[Airbus Amber]

NATO Symposium SET-275

Collaborative Navigation

Using Relative Sensor Measurements to Aid and Synchronize the Absolute Navigation of Swarm Members

DEFENCE AND SPACE

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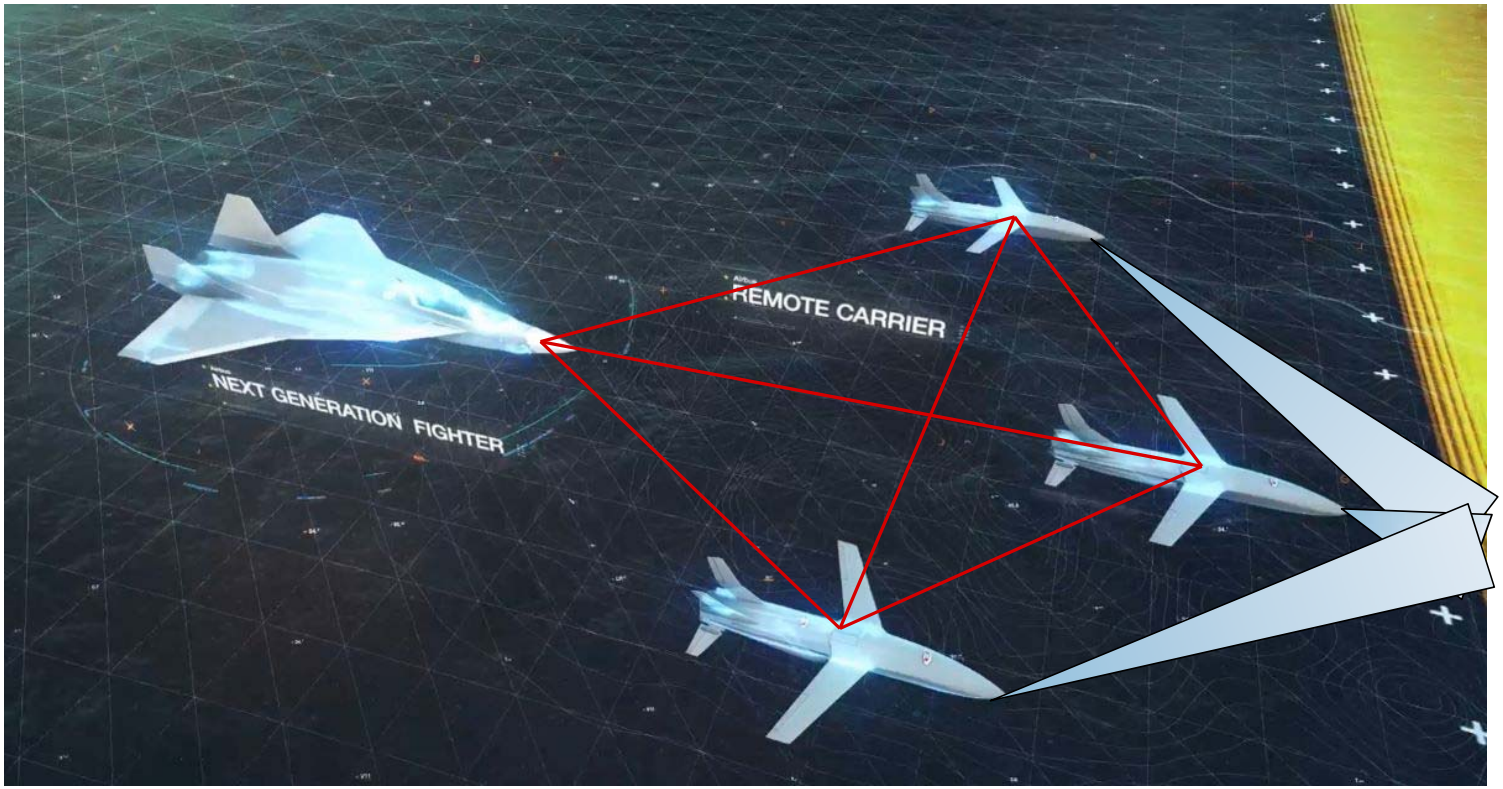
Collaborative Navigation – Problem Description



- High accurate **relative** and **absolute** positioning required (Formation Flight, Distributed Sensing, ...)
- **GNSS-denied environment**

- **Sensor Fusion** of **absolute** and **relative** sensor information

→ How to aid INS with relative sensor measurements?

