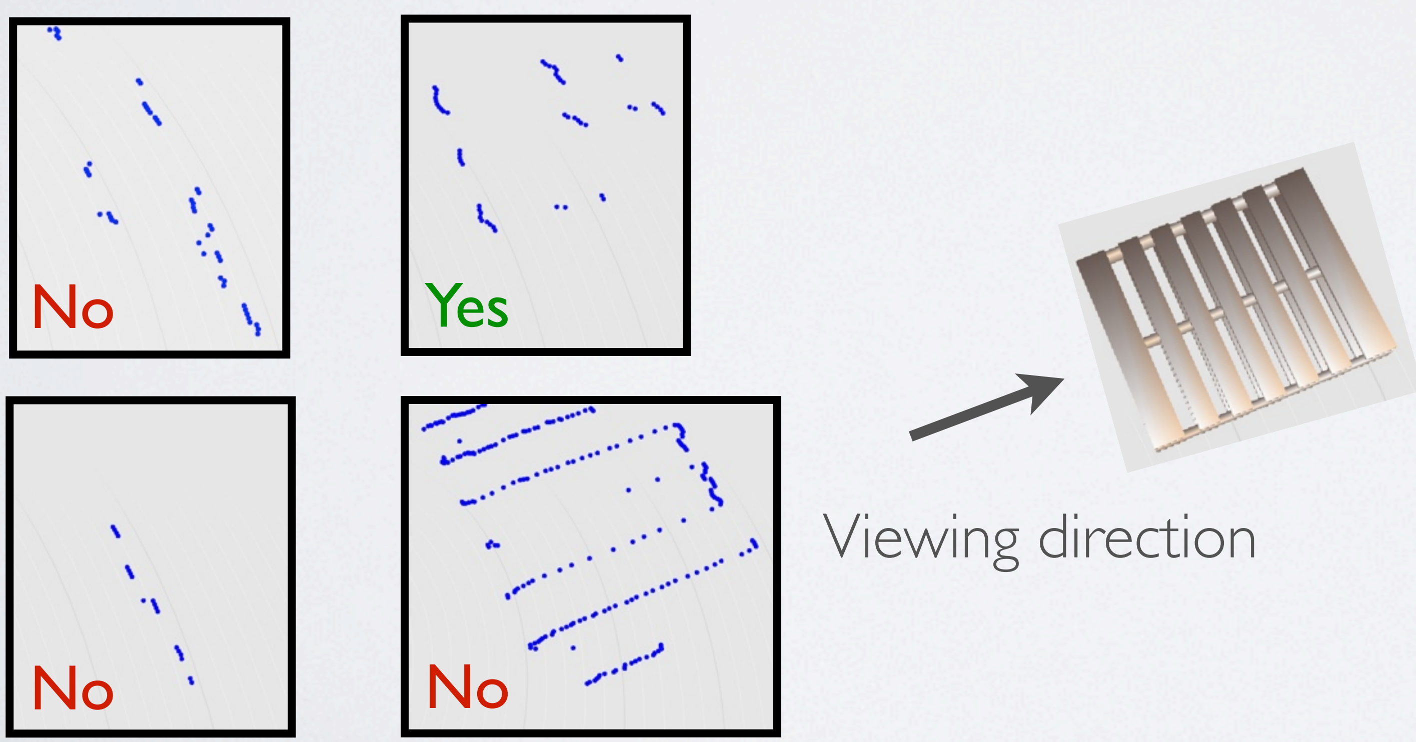
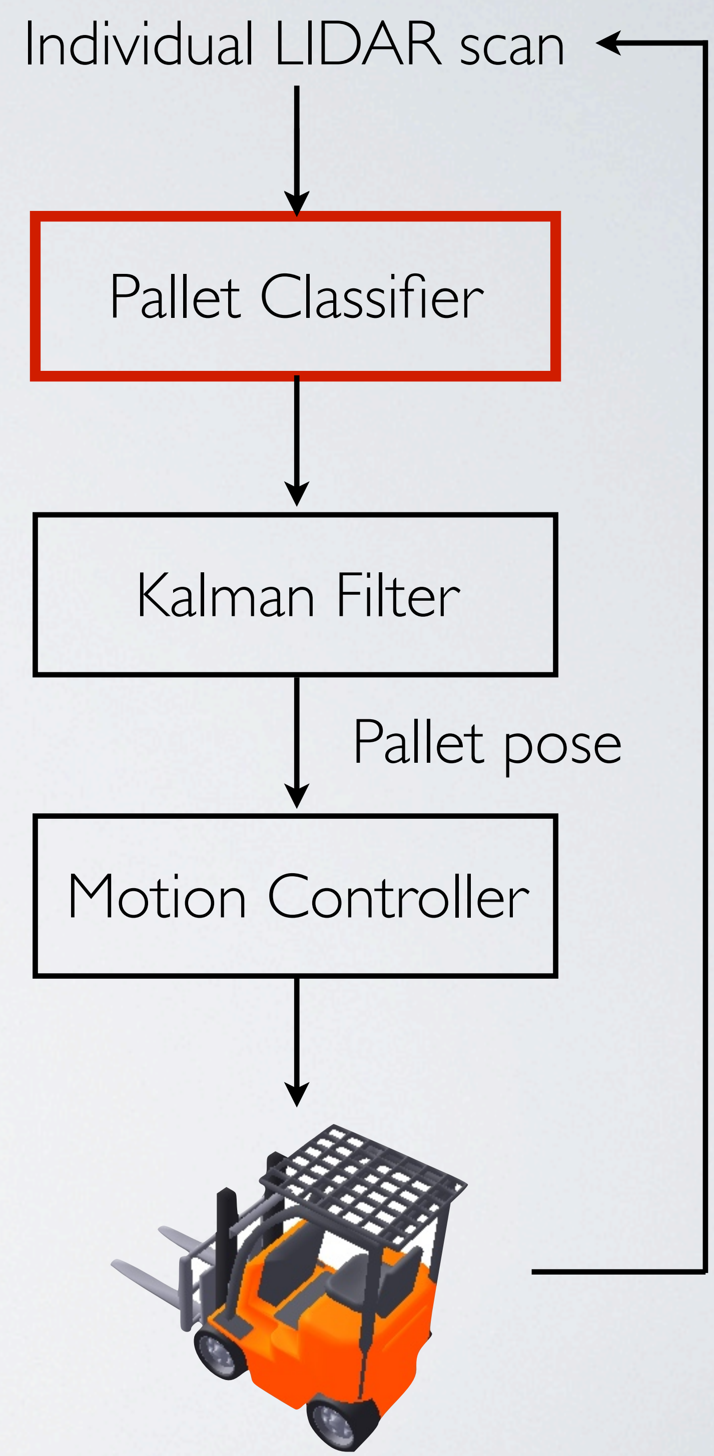
PALLET DETECTION

