

Sensor Fusion for Robust Path Duplication in Automated Ground Vehicle Convoys

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GPS & Vehicle Dynamics
Laboratory

- Motivation
- Problem Statement
- Relative Path Following
 - Virtual lead following
 - Relative path generation
 - Relative observations used for path generation
- Graph-Based Relative Path Estimation
 - State vector and graph representation
 - Methodology/graph optimization
- Results
- Future Work

Potential Benefits of Automated Convoys

- Transport efficiency
- Increased safety
- Reduced stress on end user

Design Considerations

- Path following accuracy
 - Reduced footprint
 - Improved fuel savings
- Availability
 - Potential for compromised GPS/coms reception
 - Mission environment may not be conducive to additional infrastructure
- Reliability
 - Observation redundancy to handle measurement faults



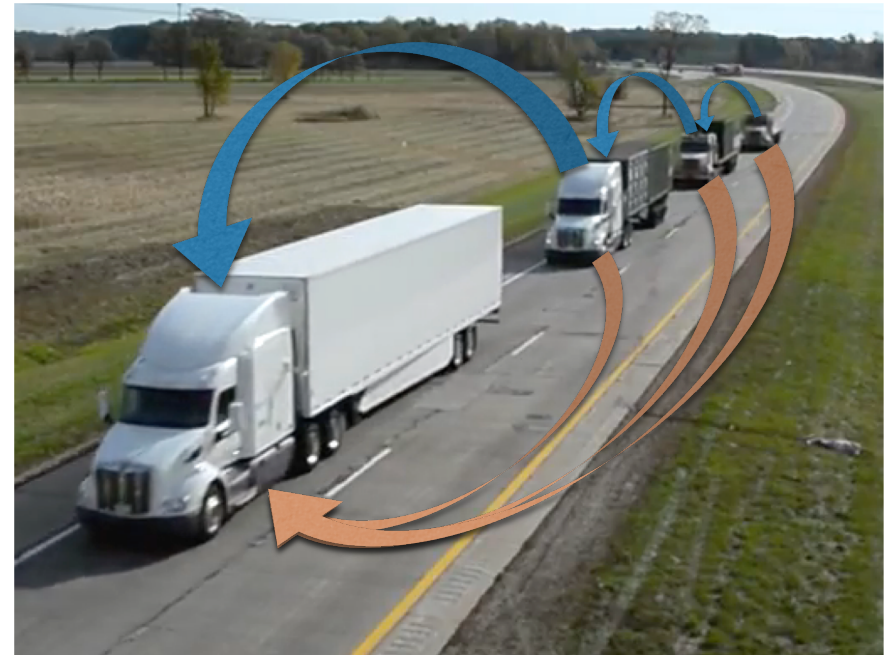
System Description

- Four fully actuated tractor-trailers
 - Novatel PwrPak7 GNSS receiver
 - Interface to onboard CAN bus providing wheel-based speed/yaw rate, etc
 - DSRC radio (exchanging GNSS and vehicle state observations)
 - Delphi Electronic Scanning Radar (ESR)



