Self-Organizing 3D Wireless Local Positioning Networks for Robot Swarms

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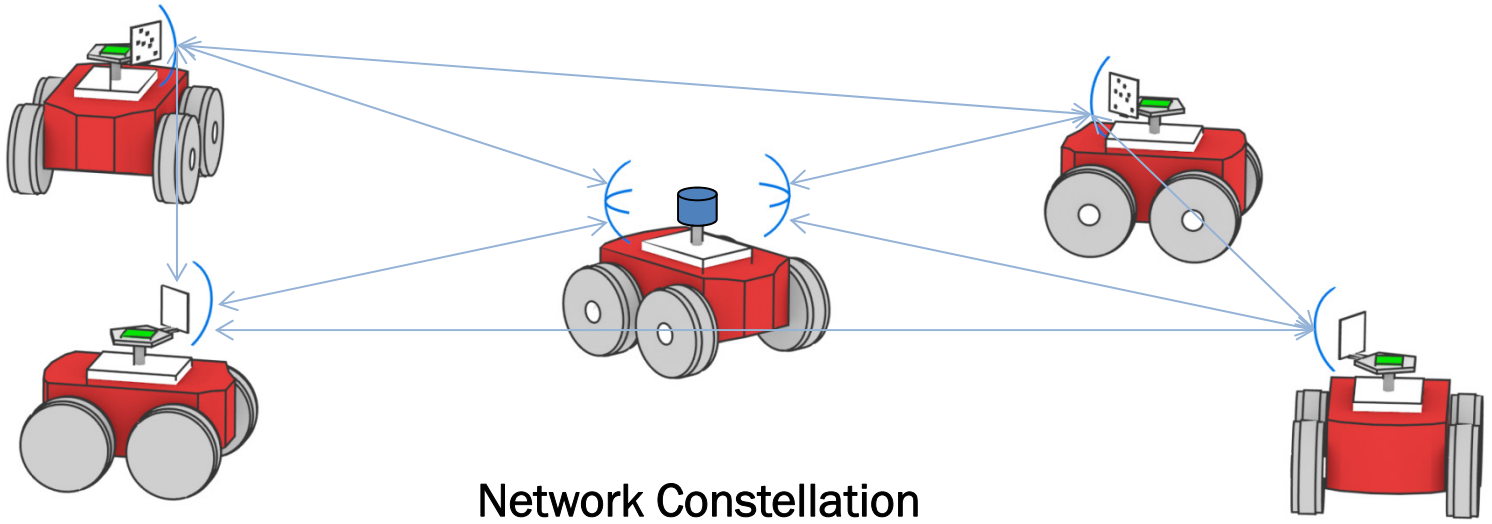
Autonomous Robot Swarm

- Self-organizing mobile robot swarm
- Application: Planetary exploration → No GNSS available
- 3 translational and 3 rotational degrees of freedom per robot
- Very high degree of freedom → Challenging self-organization