Approach: Supervised classification of identified structure

- Use LP closest edge algorithm to detect candidate face
- For each face, search for pallet structure via repeated calls to LP closest edge algorithm to identify features: width, slot geometry, ...
- Pallet classification based upon rough prior





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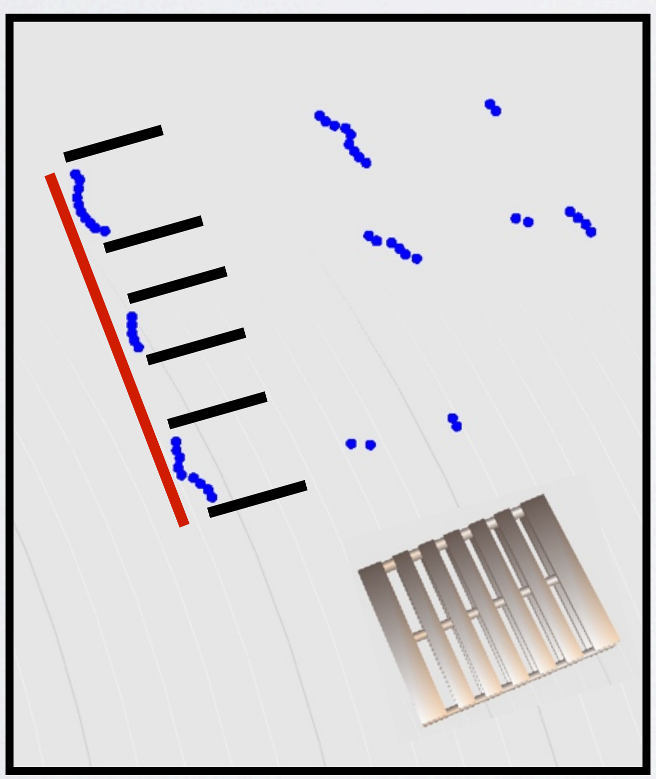