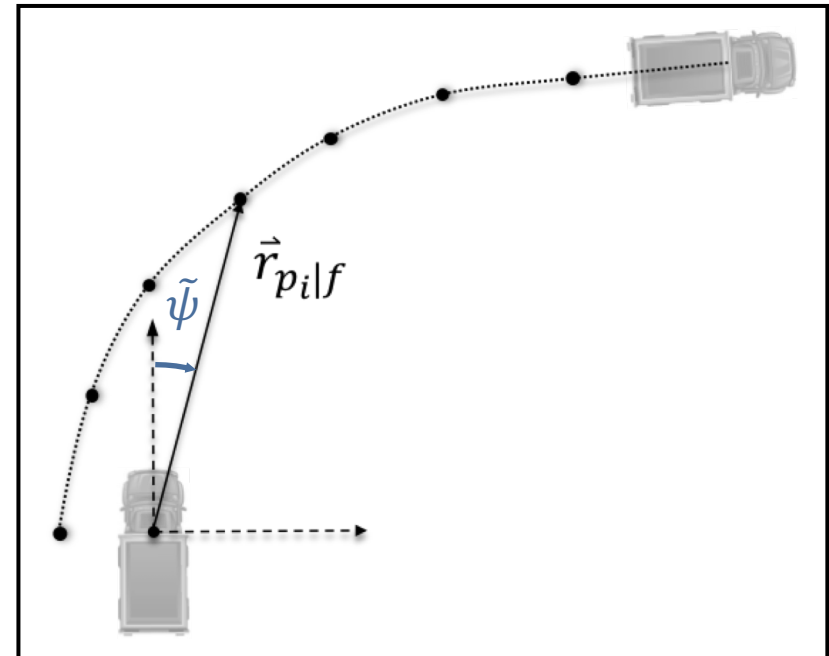
Path Following Approach

- Lane markings are not always available – lateral control is realized by duplicating the path of a leading vehicle
- Two main frameworks for convoy networks:
 - **Immediate Lead Following** – stability issues from accumulated errors
 - **Ultimate Lead Following** – large following distances of trailing vehicles



- Virtual Lead Following
 - The follower references a “virtual lead” at some user-defined lookahead distance
 - Choice of lookahead distance changes the effective damping
 - Classical heading controller acts to drive the relative bearing ($\tilde{\psi}$) to zero

$$\tilde{\psi} = \text{atan2}(y, x)$$



- Prerequisite: Set of relative position vectors (RPVs) representing past positions of lead, relative to the follower vehicle, and resolved in the follower vehicle body frame

Global Path Generation

- Also known as “breadcrumb method”
- Both vehicles can measure absolute position (e.g. North, East)
- Leader saves path and shares with follower
- Requires base-station infrastructure for sufficient accuracy

Relative Path Generation*

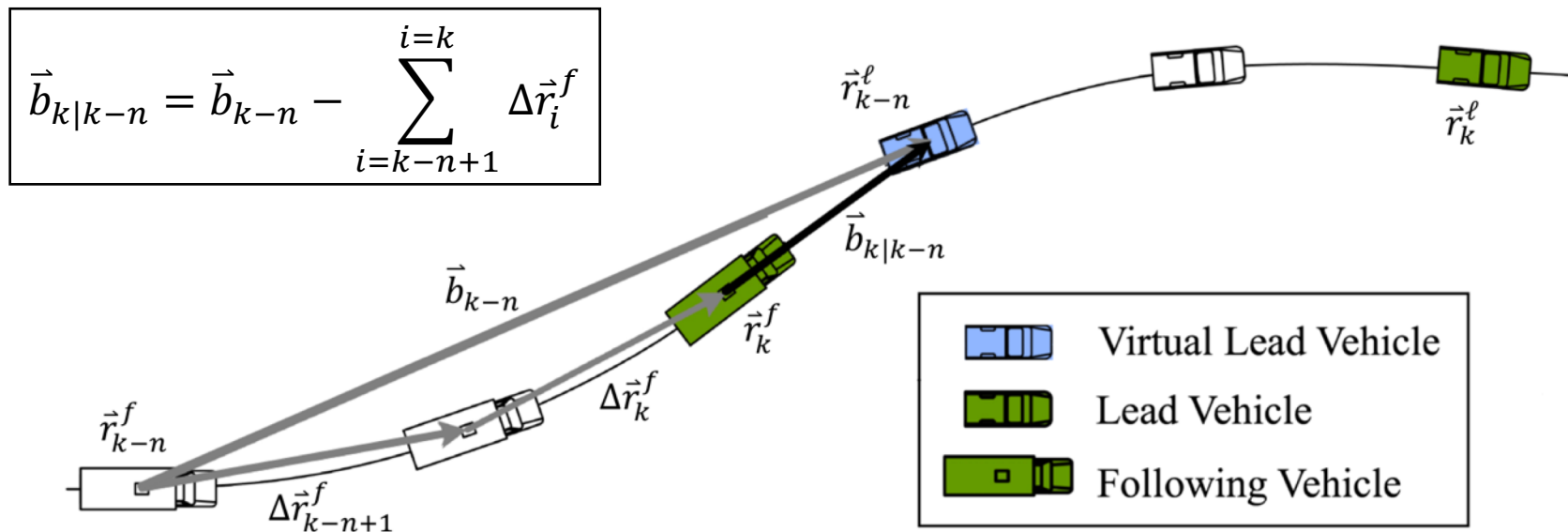
- Accurate inter-vehicle RPV measurements
- RPV measurement combined with vehicle odometry (change in position in time) allows for path generation