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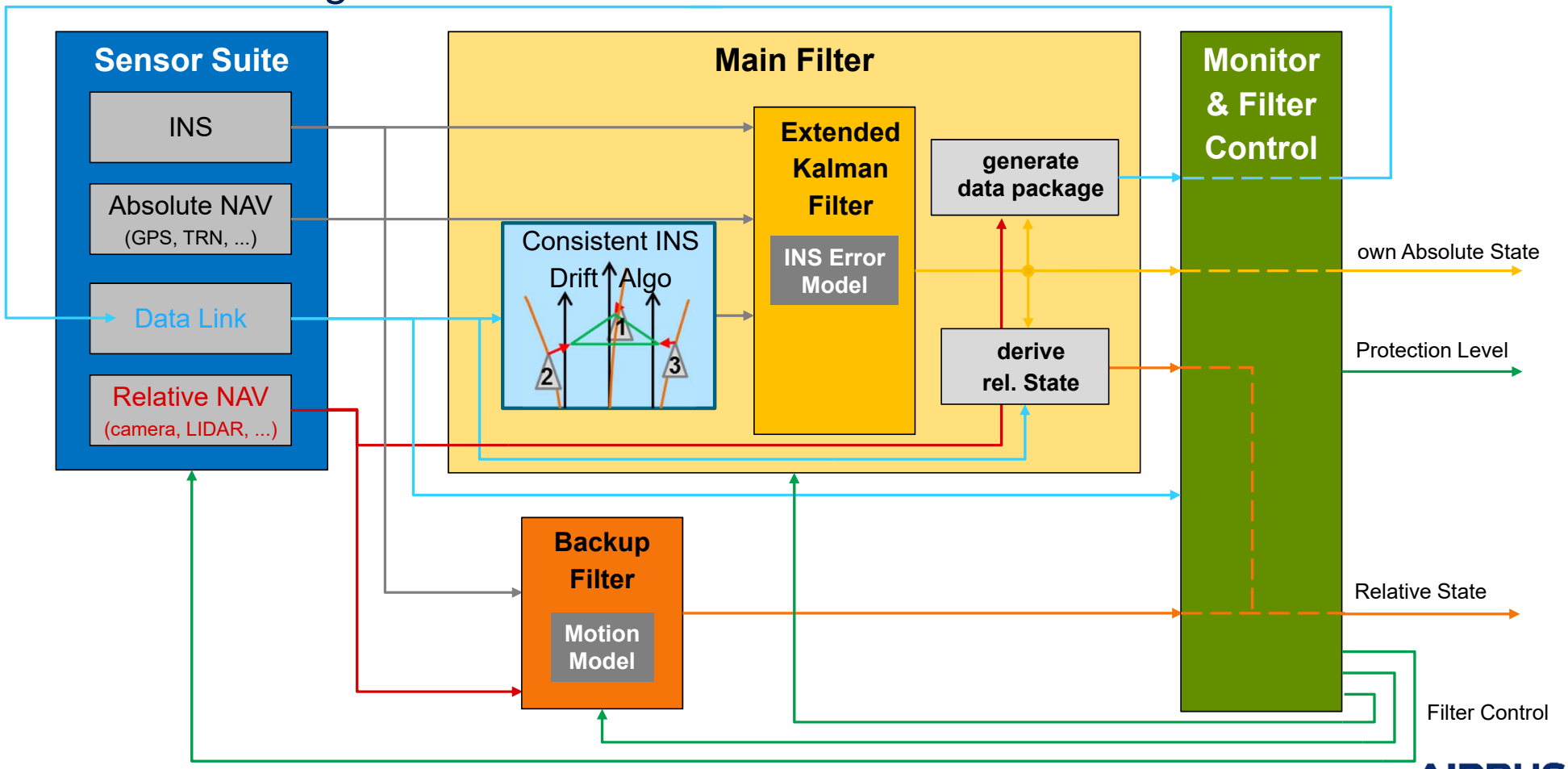
Collaborative Navigation Architecture



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Collaborative Navigation Architecture – Operational Conditions

	GNSS available	GNSS-denied environment
Data link available	Good absolute and relative position accuracy	Relative position accuracy is maintained. Absolute navigation solution will drift as INS drifts. At least one formation member is required with an alternative absolute navigation mean such as TRN to maintain absolute position accuracy of the entire formation
Data link not available (e.g. due to required stealth or jamming)	Fly in formation based on absolute position* In close formation, GNSS errors, such as ionospheric or tropospheric ones, cancel out → use same satellites (e.g. ensured by mission planning)	Sensor Fusion of relative and absolute position not feasible. However, graceful degradation of "[illegible] navigation solutions after entering [illegible]e