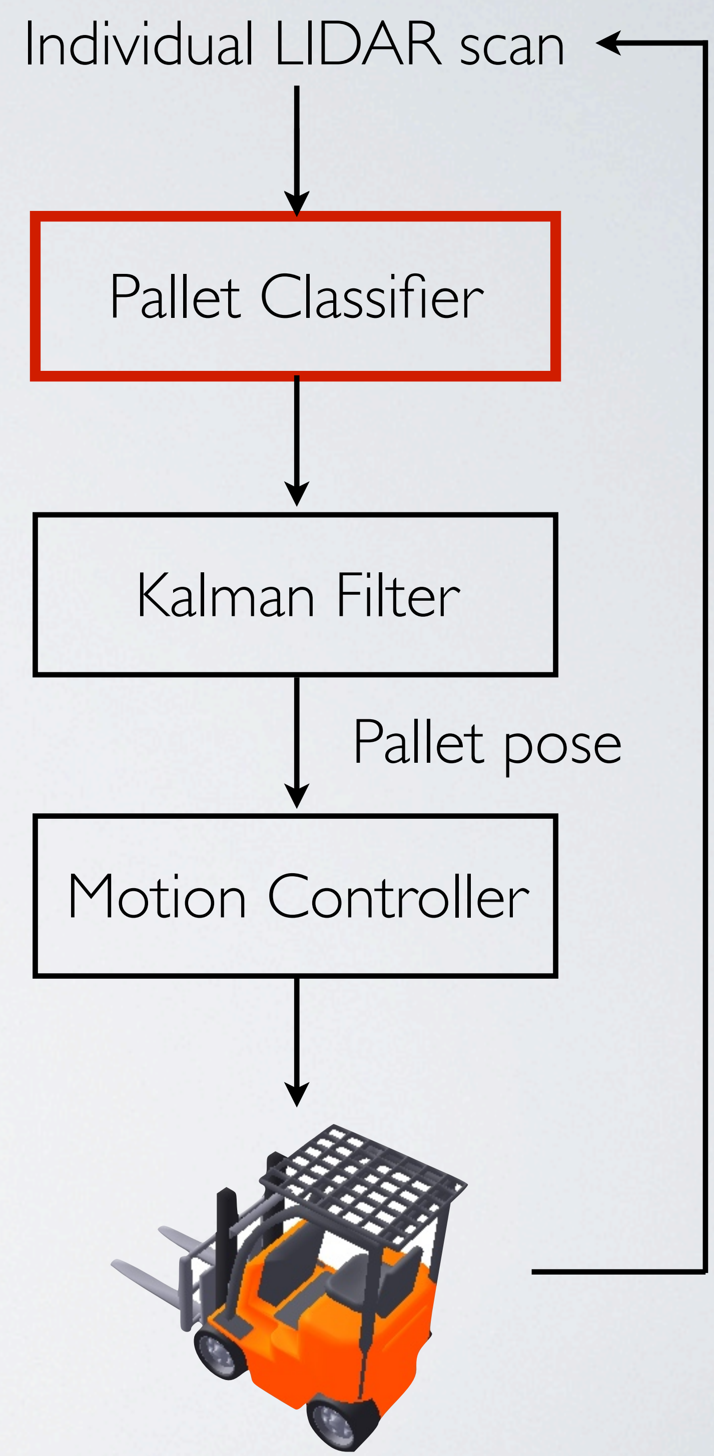

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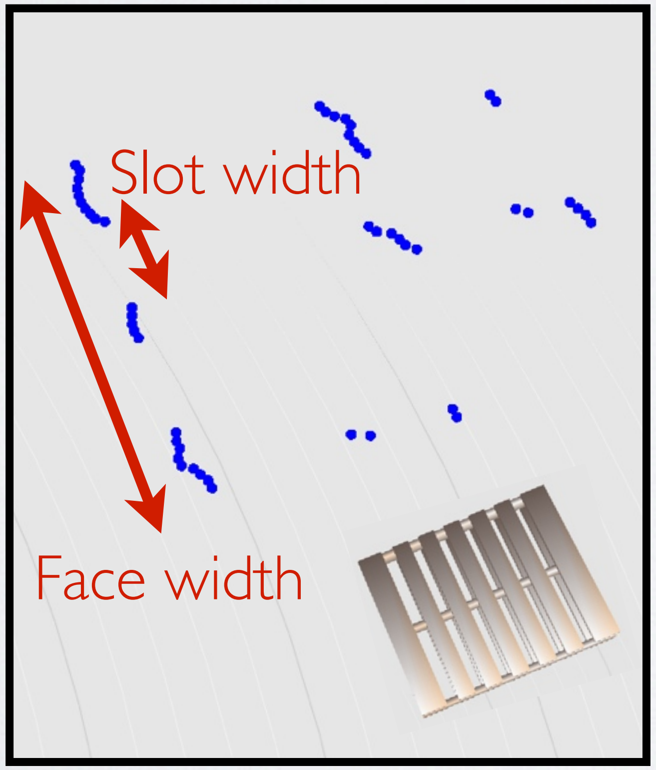