*Main focus of the presented work



Relative Path Generation

- **Odometry** of following vehicle is used to generate a dead reckoning position/orientation (pose) w.r.t. arbitrary origin
- Measurements of **inter-vehicle RPV** used to form the set of path waypoints
- Since the path is relative, the impact of dead reckoning errors only accumulate for n epochs (function of following distance and speed)



Limitations

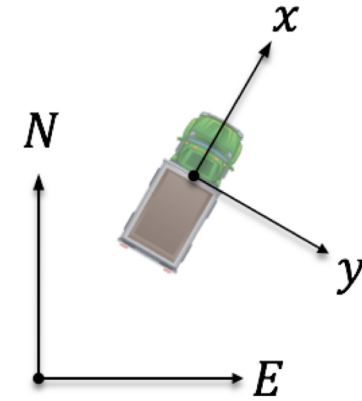
- Depends on consistent availability of RPV and odometry
- Unbounded error growth with respect to separation distance

Proposed Solution

- Incorporate additional measurements:
 - Lead vehicle odometry ($\Delta \vec{r}_i^{\ell}$)
 - Redundancy in odometry/RPV (e.g. ego-motion from wheel speed+yaw rate/inter-vehicle RADAR observations)
- Fuse measurements in a graph-based estimation framework

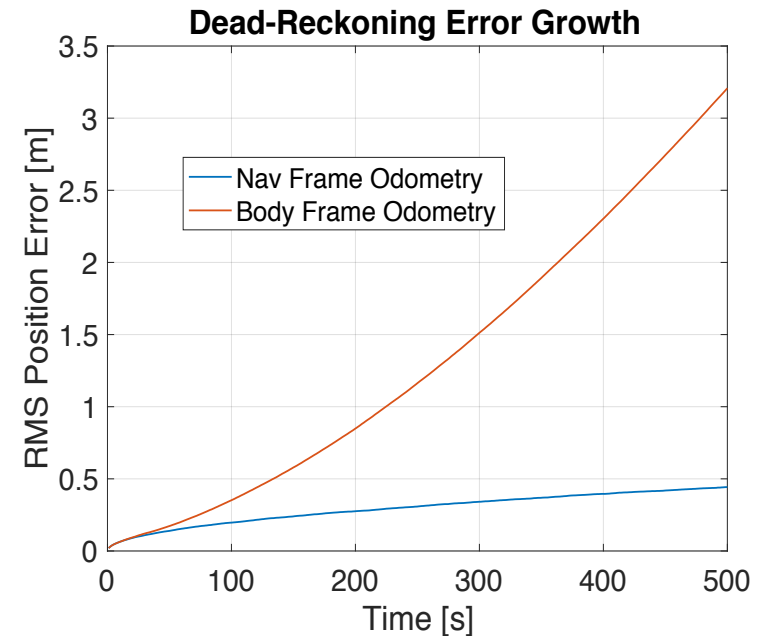
Body-Centric Odometry

- Change in body frame position ($\Delta x, \Delta y$) and heading ($\Delta\psi$) over sampling period
- Calculated using wheel speed and yaw rate
- (+) good availability and high sample rate
- (-) dead reckoning position uncertainty grows relatively fast



Time Differenced Carrier Phase (TDCP)

- Change in navigation frame position ($\Delta N, \Delta E$) over sampling period
- (+) millimeter level accuracy
- (+) position uncertainty grows linearly
- (-) limited availability

