Sensor Fusion for Robust Path Duplication in Automated Ground Vehicle Convoys

Dan Pierce and David Bevly

ITSNT 2018
Toulouse, France

AUBURN UNIVERSITY

GPS & Vehicle Dynamics Laboratory

Outline

- 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

Motivation

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)

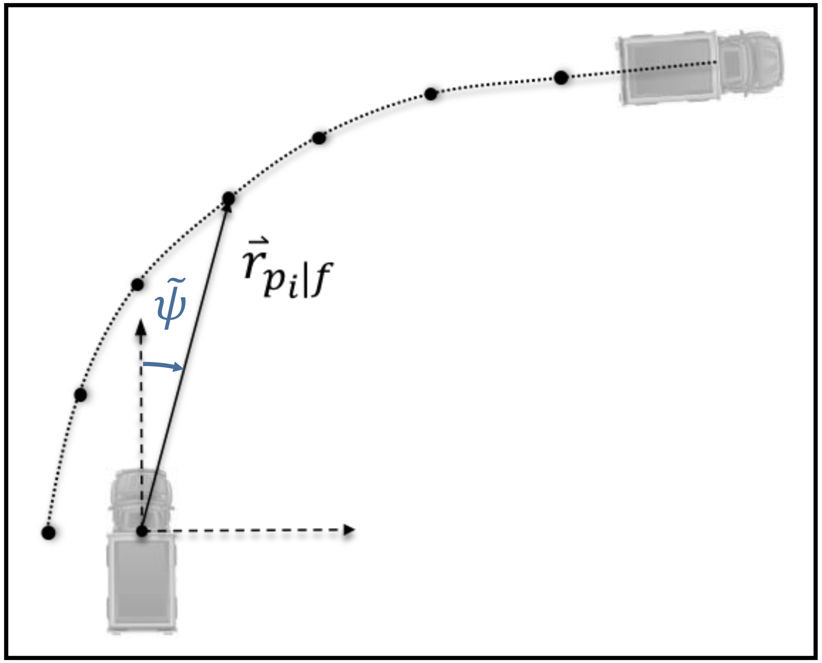
Path Following Approach

- 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

Path Following Approach

- 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

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



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

Path Generation Approaches

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*

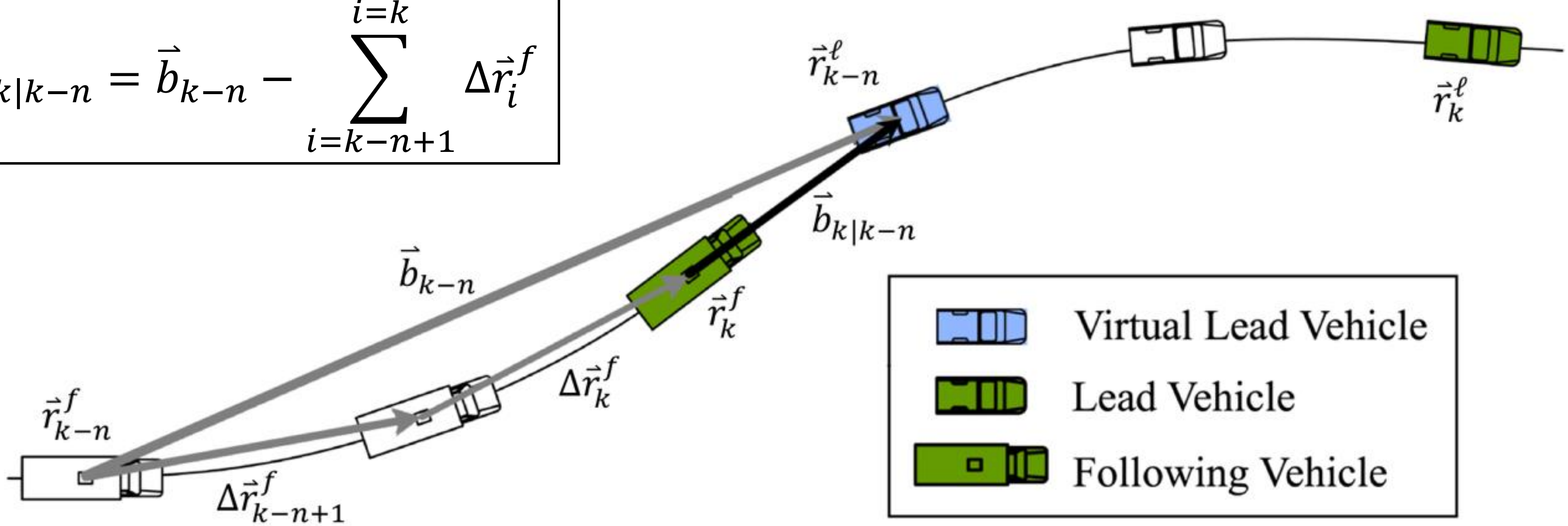
- Accurate inter-vehicle RPV measurements
- RPV measurement combined with vehicle odometry (change in position in time) allows for path generation