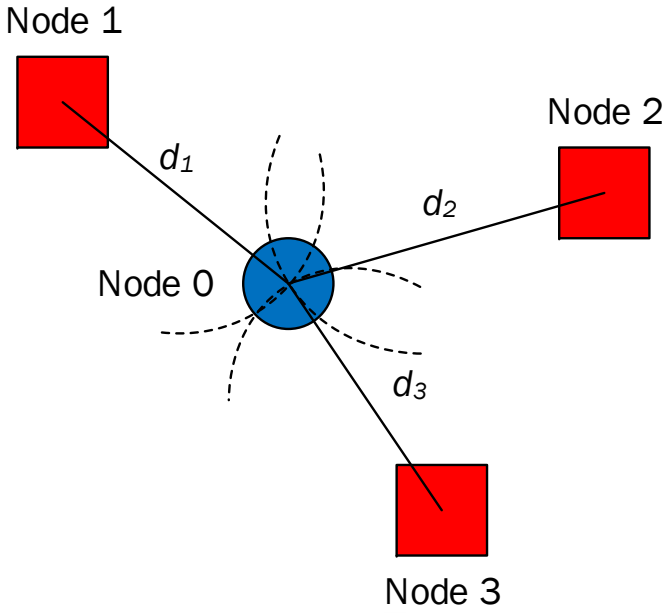


Network Constellation

Wireless Loc. Network

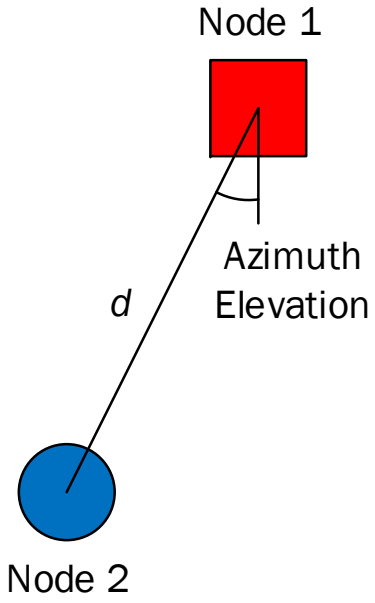
UWB multilateration systems (TDOA / TOA / RTOF)

- Complex infrastructure
- Low reliability
- No orientation



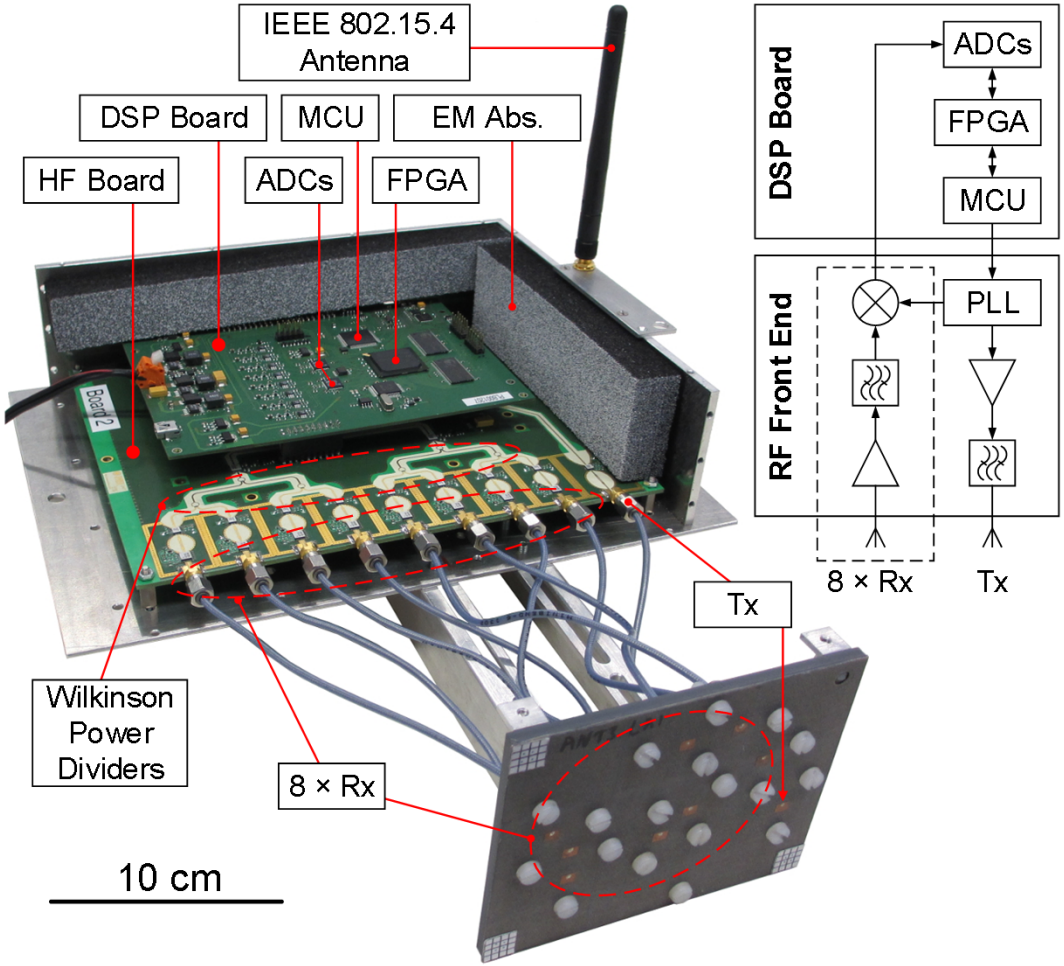
Proposed solution (bilateral RTOF + 2D DOA)