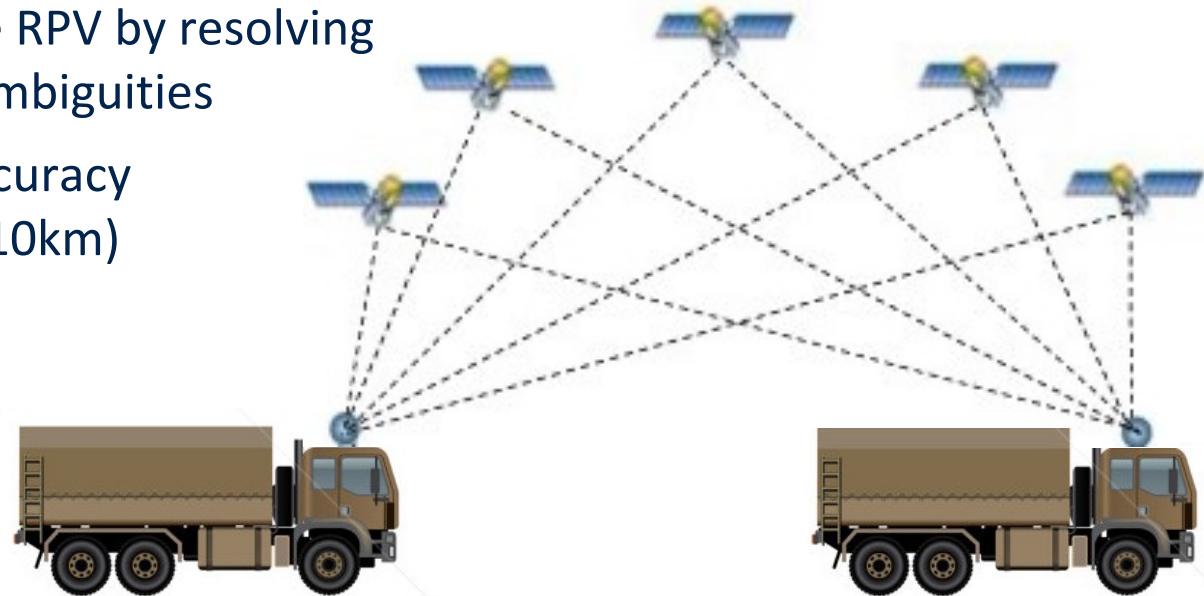


RADAR Observation

- Range/bearing of leader with respect to the follower
- (+) Does not require coms or GPS reception
- (+) High sample rate
- (-) Poor availability (FoV, signal shadowing from neighboring vehicles, etc.)

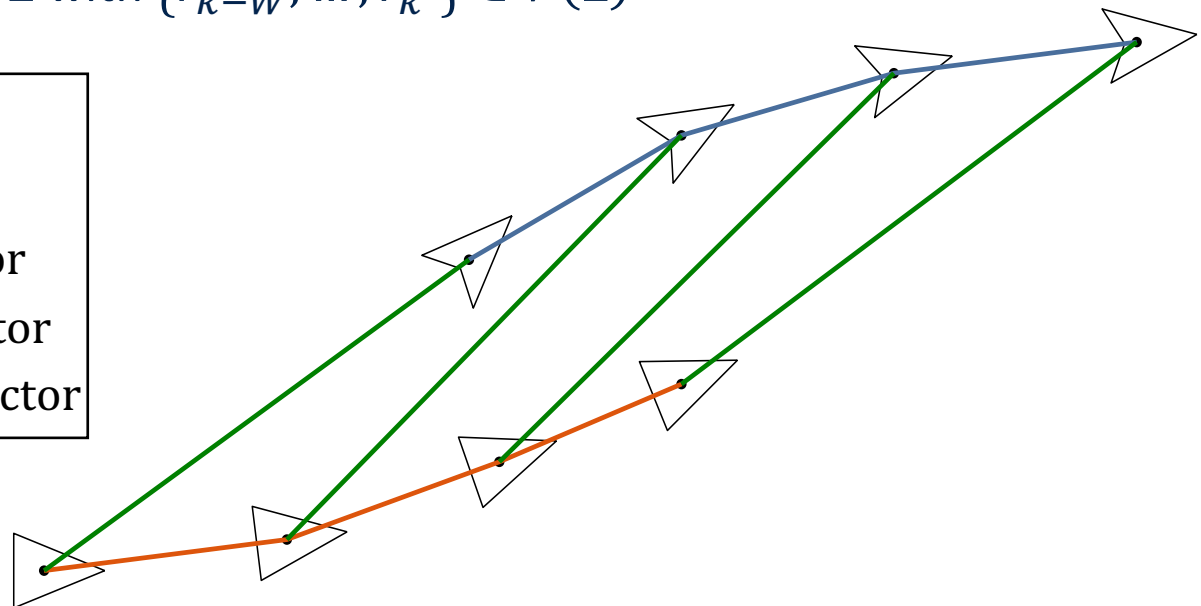
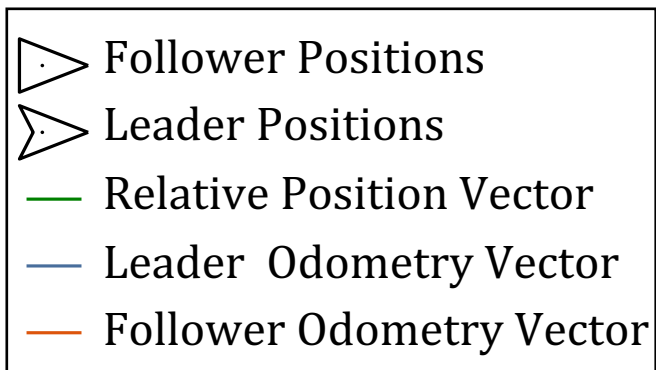
Dynamic-Base RTK (DRTK)