*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)

$$\vec{b}_{k|k-n} = \vec{b}_{k-n} - \sum_{i=k-n+1}^{i=k} \Delta\vec{r}_i^{\,f}$$



Relative Path Generation

Limitations

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

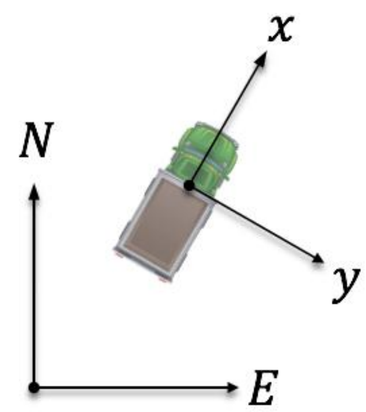
Proposed Solution

- 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

Odometry Methods

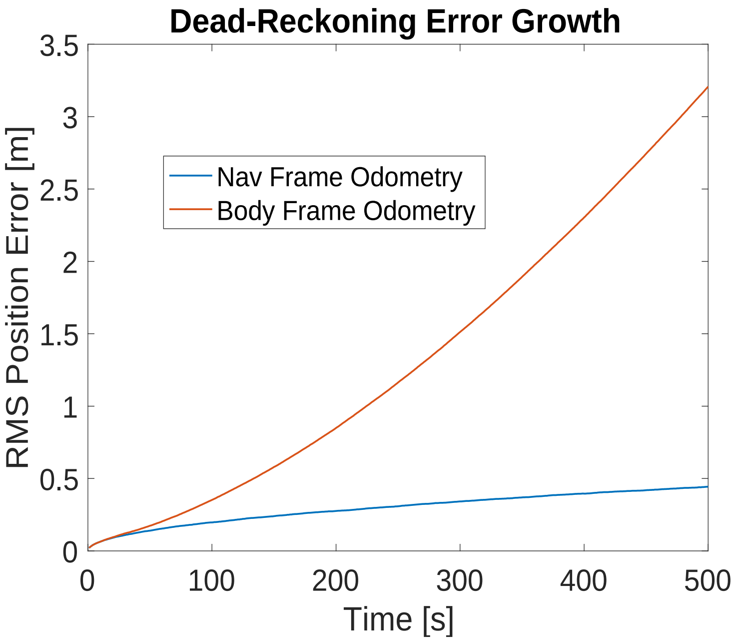
Body-Centric Odometry

- 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



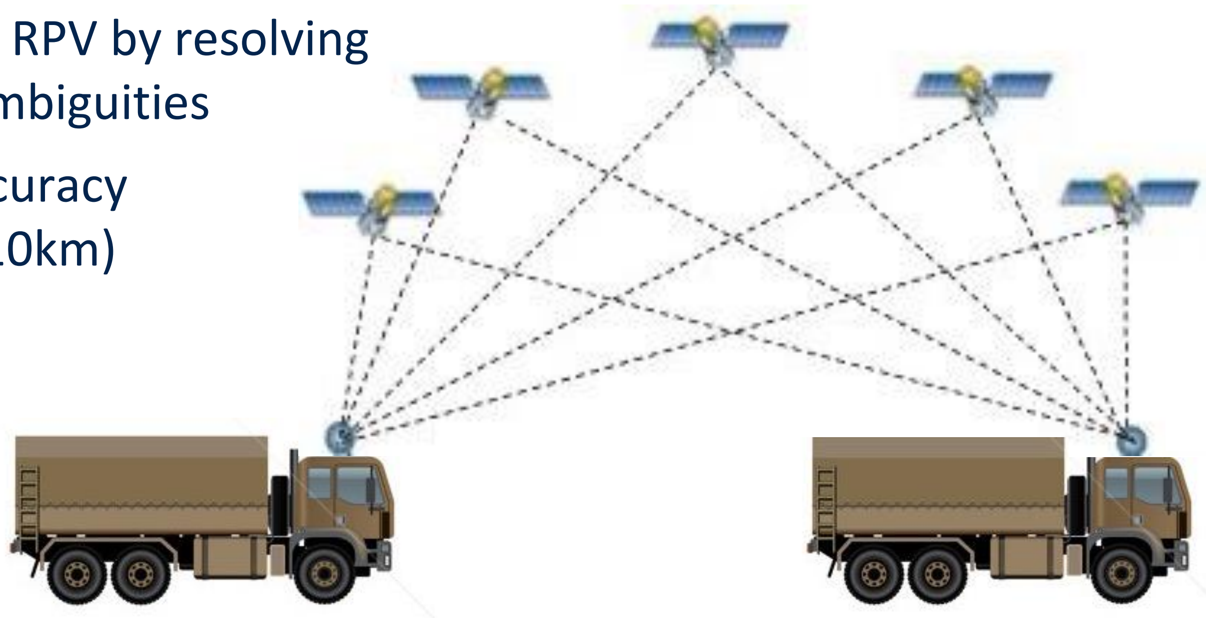
RPV Methods