- Minimum infrastructure
- High reliability
- Orientation estimation



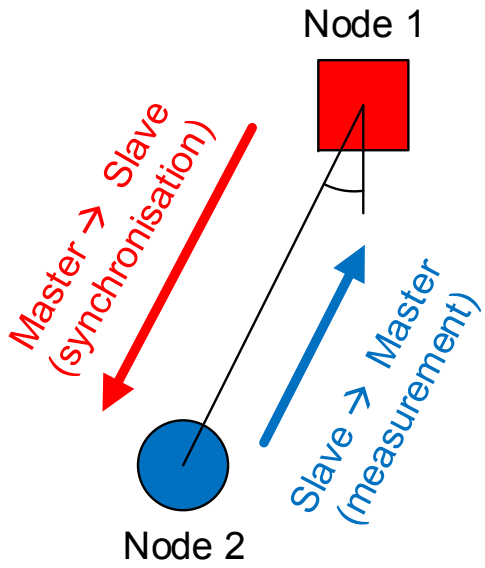
Hardware Description

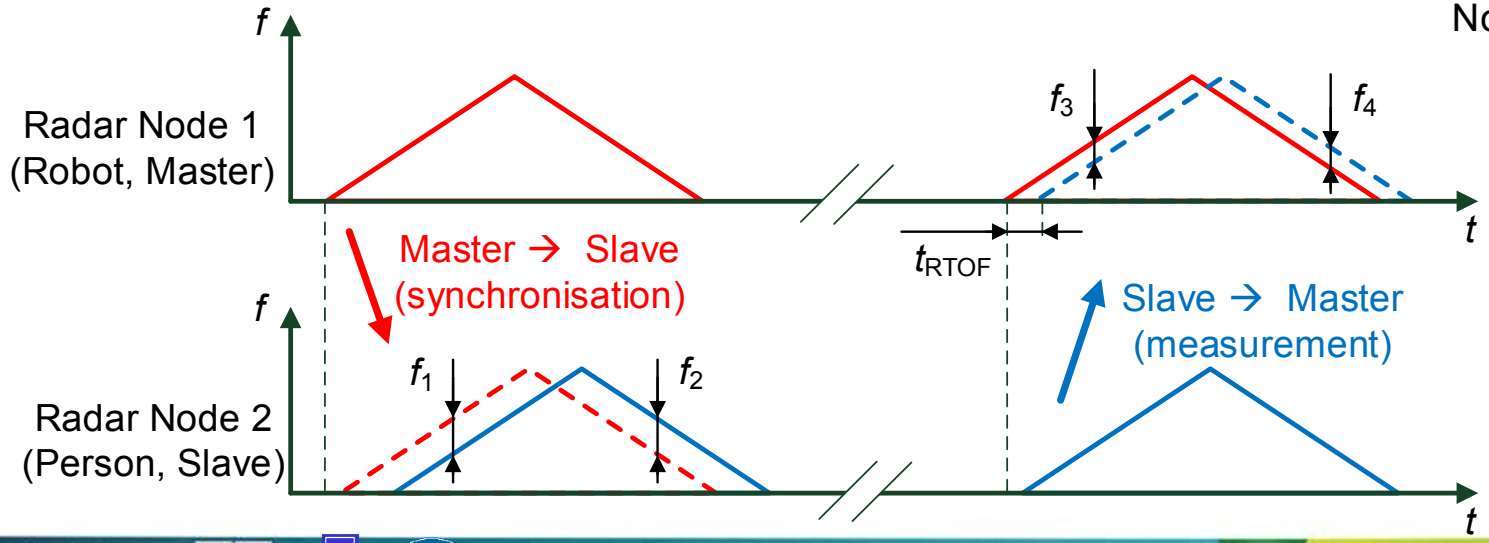
- 8 channel FMCW SIMO
- 2D sparse antenna array
  - Azimuth and elevation DOA estimation
- RF front end
  - Center frequency: 24.125 GHz
  - Sweep Bandwidth: 250 MHz
- DSP board
  - 14-bit ADCs
  - Signal processing on FPGA / ARM CPU