- Calculates inter-vehicle RPV by resolving carrier phase integer ambiguities
- (+) Centimeter level accuracy over long distances (~10km)
- (-) Poor availability in certain environments



Graph-Based Path Estimation

- Graph-based estimation framework is considered to smooth path and span GPS/coms outages
- Graph edges \rightarrow measurements (weighted by uncertainty)
- Graph vertices \rightarrow state estimates (2D position)
 - Follower subgraph F with $\{\vec{r}_{k-W}^f, \dots, \vec{r}_k^f\} \in V(F)$
 - Lead subgraph L with $\{\vec{r}_{k-W}^l, \dots, \vec{r}_k^l\} \in V(L)$

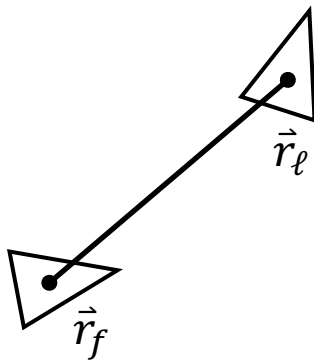


Graph-Based Path Estimation

- Each measurement's contribution is stored in the information matrix ($\Omega \in \mathbb{R}^{n \times n}$) and information vector ($\xi \in \mathbb{R}^{n \times 1}$)
- The normalized innovation is added to the rows/columns that correspond to the adjacent states as shown below

$$\begin{aligned}\Omega_{[ij]} &+= H_{ij}^T R_{ij}^{-1} H_{ij} \\ \xi_{[ij]} &+= H_{ij}^T R_{ij}^{-1} z_{ij}\end{aligned}$$

R measurement covariance matrix
H measurement matrix
z measurement vector
 i, j adjacent state indices



Example: RPV measurement

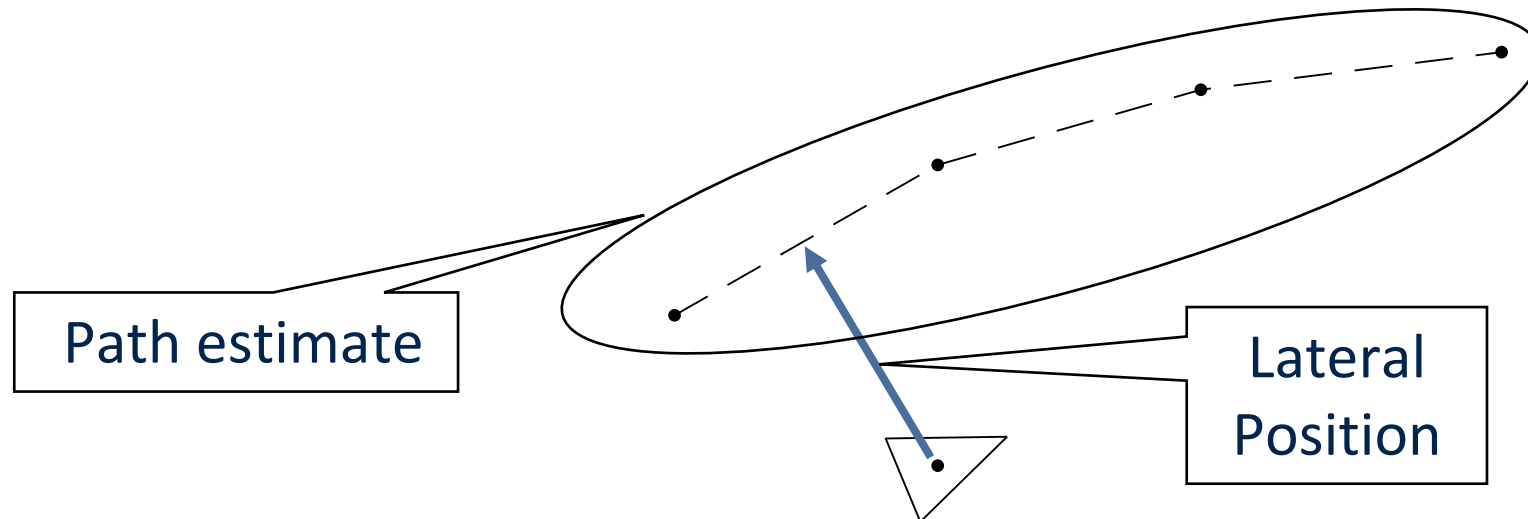
$$H = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