Main Filter

Backup Filter

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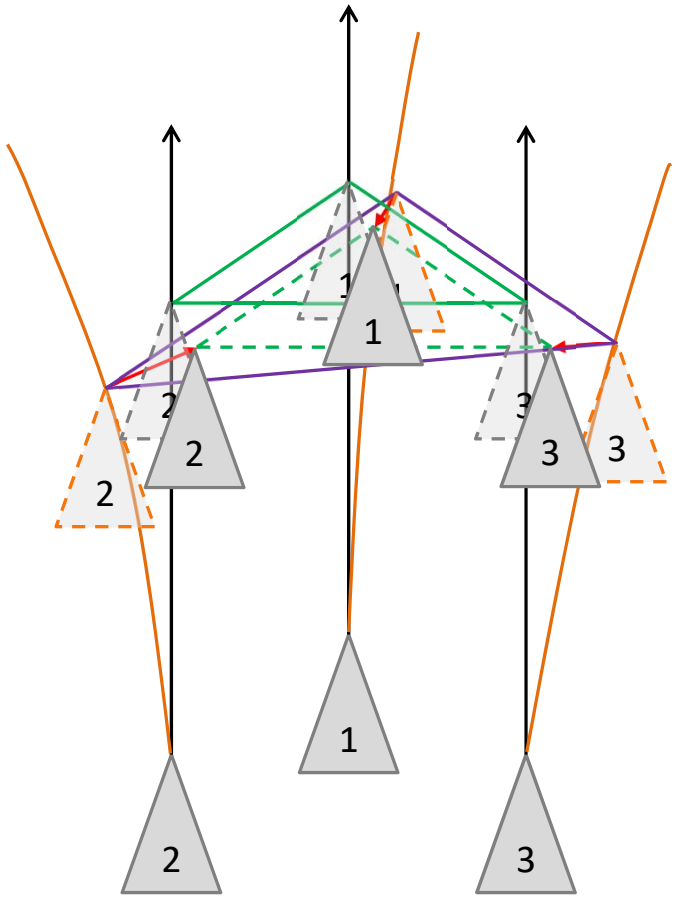
Consistent INS Drift Algorithm – Working Principle

ground truth
abs. state estimation
rel. measurement
est. rel. measurement
innovation



$\tilde{z}_{ij}$
measurement

$\hat{z}_{ij} = h(x_{old,j} - x_{old,i})$
estimated measurement

$H(\delta x_i - \delta x_j) = \hat{z}_{ij} - \tilde{z}_{ij}$
innovation

$x_{new,i} = x_{old,i} + \delta x_i$
update

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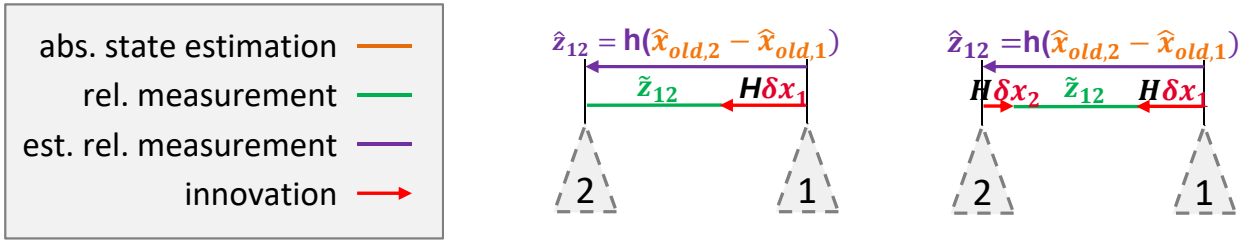
Consistent INS Drift Algorithm – Constraint

The **new state estimations cannot be uniquely determined yet** as the **whole swarm can be shifted** in position for instance while **still reproducing the relative measurements**.



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Consistent INS Drift Algorithm – Constraint

In order to obtain an unique solution for the new state estimation, respectively innovation, a constraint is introduced such that

- The **weighted sum of innovations shall be zero**:

$$W_Q^{-1} \sum_{i=1}^{n} Q_i^{-1} \delta x_i = 0 \quad with \;\; W_Q := \sum_{i=1}^{n} Q_i^{-1}$$

  - The **weighting** is performed according to the **inverse of the innovation covariance** Q_i.
  - The idea behind the weighting is that a swarm members with a **very accurate state estimation need less of the innovation** than a formation member *j* with a poor state estimation ($P_{old,i} << P_{old,j}$) (high quality INS drifts slower than a low-cost INS, and hence, the position (states estimates) of the formation member with the high quality INS have to correctly only a little bit)

  → That the weighted sum of innovations is zero implies that **weighted center of the swarm does not change**

  → Which makes sense since the **relative measurements have no reference to the absolute outer world** but are encapsulated in the formation, and hence, cannot cause the weighted swarm center to shift