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

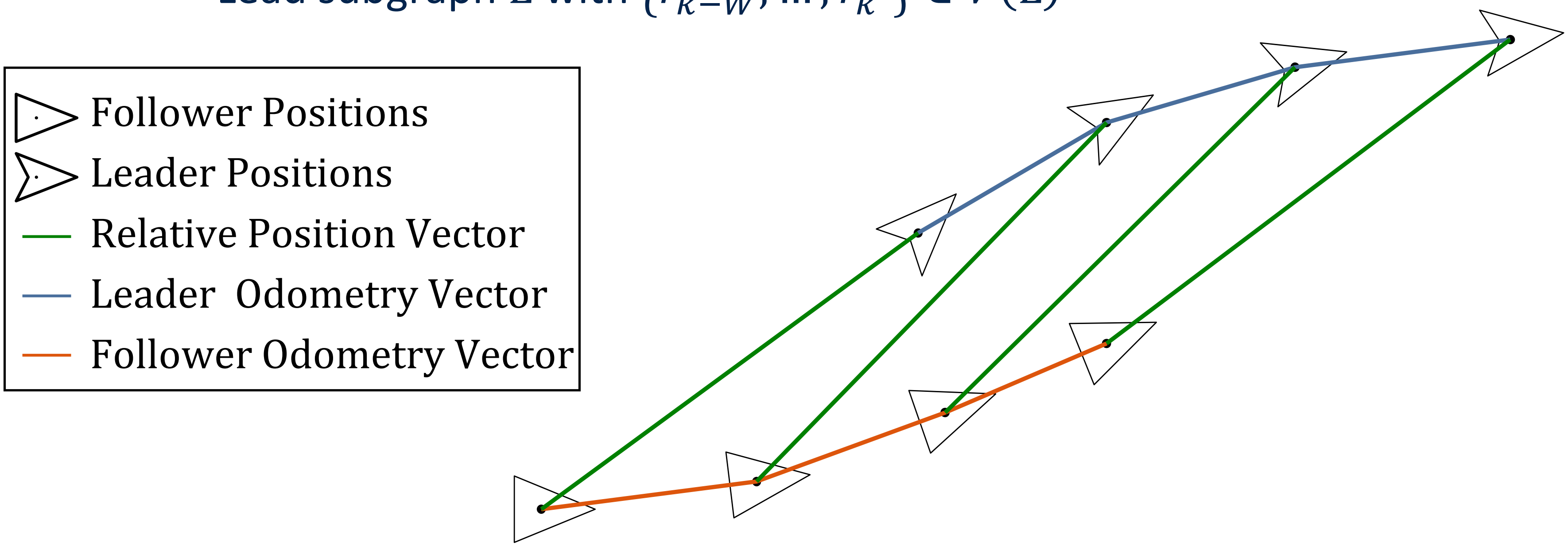


Graph-Based Path Estimation

- Graph-based estimation framework is considered to smooth path and span GPS/coms outages
- Graph edges → measurements (weighted by uncertainty)
- Graph vertices → state estimates (2D position)

  - Follower subgraph F with $\{\vec{r}^{\,f}_{k-W}, \ldots, \vec{r}^{\,f}_{k}\} \in V(\mathrm{F})$

  - Lead subgraph L with $\{\vec{r}^{\,\ell}_{k-W}, \ldots, \vec{r}^{\,\ell}_{k}\} \in V(\mathrm{L})$

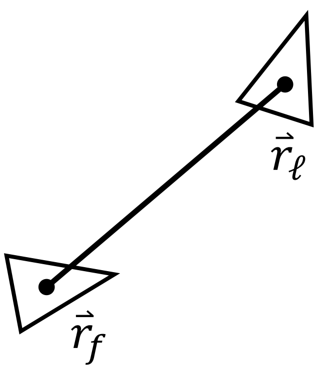