$$R = E[vv^T]$$

$$z = (\vec{r}_\ell - \vec{r}_f) + v$$

Graph-Based Path Estimation

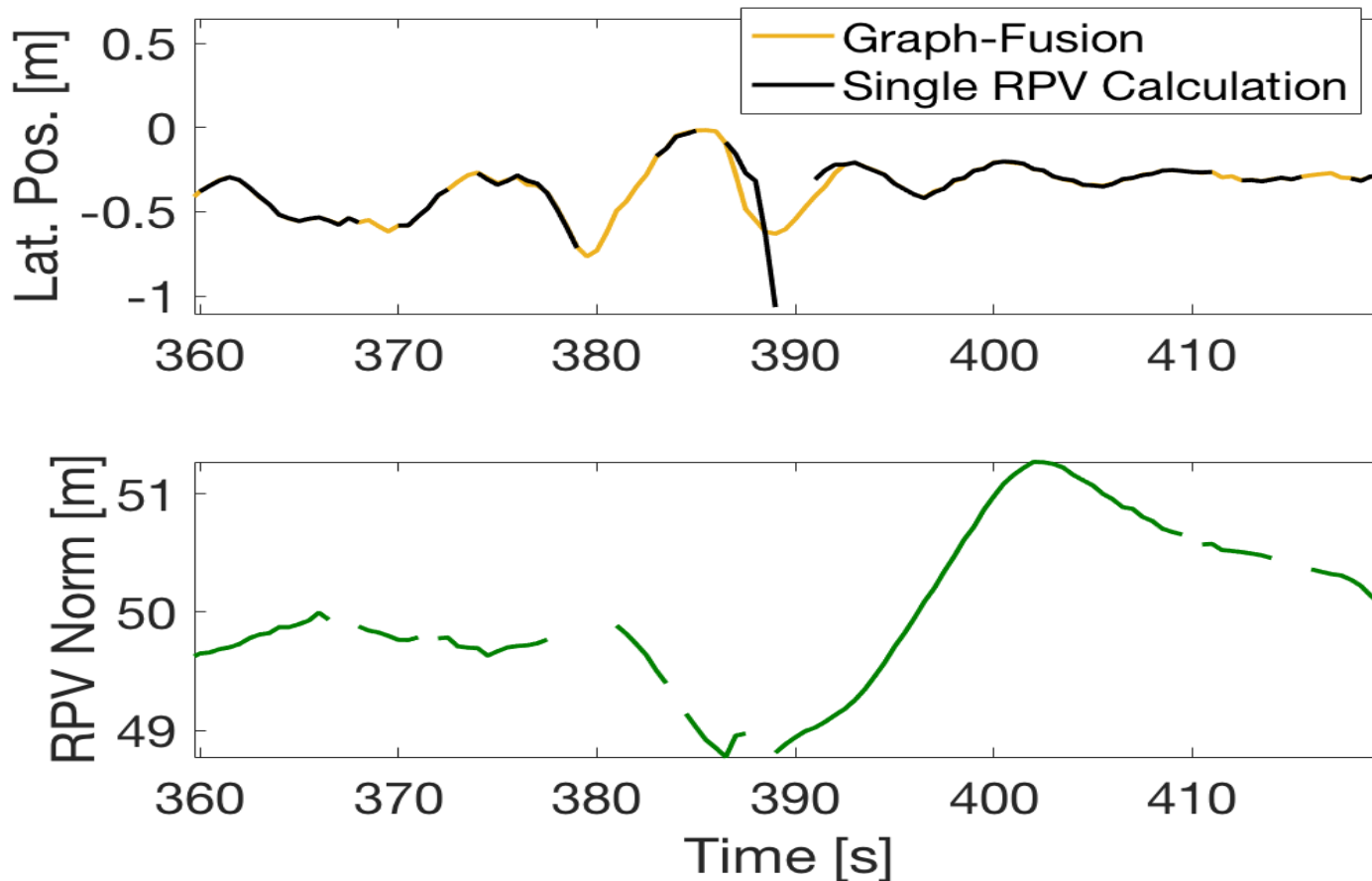
- After accounting for each measurement in the graph, the estimated state (\hat{x}) is calculated by solving
$$\Omega \hat{x} = -\xi$$
- The state estimate contains the relative path of the leader, which is used to calculate the follower vehicle's control input
- This process is repeated at each time epoch for continued control of the follower