24 GHz Secondary Radar

- Master sends synchronization FMCW ramps
- Slave synchronizes precisely in time and frequency
- Slave sends measurement FMCW ramps
- Master calculates distance from RTOF





3D Localization

- Signal model for IF signal

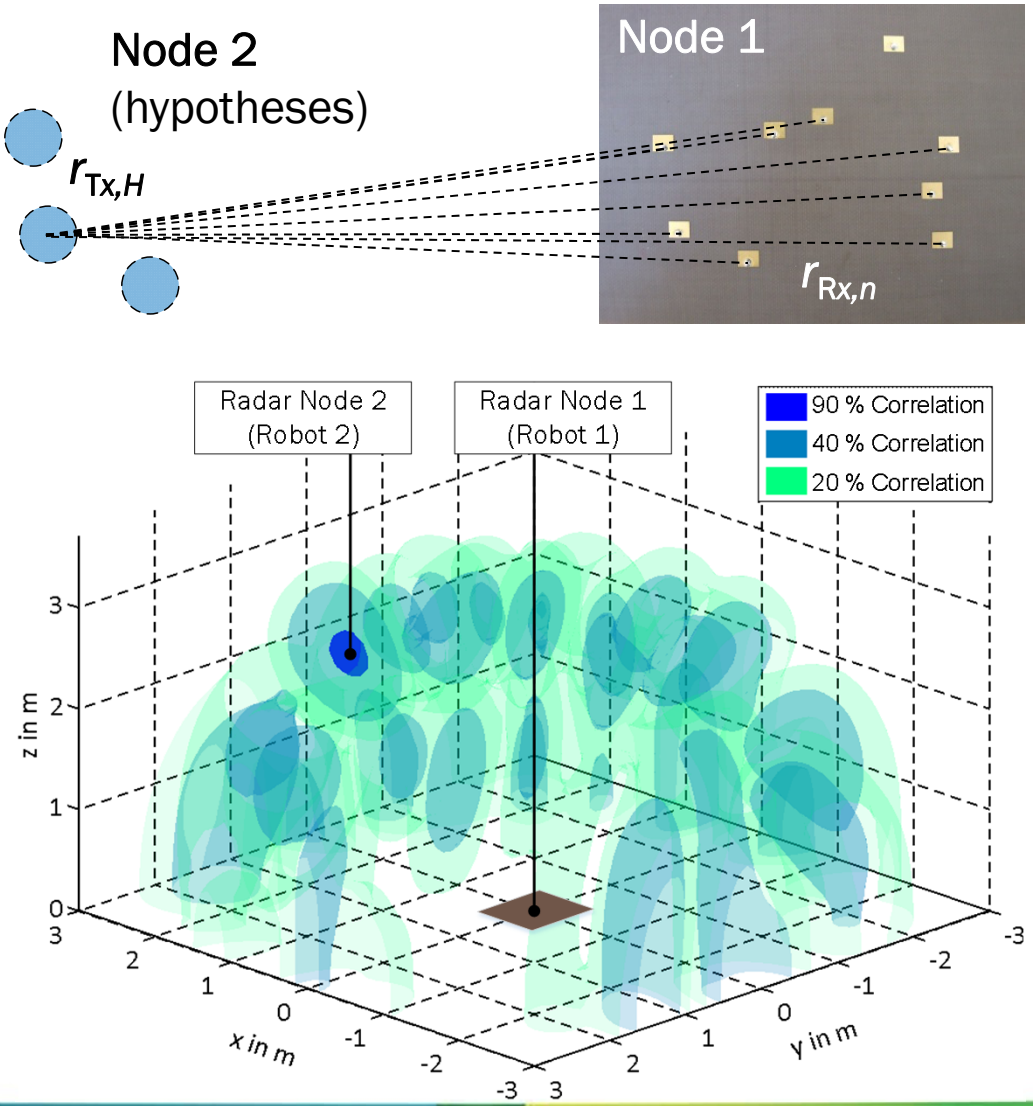
$$s_n(t) = A_n \cos(2\pi f_n t + \varphi_{g,n} + \varphi_{c,n})$$