Graph-Based Path Estimation

- 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

$$\Omega_{[ij]} \mathrel{+}= \mathrm{H}_{ij}^{T} \mathrm{R}_{ij}^{-1} \mathrm{H}_{ij}$$
$$\xi_{[ij]} \mathrel{+}= \mathrm{H}_{ij}^{T} \mathrm{R}_{ij}^{-1} z_{ij}$$

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



Example: RPV measurement

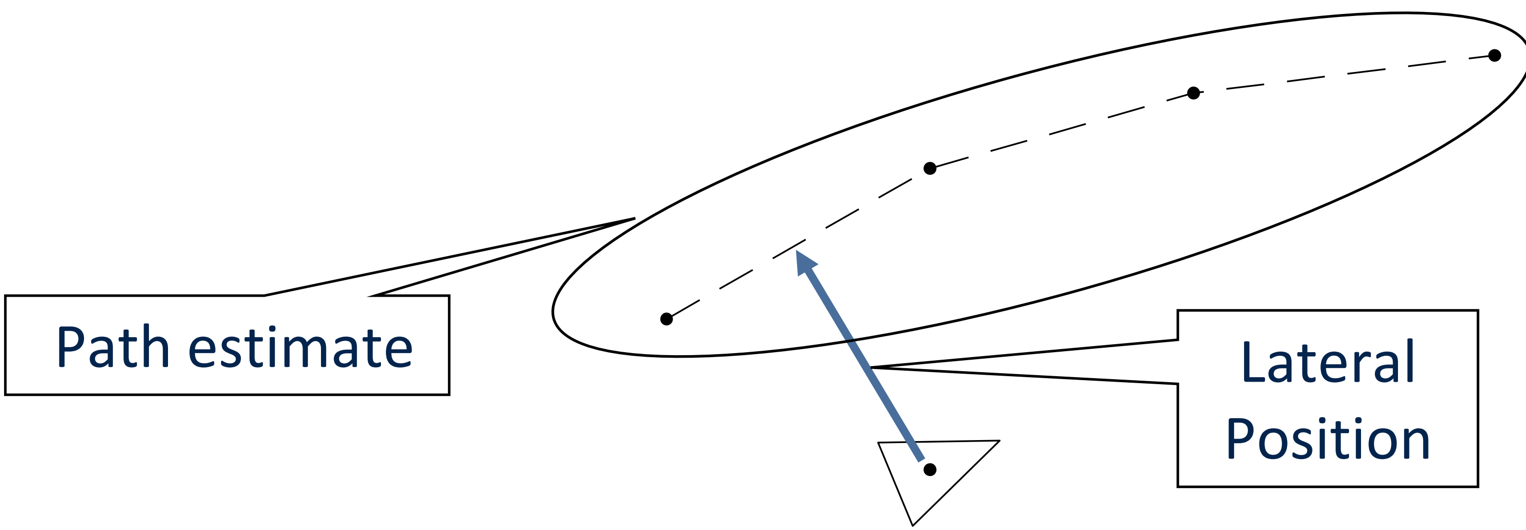
$$\mathrm{H} = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$
$$\mathrm{R} = \mathrm{E}[\nu \nu^{T}]$$
$$z = (\vec{r}_\ell - \vec{r}_f) + \nu$$