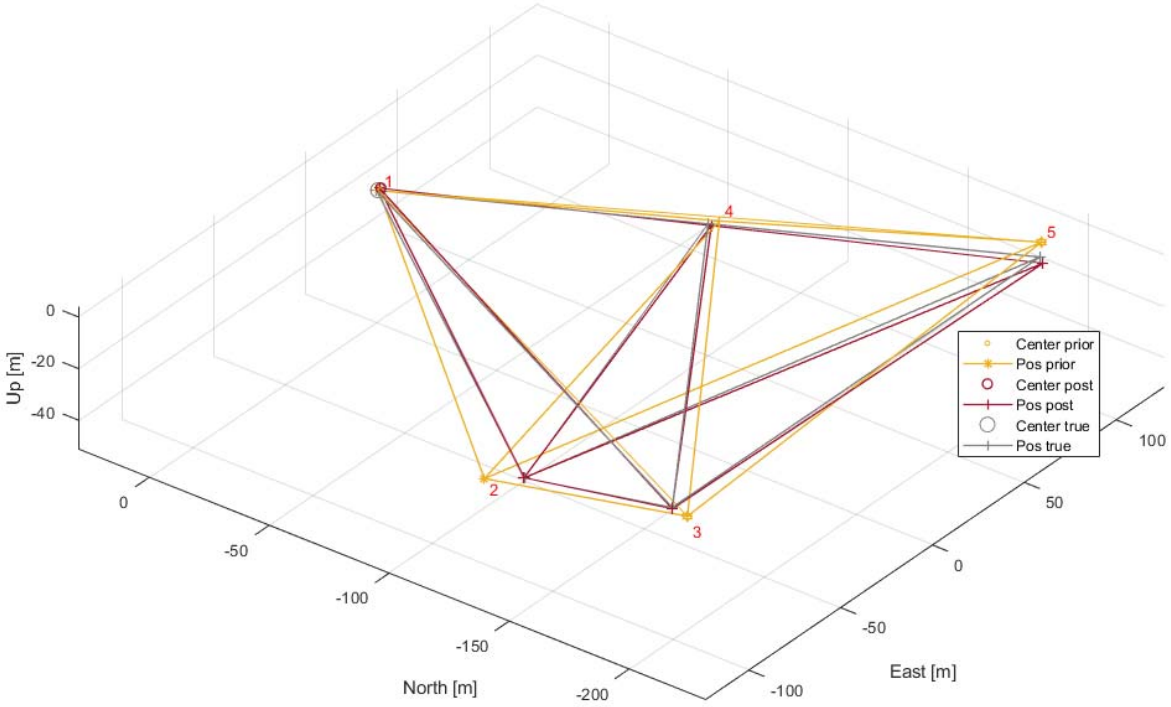
$$W_Q^{-1} \sum_{i=1}^{n} Q_i^{-1} x_{new,i} = W_Q^{-1} \sum_{i=1}^{n} Q_i^{-1} (x_{old,i} + \delta x_i) = W_Q^{-1} \sum_{i=1}^{n} Q_i^{-1} x_{old,i} + W_Q^{-1} \underbrace{\sum_{i=1}^{n} Q_i^{-1} \delta x_i}_{0} = W_Q^{-1} \sum_{i=1}^{n} Q_i^{-1} x_{old,i}$$

$$W_Q^{-1} \sum_{i=1}^{n} Q_i^{-1} x_{new,i} = W_Q^{-1} \sum_{i=1}^{n} Q_i^{-1} x_{old,i}$$

  → Moreover, it can be mathematically proven that the weighted center is statistically better than best individual state estimation

  → The **whole swarm drifts slower than the best individual INS** in the absence of any absolute navigation means

Consistent INS Drift Algorithm – Example



- Swarm Member #1 has a 10 times smaller position uncertainty compared the remaining swarm members
  → the swarm center is located close to Swarm Member #1
- The **remaining swarm member benefit from the good position estimation** of swarm member #1

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Advantages of the Main Filter thanks to the Consistent INS Drift Algorithm

Properties

- The **absolute positions** of the swarm members are **consistent / synchronized** by aiding the INS with relative sensor measurements (→ long-term stability of relative accuracy)
- In **absence of any drift-free absolute navigation means** (e.g. GPS) **the overall swarm drifts statistically slower** than the best individual Inertial Navigation System / absolute state estimation
- In case that **at least one swarm member** has an **absolute navigation** mean available, the **whole swarm does not drift** due to the synchronized INSs
- In case one or several **swarm members** are "**blind**" (e.g. failure of Formation Sensing) the blind swarm members can be **fed with updates from healthy swarm members**.

Heterogeneous navigation systems, and hence, **true collaboration** are natively **supported**:

E.g. some swarm members may be equipped with specialized navigation system while the other swarm members may be equipped with the bare minimum to save SWaP (Size Weight and Power) for mission equipment for instance