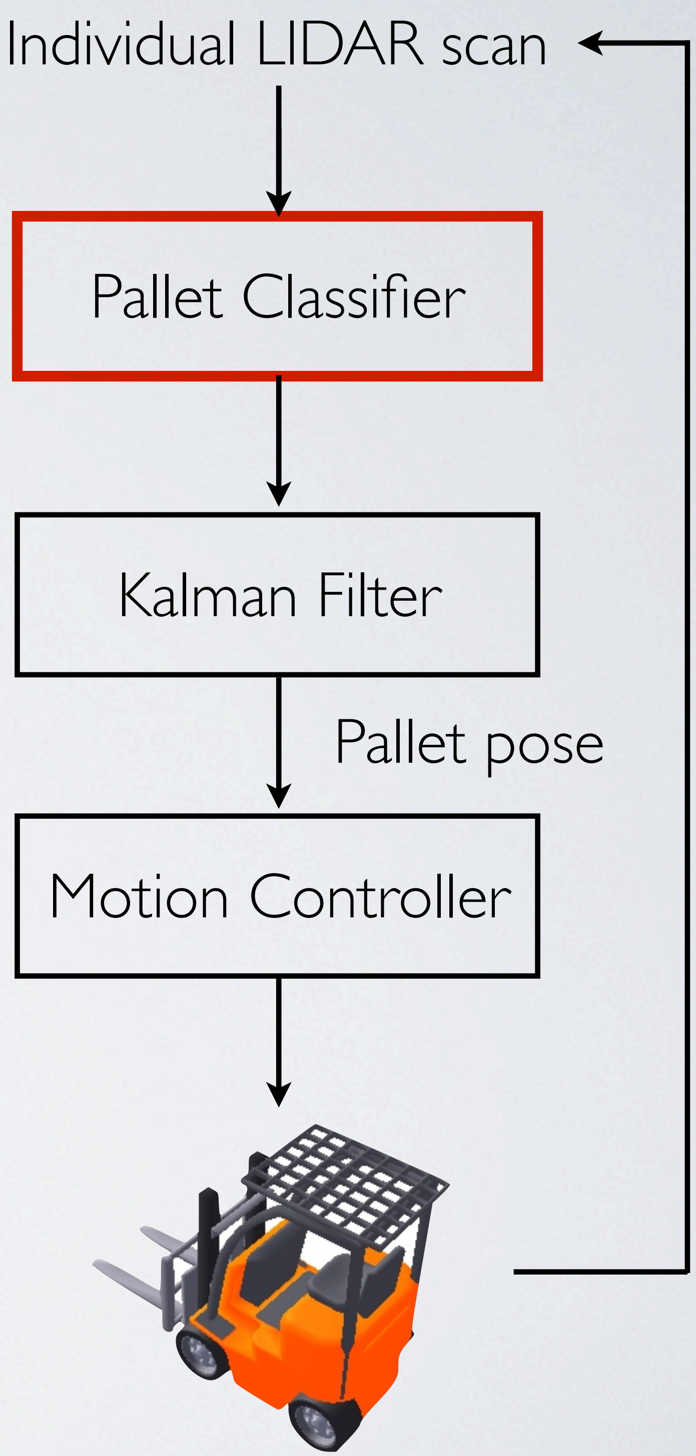

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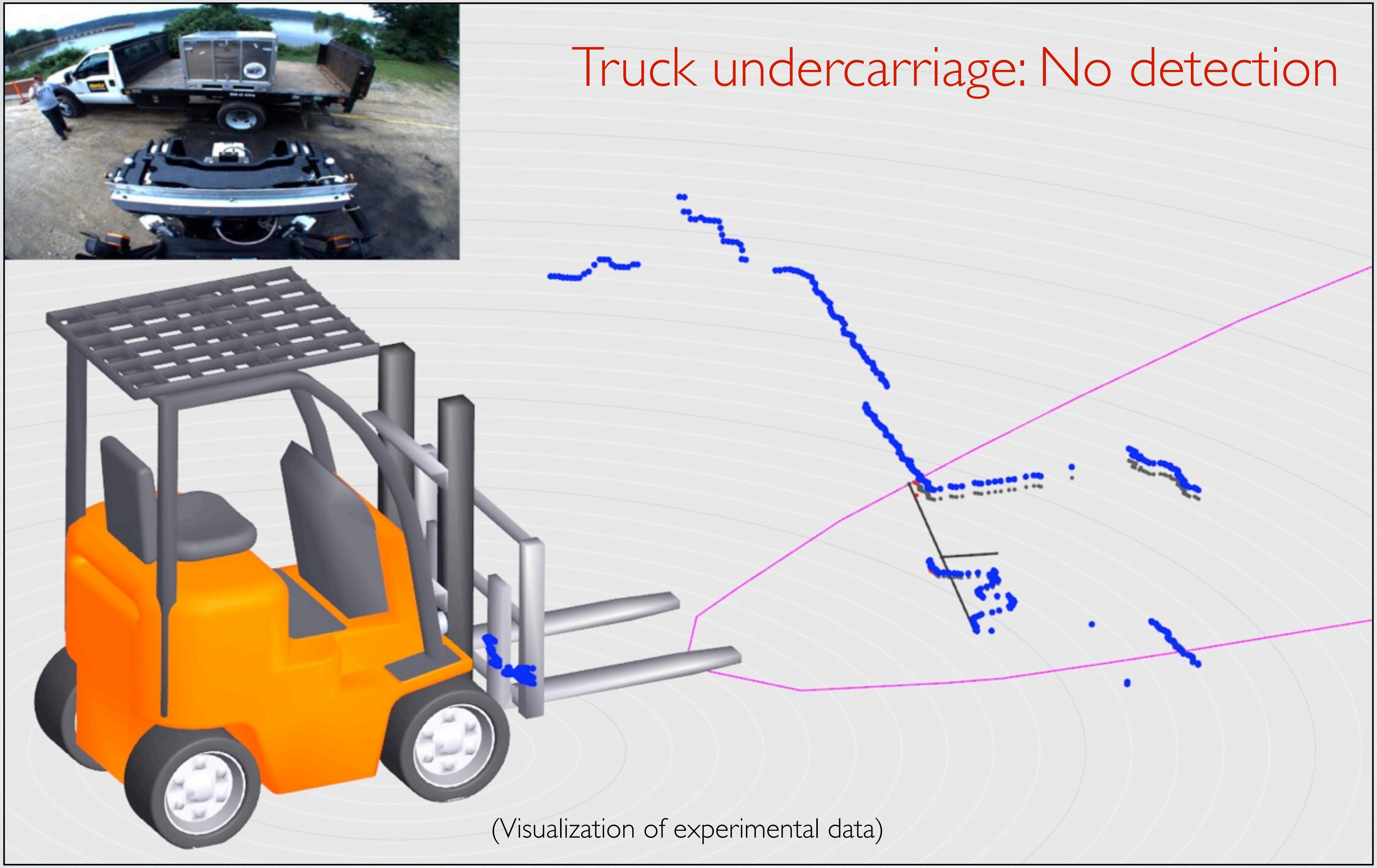
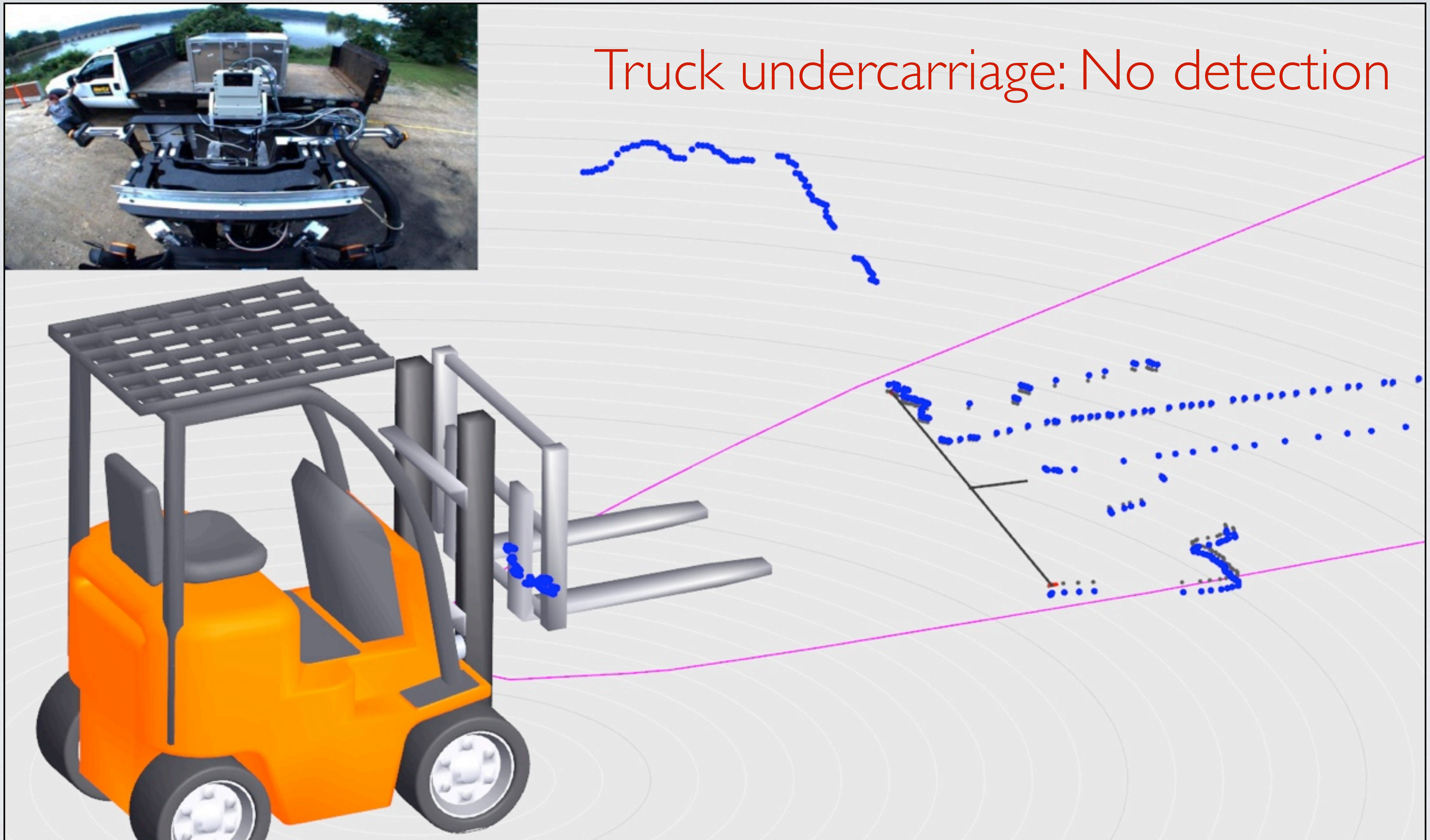


(Visualization of experimental data)