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



Results

- 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:

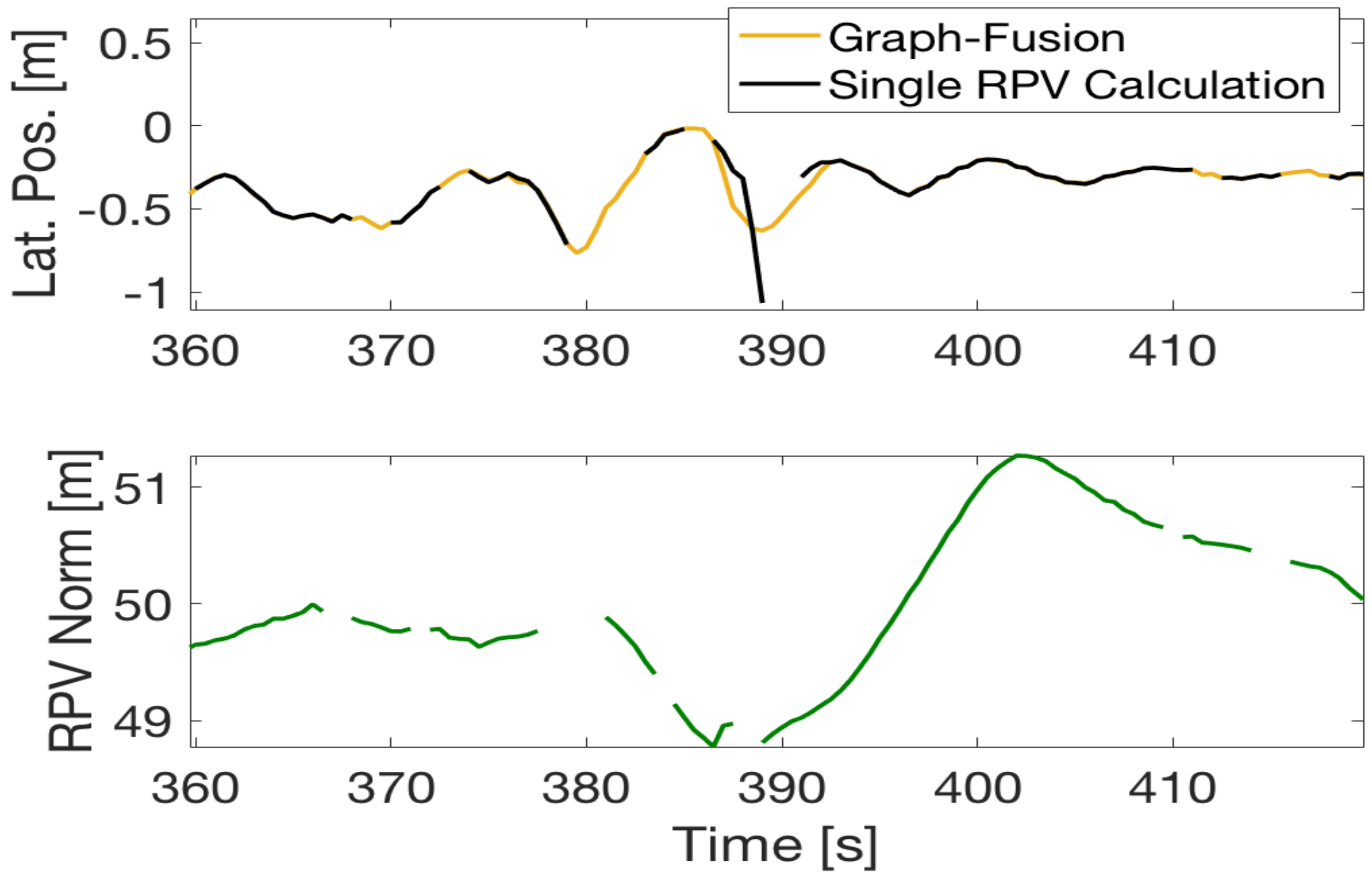
  1) DRTK RPV outliers from false integer ambiguity