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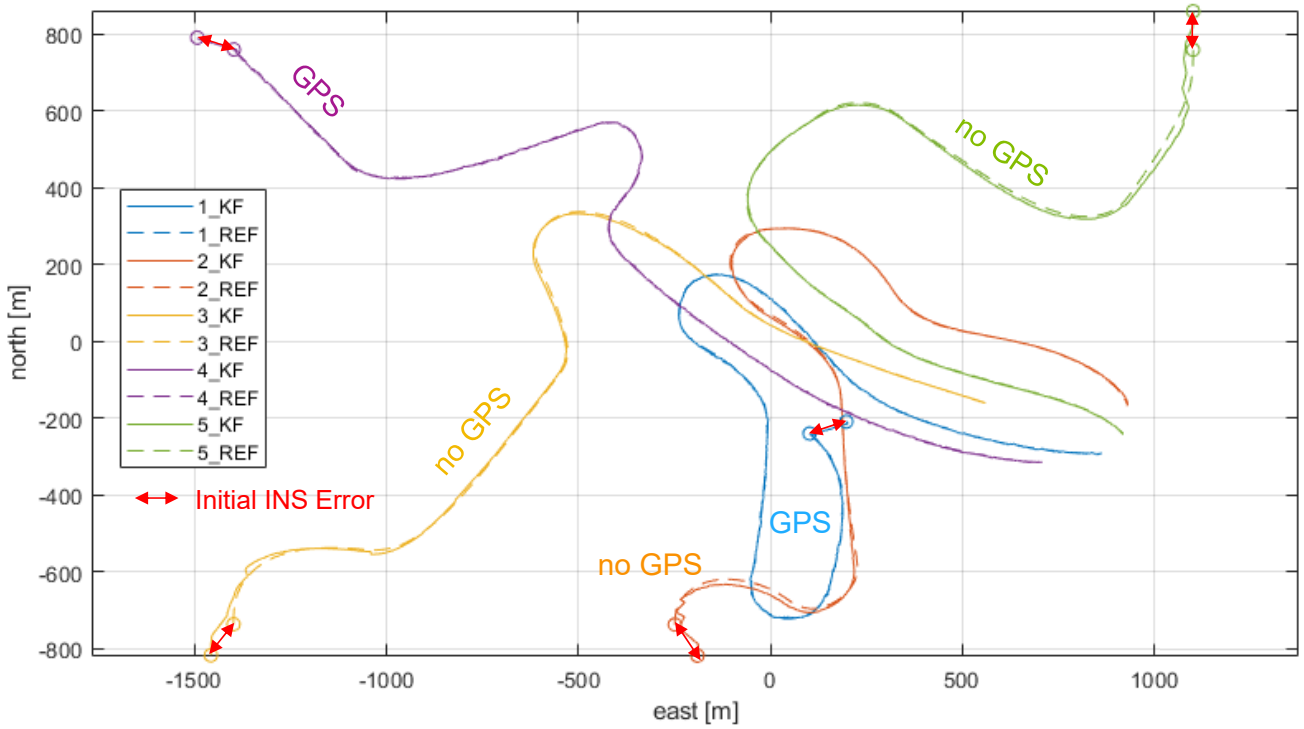
Simulation Results of Collaborative Navigation
2 Swarm Members with GPS & 3 Swarm Members w/o GPS



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Simulation Results of Collaborative Navigation
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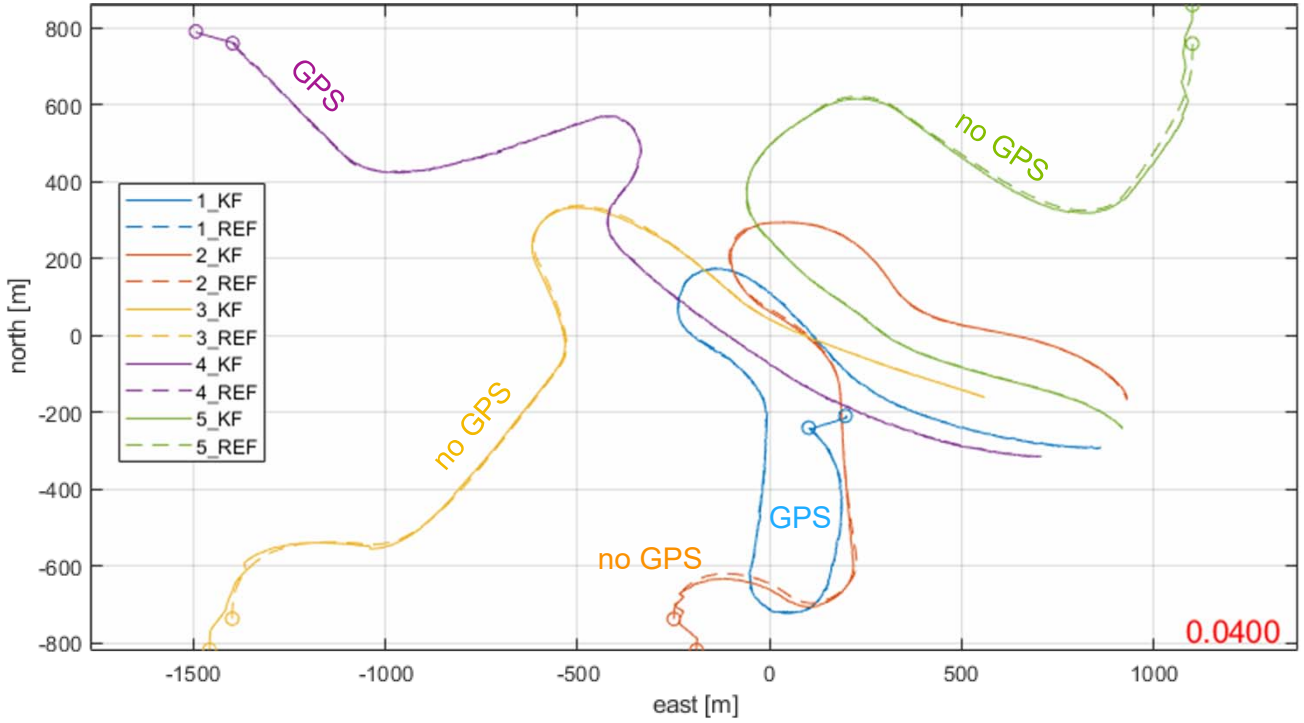