  - f_n: frequency in channel n
  - $\varphi_{g,n}$: Phase due to geometry
  - $\varphi_{c,n}$: Error phase term
- 3D spatial matched filter H_n

$$H_n = \exp\left(-j2\pi \frac{\left\| \boldsymbol{r}_{Rx,n} - \boldsymbol{r}_{Tx,H} \right\|_2}{\lambda}\right)$$

  - $\boldsymbol{r}_{Rx,n}$: 3D location of antenna n
  - $\boldsymbol{r}_{Tx,H}$: Hypothesis in 3D
- 3D correlation

$$I(\boldsymbol{r}_{Tx,H}) = \left| \sum_{n=1}^{8} S_n H_n \right|, S_n = \mathcal{F}(s_n(t))$$



Calibration

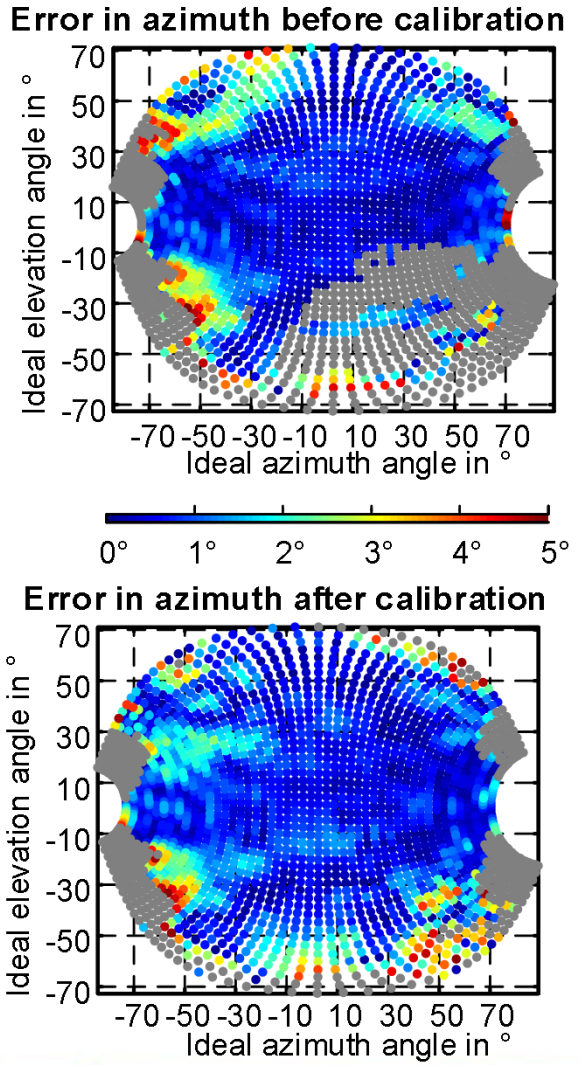
- Problem: Ambiguities in angle estimation due to phase error term $\varphi_{c,n}$

  $s_n(t) = A_n \cos(2\pi f_n t + \varphi_{g,n} + \varphi_{c,n})$

- Model channel mismatch and mutual coupling by 8 × 8 complex matrix C
  - Measurements to a target at multiple known positions in anechoic chamber
  - Formulate and solve least-squares problem to obtain C
  - Apply calibration to measurement S