  2) TDCP odometry outliers from multi-path

  3) Complete GNSS outage (e.g. tunnel)

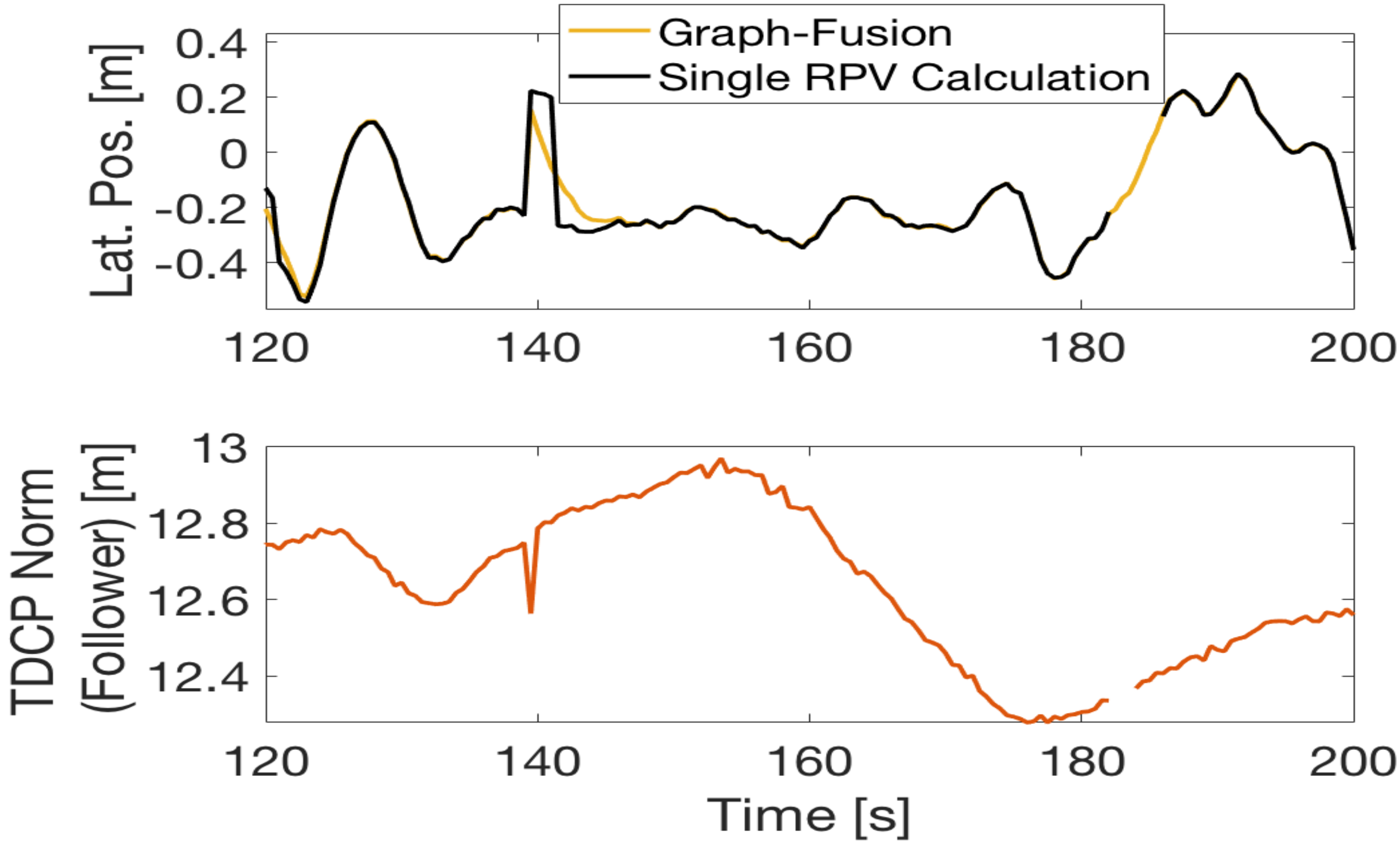
Results: RPV outlier case

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