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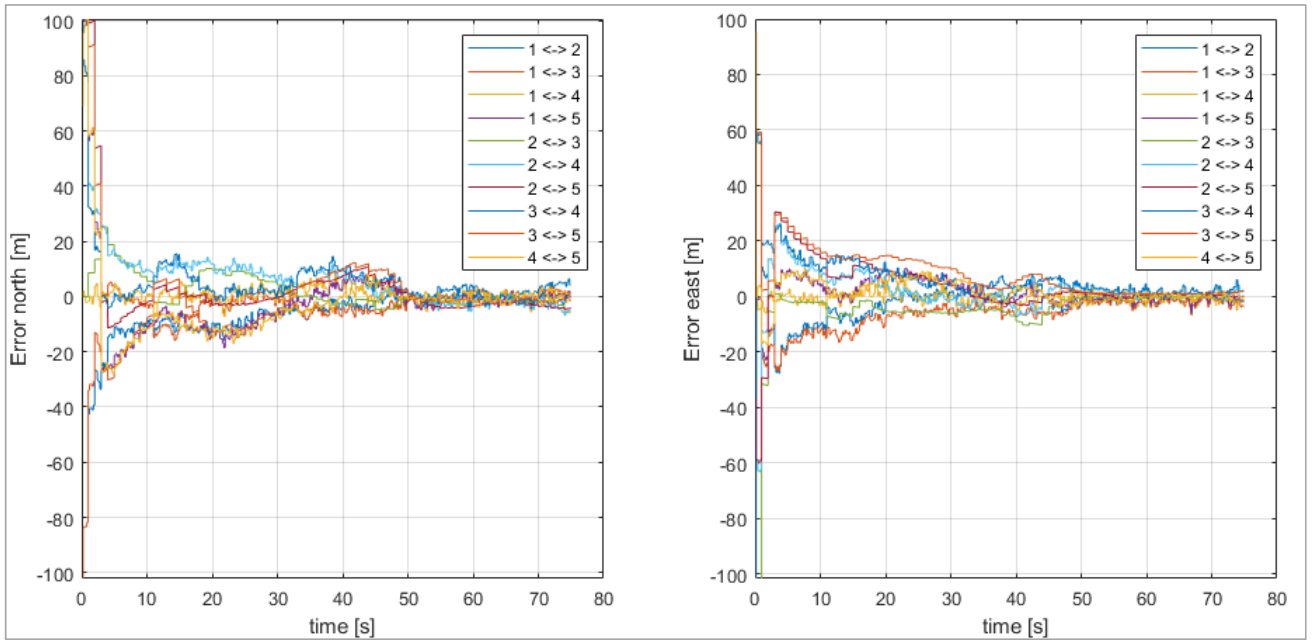
Simulation Results of Collaborative Navigation
2 Swarm Members with GPS & 3 Swarm Members w/o GPS

Relative navigation error between Swarm Members:



- The initial relative error decreases quickly in the horizontal plane and reaches < 5 m after the swarm fly fixed formation (at ~ 50 s)

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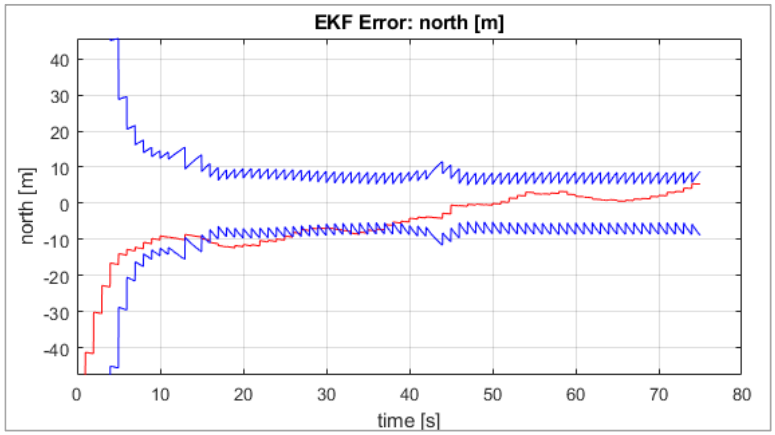
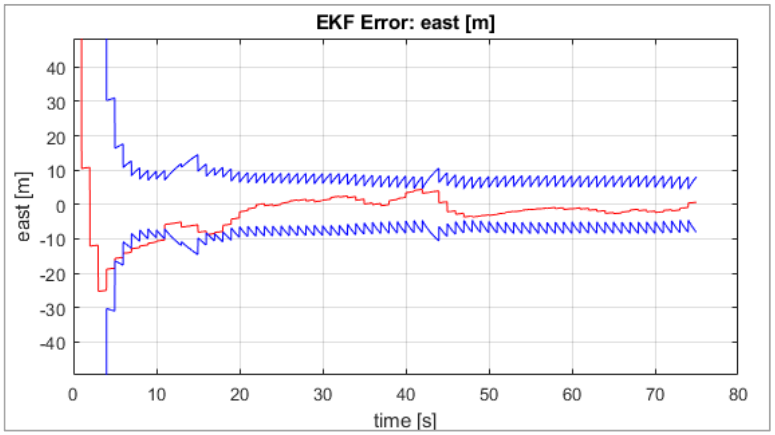
Simulation Results of Collaborative Navigation
2 Swarm Members with GPS & 3 Swarm Members w/o GPS