PALLET DETECTION



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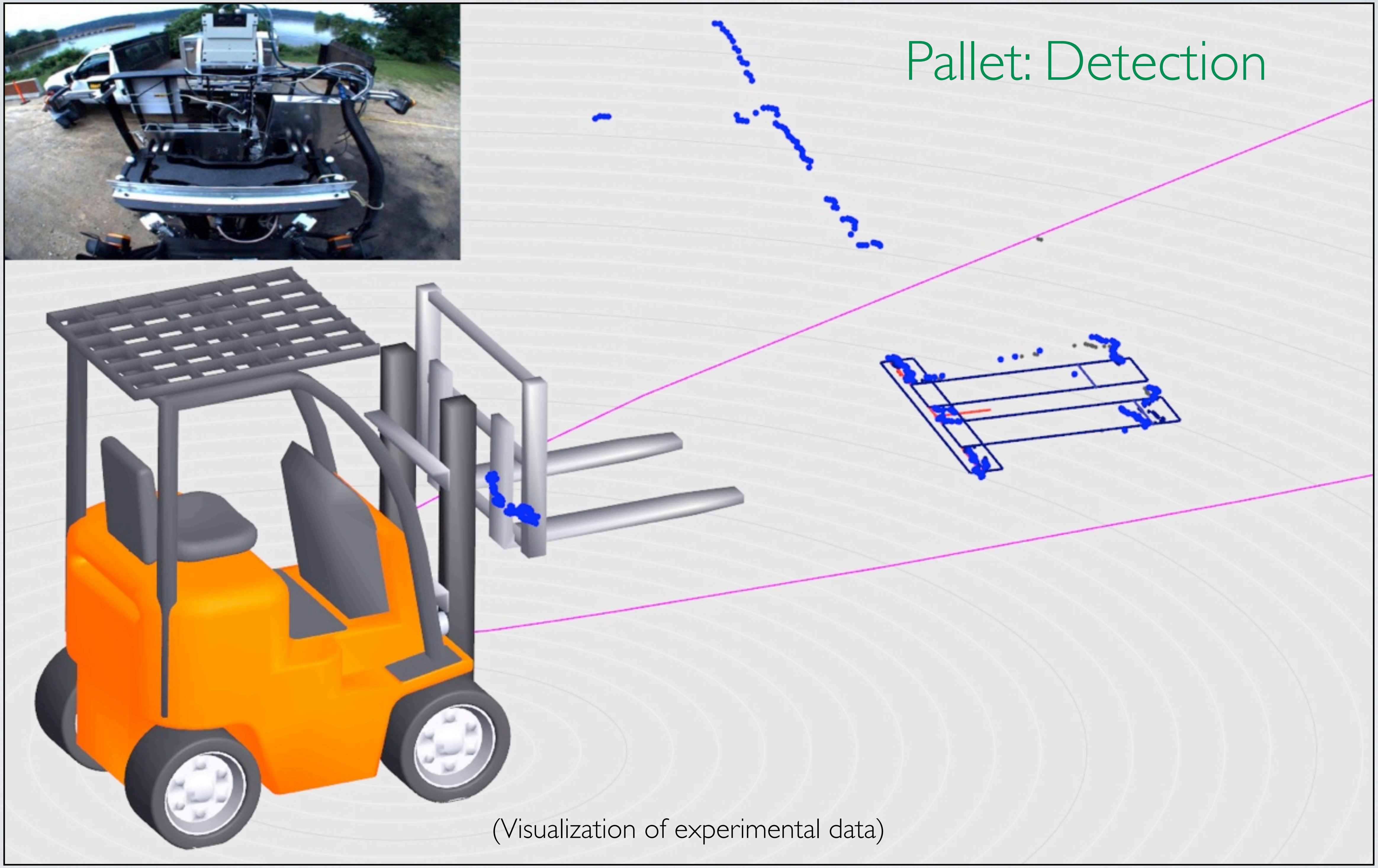
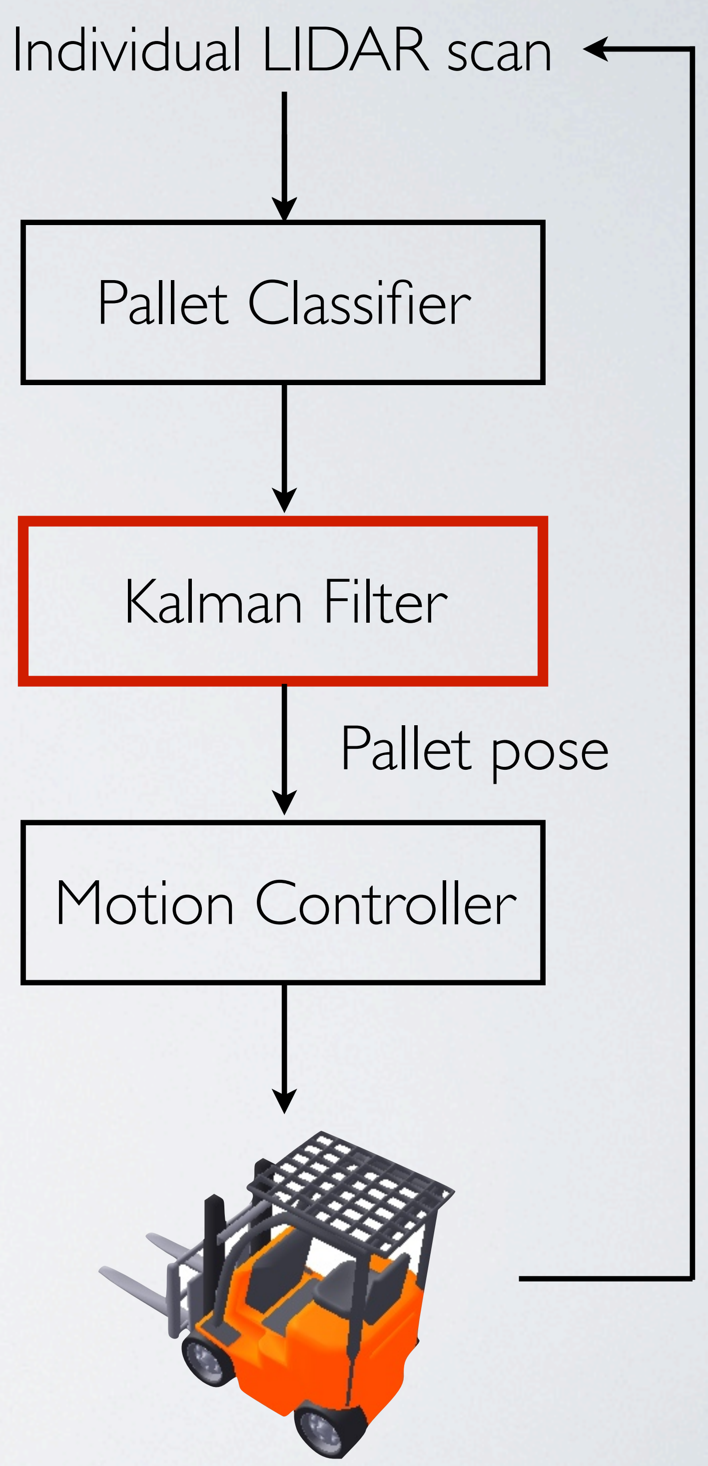