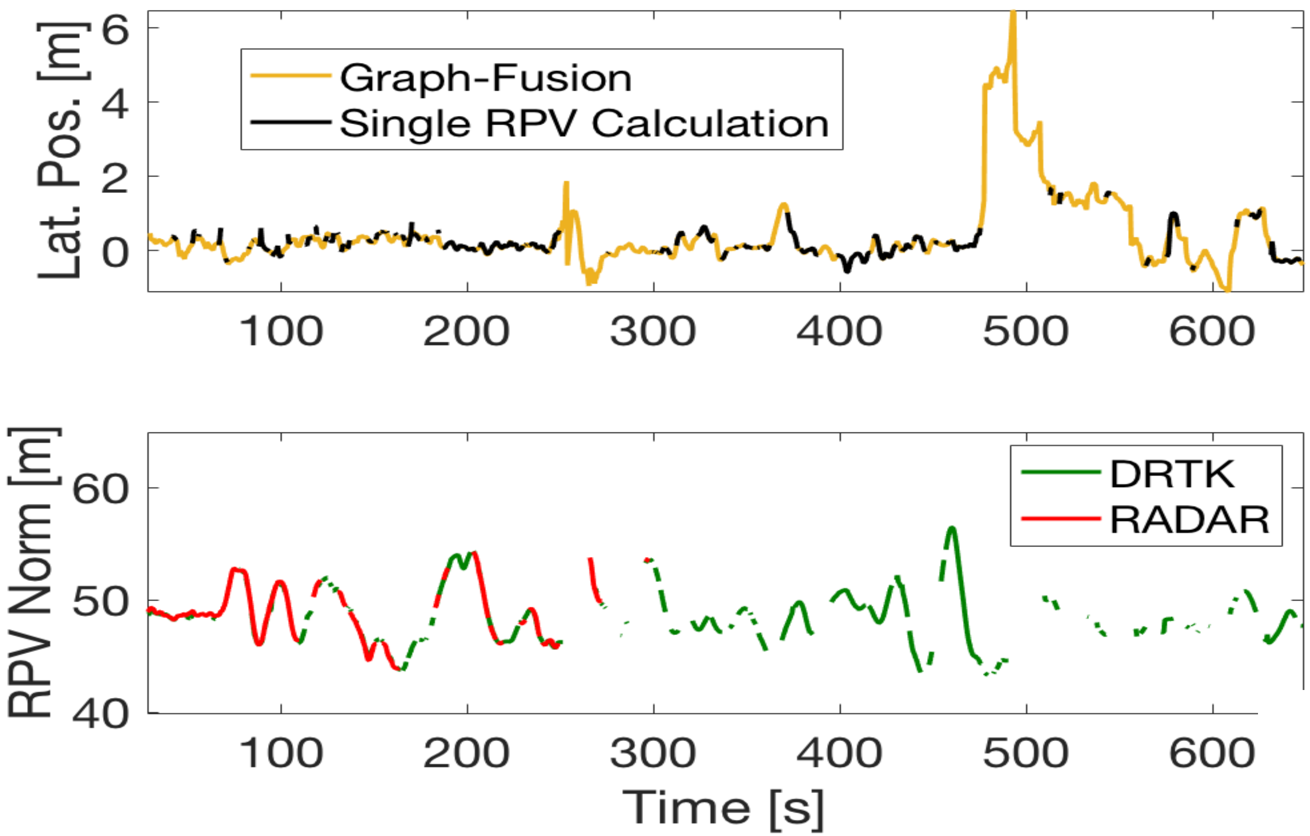
Results: Odometry outlier case

- 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



Future Work

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!