- Data from CACC demonstrations in two environments: 1) Oval test track 2) Forest road
- Lateral position is used as performance metric
- No ground truth in this data set – results are based on improved availability
 - Path generation using only DRTK + follower TDCP
 - Path estimate from graph-based fusion
- Three main scenarios to consider:
 - 1) DRTK RPV outliers from false integer ambiguity
 - 2) TDCP odometry outliers from multi-path
 - 3) Complete GNSS outage (e.g. tunnel)

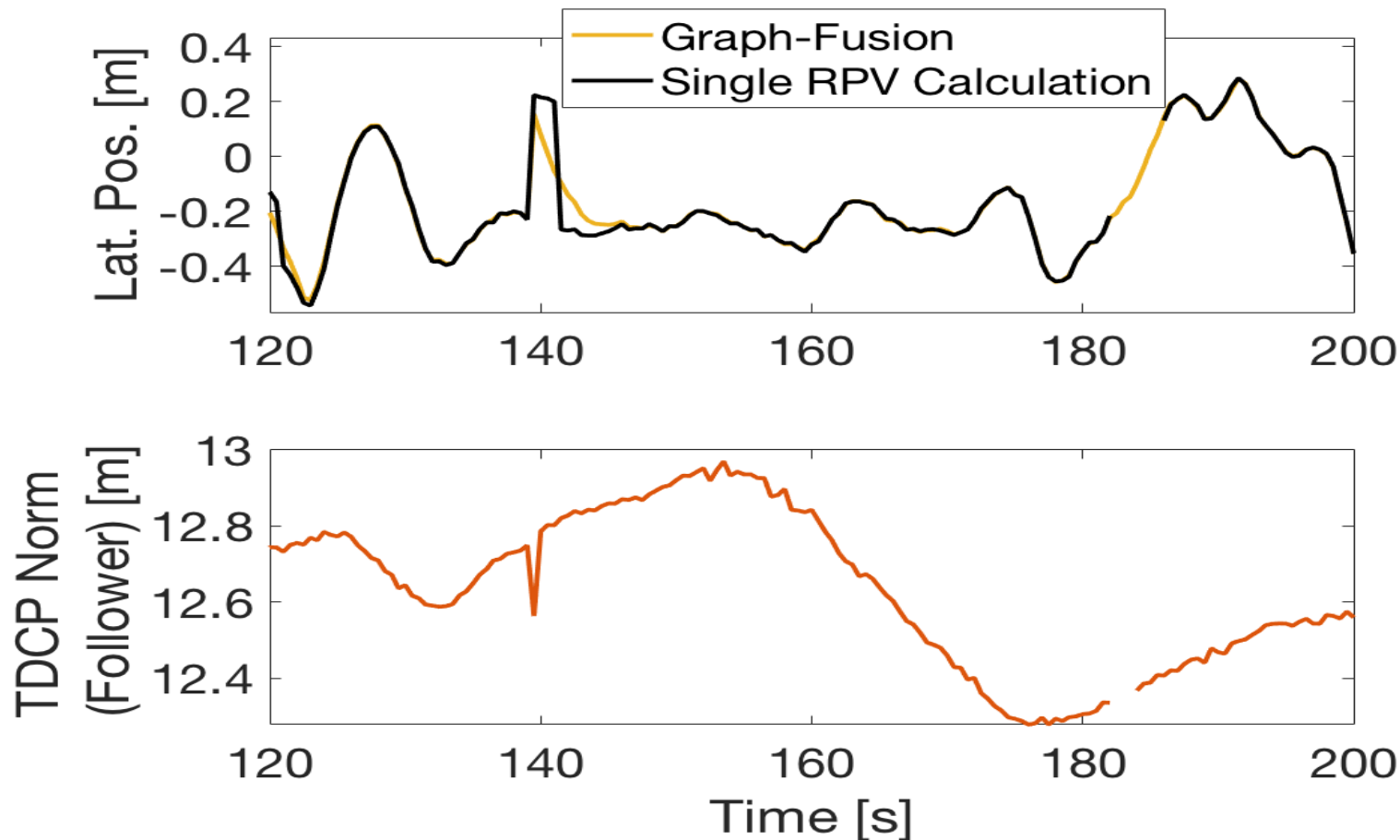
Results: RPV outlier case

- Spikes/outages in RPV -> spikes/outages in path
- Graph fusion spans gaps and dampens spikes