(Visualization of experimental data)

PALLET POSE FILTERING

- Positive detections serve as observations for vanilla Kalman Filter
- Estimate pallet pose:
  - Position
  - Heading
  - Slot locations
  - Width and depth for each slot



MOTION CONTROLLER

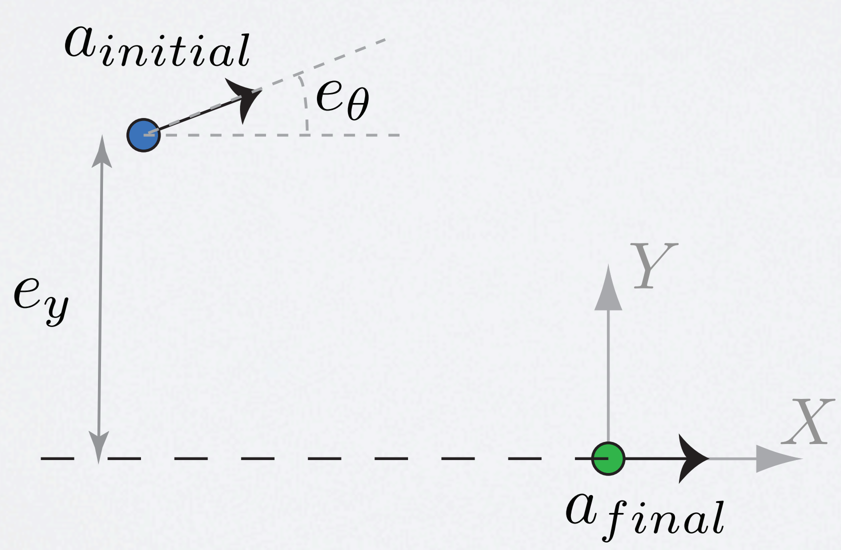
- Special case of controller by Hoffman et al. [Hoffman, ACC 2007]
- Steer to desired position and orientation, $(z_{\text{final}}, a_{\text{final}})$

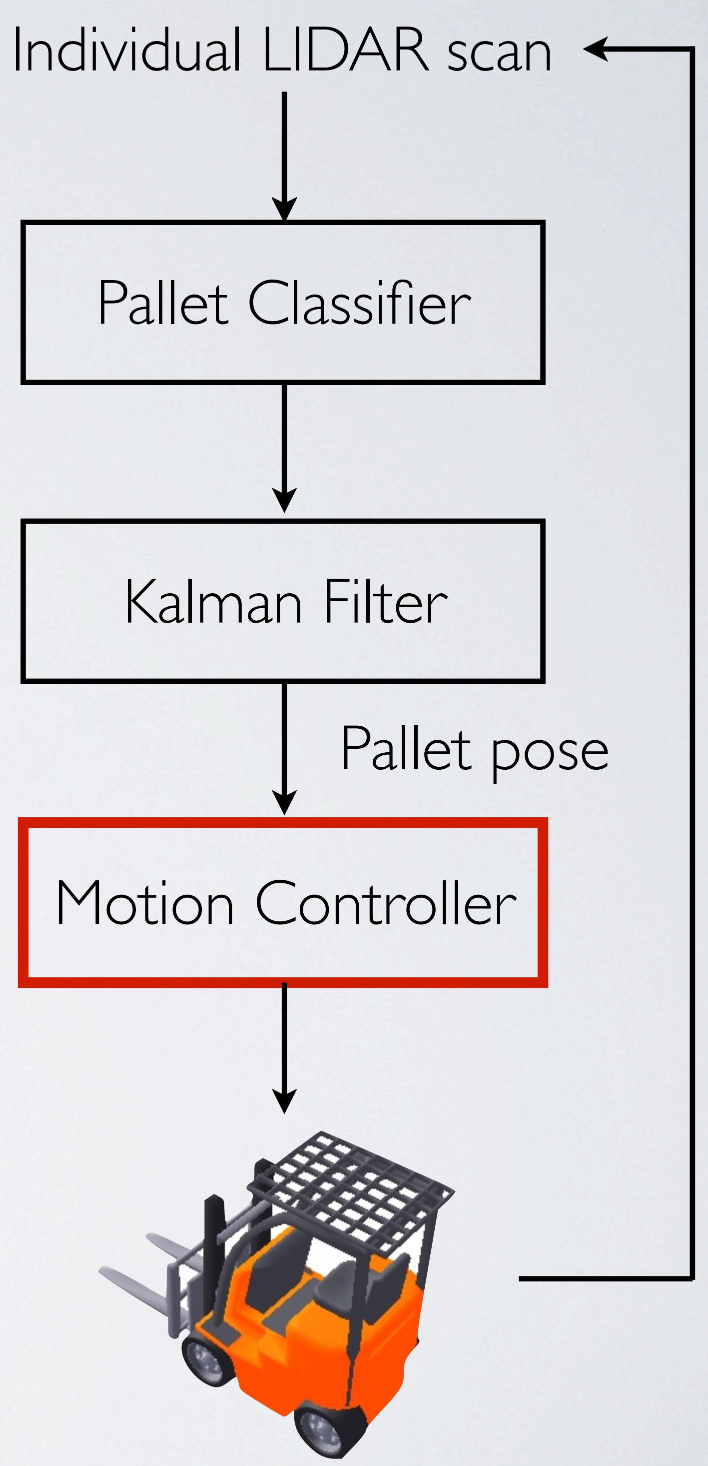
$$\delta = K_y \tan^{-1}(e_y) + K_\theta e_\theta$$

- Dubins vehicle model

$$\begin{aligned} \dot{z} &= (\cos\theta, \sin\theta), \\ \dot{\theta} &= \tan^{-1}(\delta), \end{aligned}$$