Absolute navigation error of Swarm Member #2 **without GPS**:





- The absolute position accuracy of Swarm Member #2 benefits from the Swarm Members which have with GPS available
- The absolute position error in the north and east axis decreases quickly and reaches less than 10 m

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Thank you

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Backup

Scenario “complete GNSS-denial”

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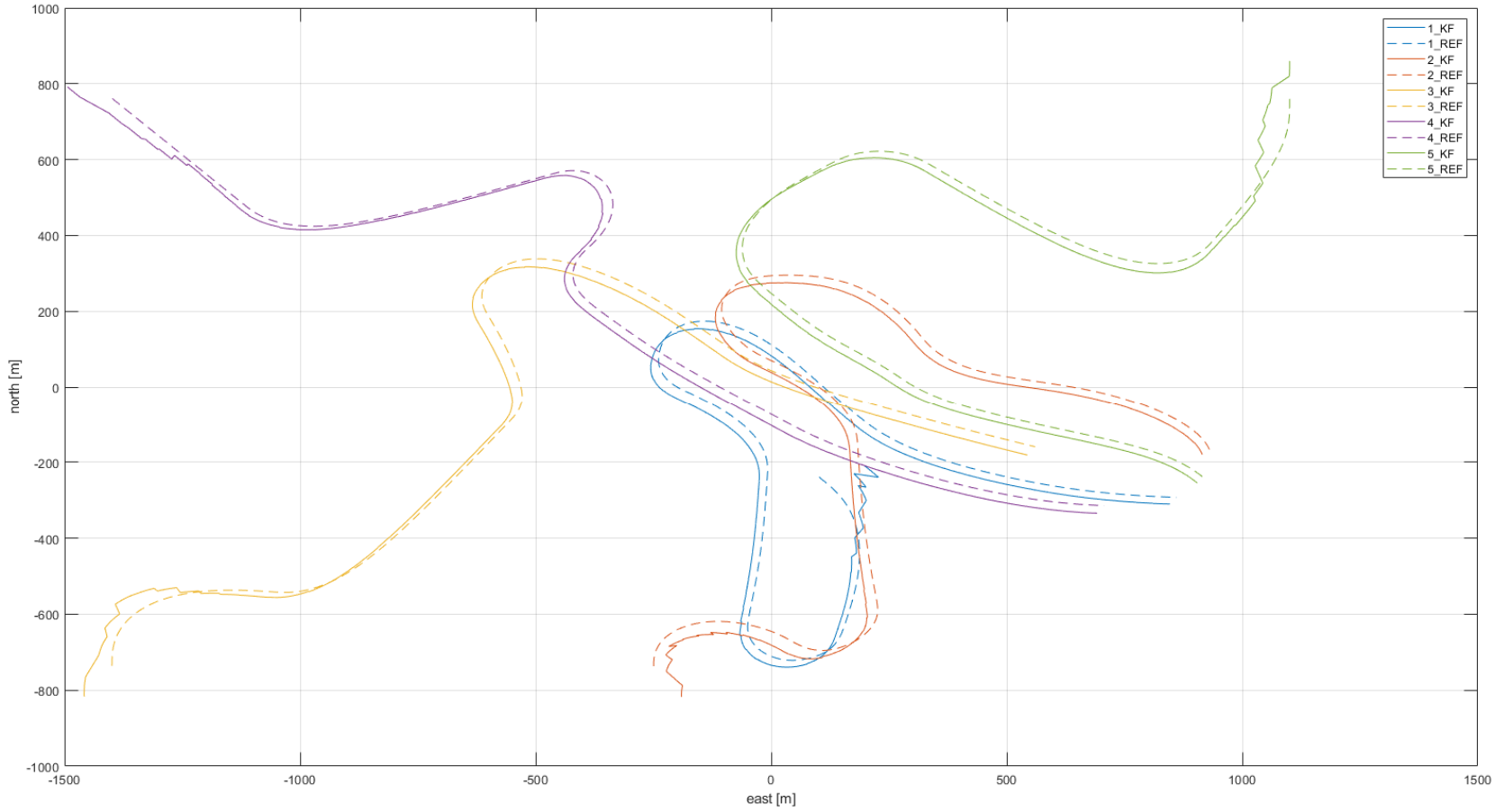
Some Results – all Swarm Members w/o GPS