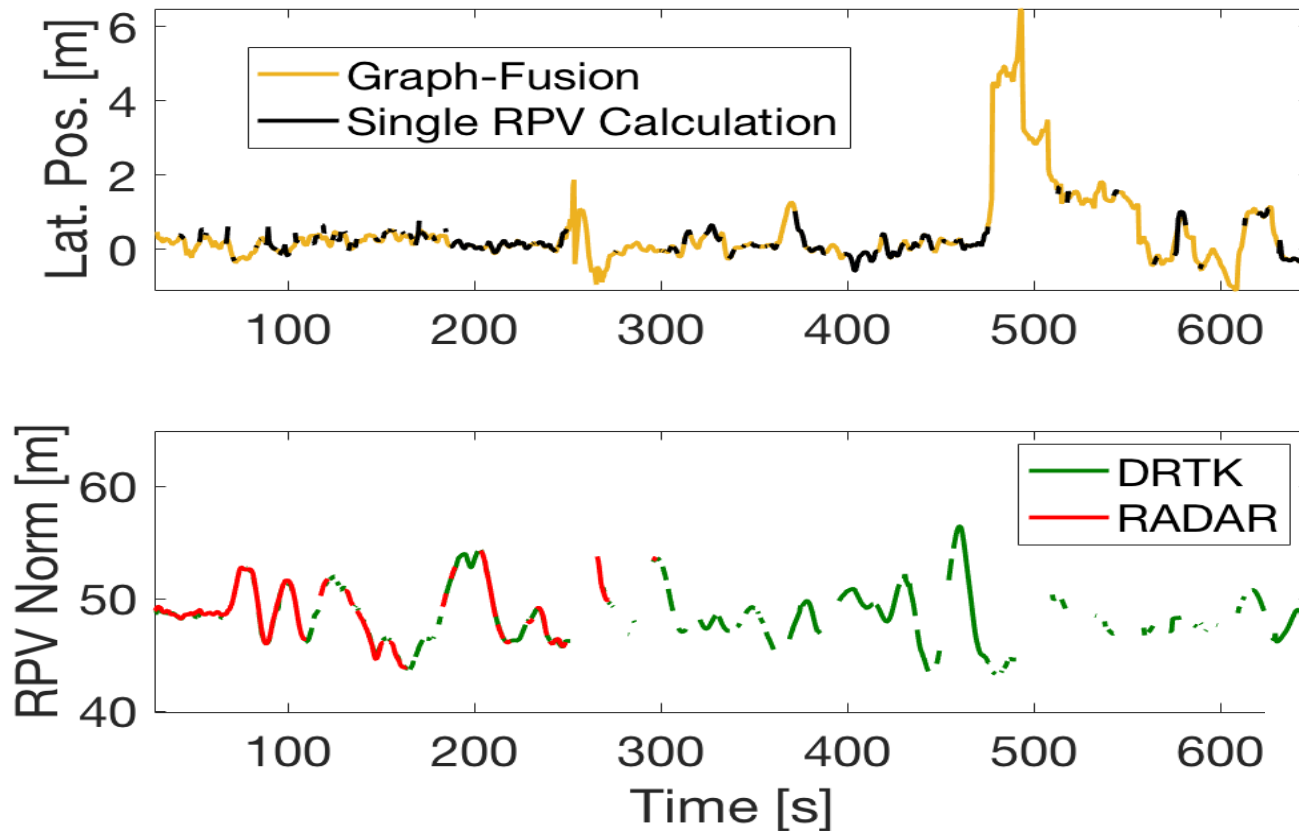
Results: Odometry outlier case

- Odometry outliers -> bias path over entire following distance
- Graph fusion spans outages, but still heavily influenced spikes



Results: GNSS outage case

- Graph-based solution relies solely on body-centric measurements during outages
- Availability is improved, but accuracy significantly diminished



Testing:

- Better performance analysis with ground truth
- Test with online controller

Algorithm:

- Graph edge outlier rejection
- Landmark exchange for GNSS-denied SLAM
- Higher resolution path using high rate measurements (RADAR CAN information at 5Hz)

Questions?

Thank You!