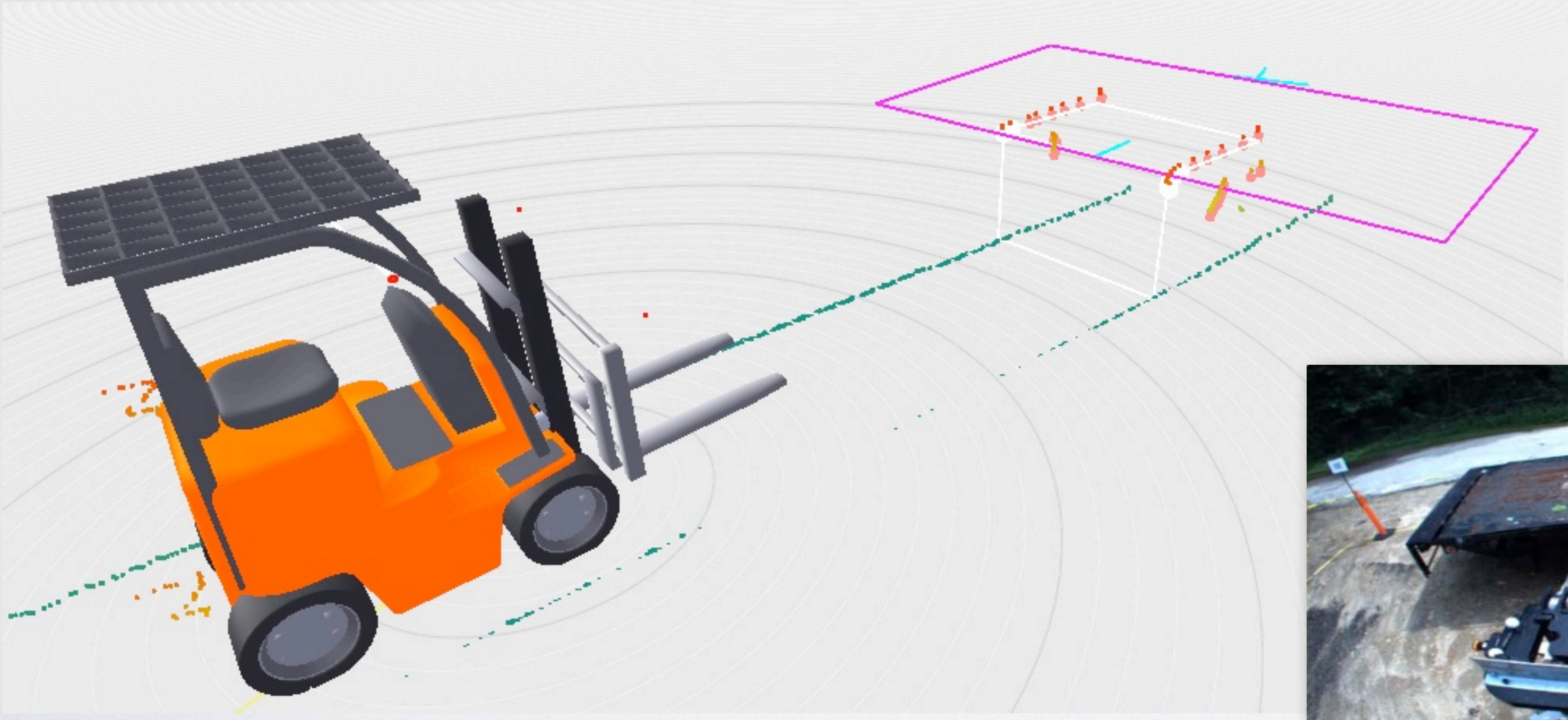
- Smooth steering policy





TRUCK DETECTION & ESTIMATION

- Input: Pair of individual scans from vertical LIDARs
- Employ same LP closest edge algorithm as input to classifiers
- Filter over distance to truck, truck orientation, & truck height



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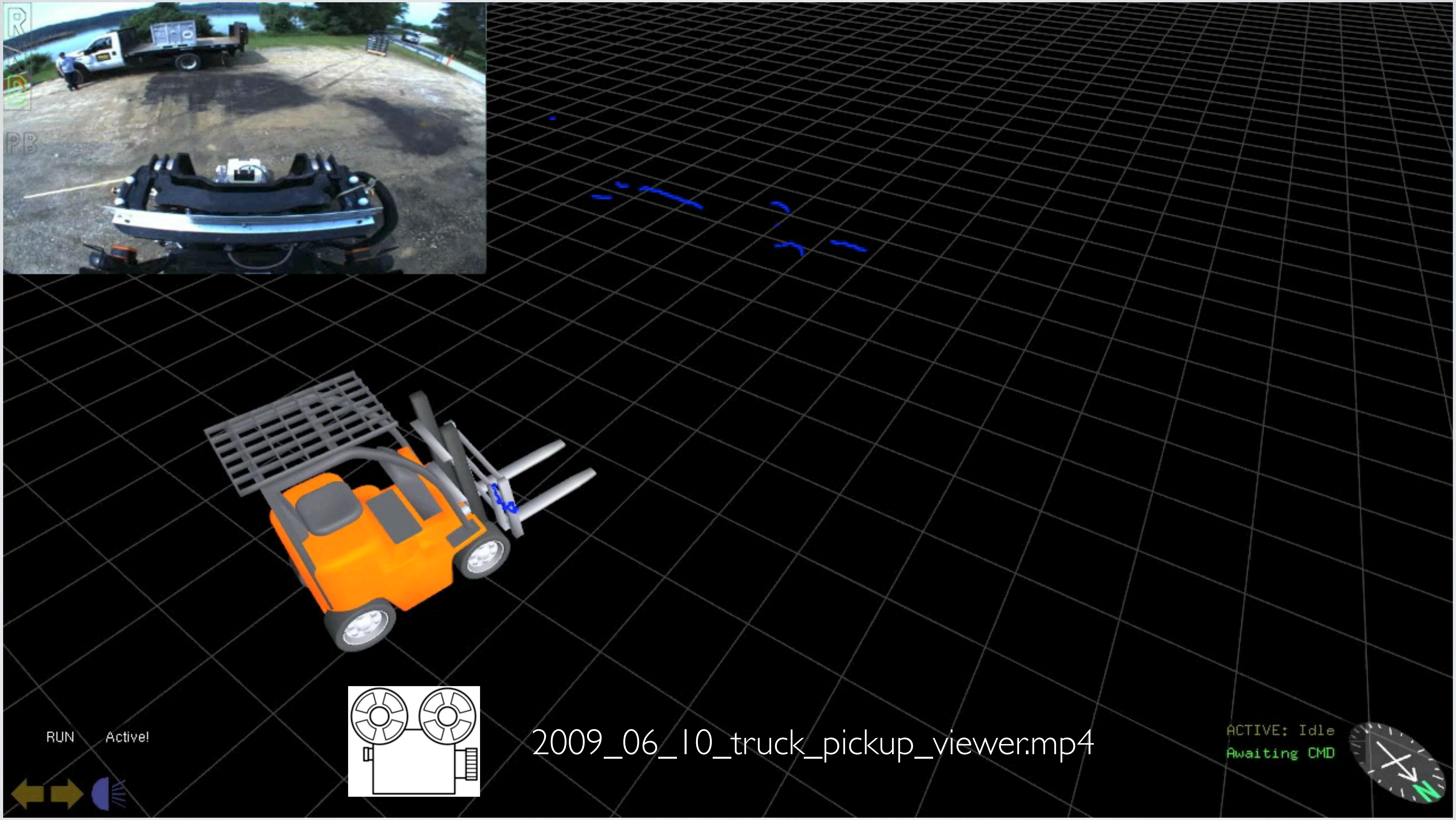