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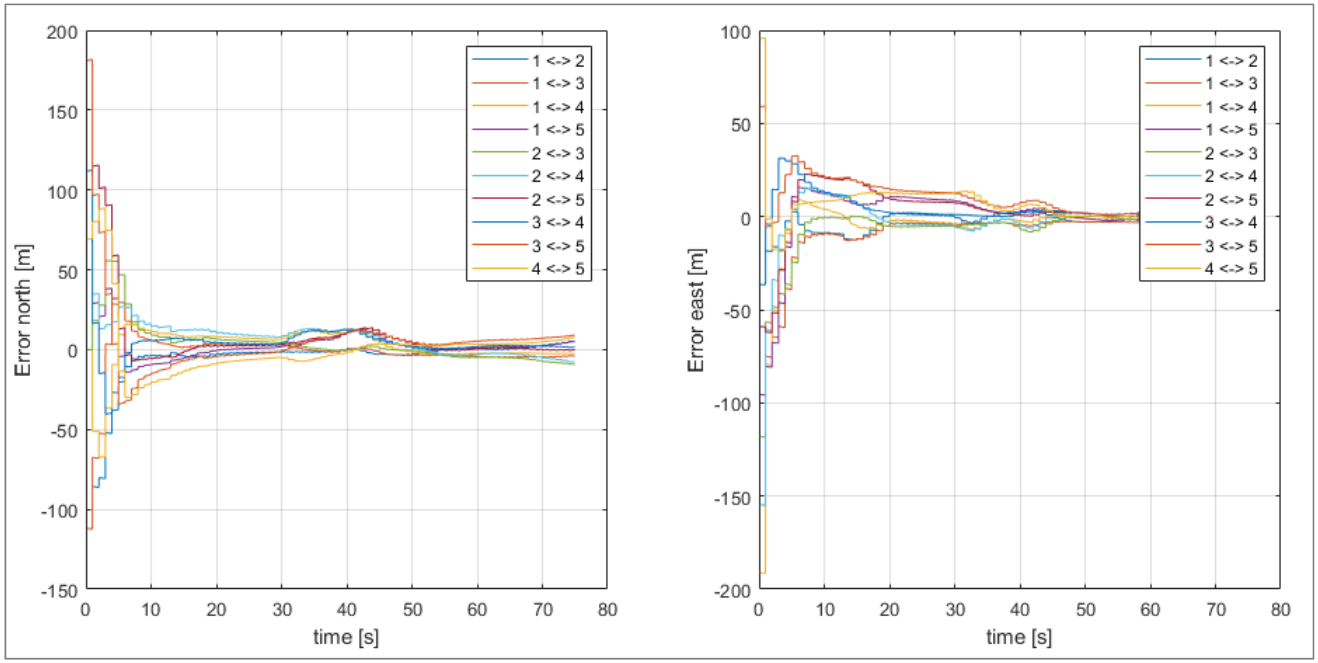
Some Results – all Swarm Members w/o GPS

Relative navigation error between Swarm Members:



- The initial relative error decreases quickly in the horizontal plane and reaches < 7 m after the swarm fly fixed formation (at ~ 50 s)

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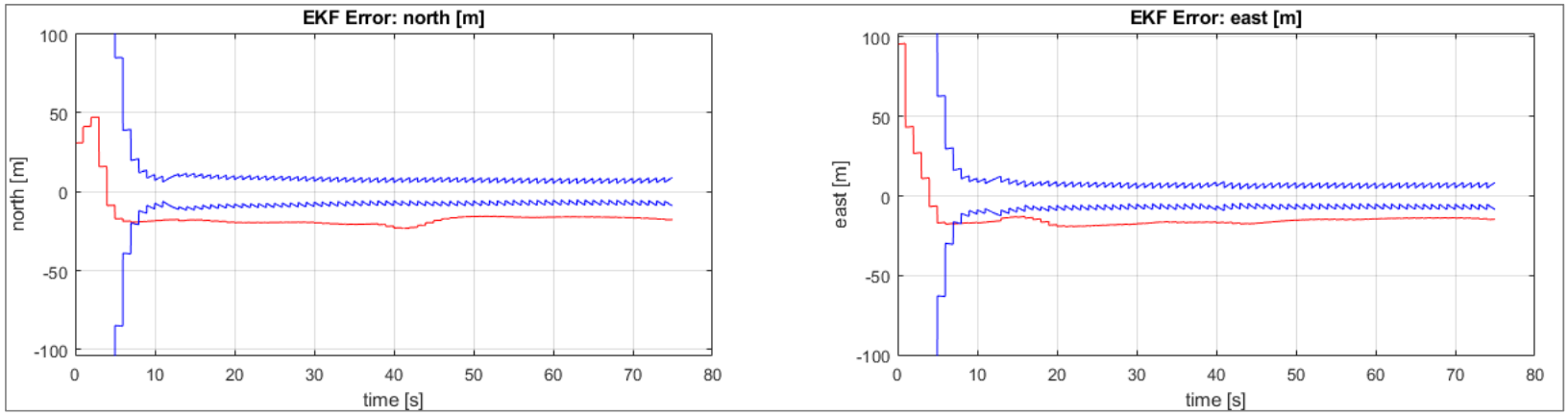
Some Results – all Swarm Members w/o GPS

Absolute navigation error of Swarm Member #2 **without GPS**:



- The absolute position accuracy of Swarm Member #2 benefits from other swarm members as the INS drifts partially cancel each other out
- An absolute position error of ~20 m remains which cannot be further reduced (not observable since no drift-free absolute navigation means are available within swarm)