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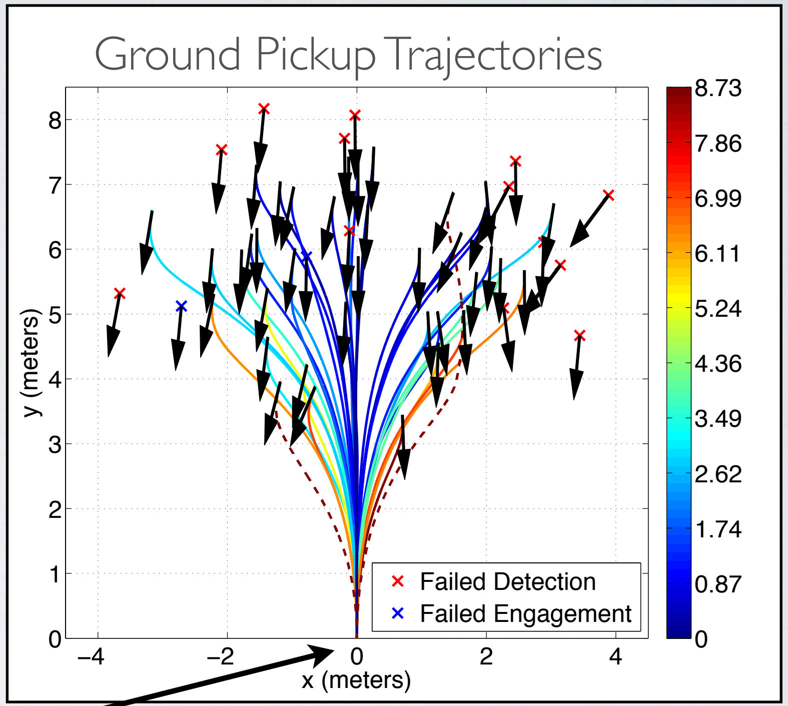
EXPERIMENTAL VALIDATION: SETUP

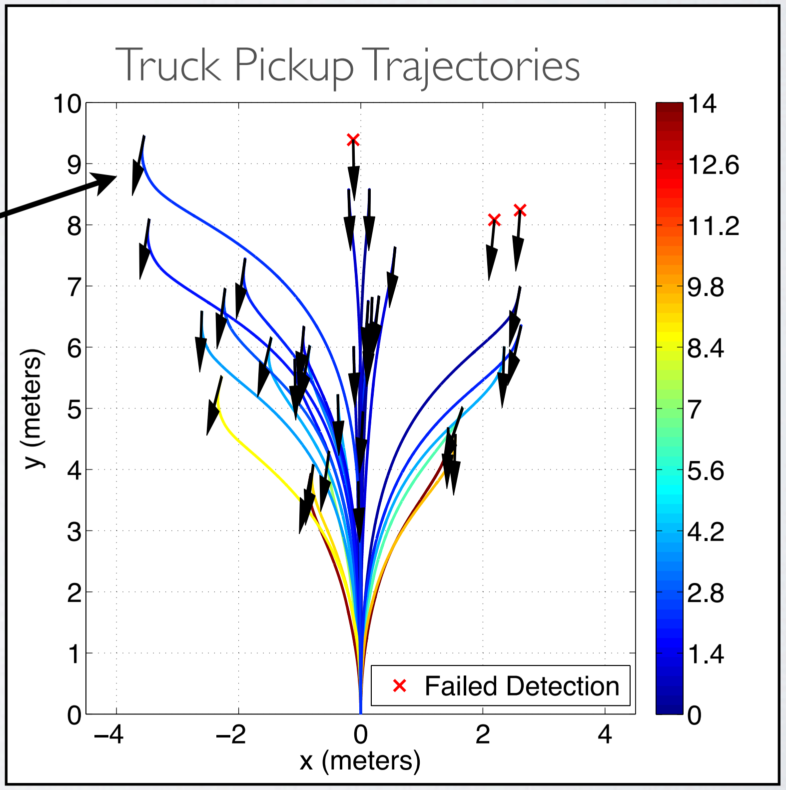
- Attempted 68 pallet pick-up attempts with pallet inside initial tine LIDAR FOV
  - 38 from the ground
  - 30 from a truck loaded with two pallets
- Three different pallet types
- Counted as a successful engagement if no detectable contact with pallet or truck occurred

EXPERIMENTAL VALIDATION: RESULTS

- 35 of 38 ground pick-ups successful
  - Failure 1: Vehicle moved pallet during insertion
  - Failures 2 & 3: Unable to reacquire pallet
- 30 of 30 truck pick-ups successful



Pallet location



Starting position
(arrow indicates forklift orientation)

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LIMITATIONS AND CURRENT WORK

- Closed-loop perception and planning:
  Macro-action forward-search using RRT
- Gesture-less detection of multiple pallets
- Pallet stacking and unstacking
- Extend outlier-robust LP to general shape estimation using kernel methods

[Video: 2010_05_04_multiple_pallet.mp4]

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QUESTIONS?

mwalter@csail.mit.edu

http://people.csail.mit.edu/mwalter

[Video: 2010_02_21_unmanned.mp4]