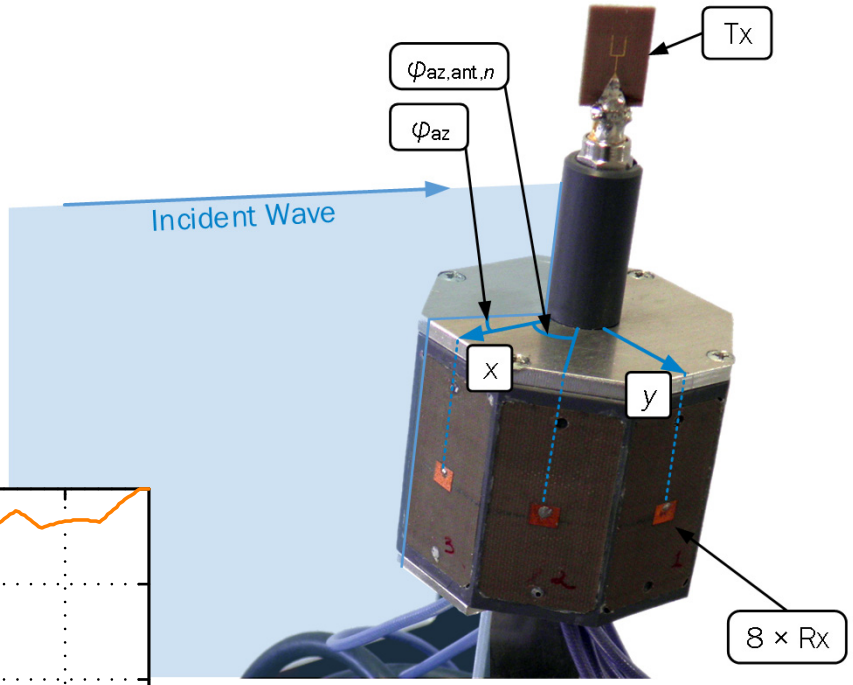
    $S_{cal} = C^{-1} S$

→ Unambiguous measurement range of >±45° in both azimuth and elevation

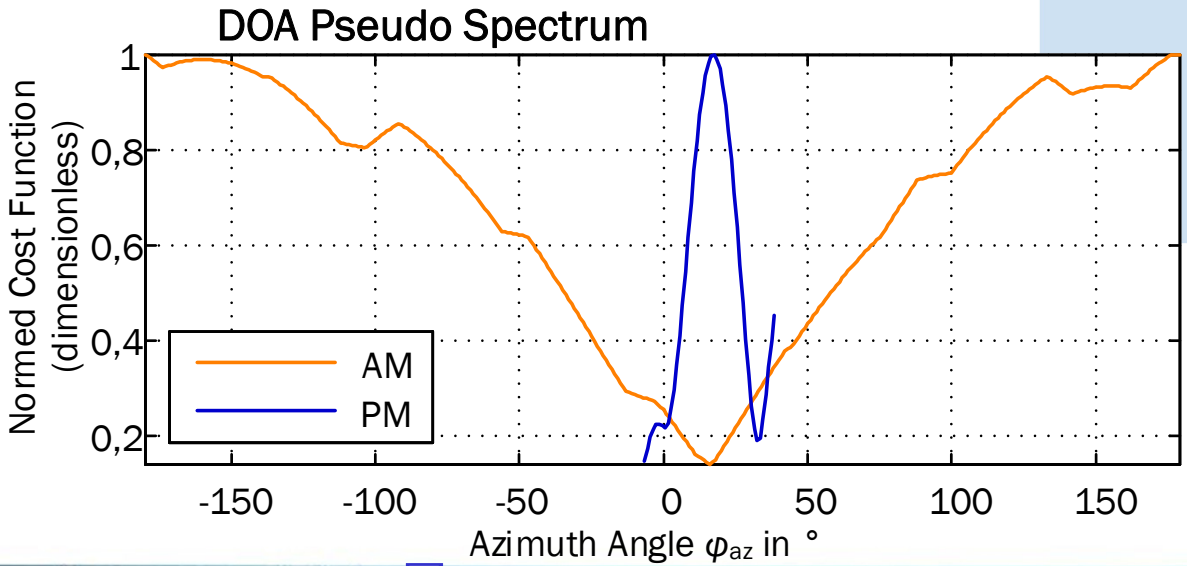


Ring Antenna Array

- Rx: 8 patch antennas at the sides of an octagonal prism
- 360° angular coverage in azimuth
- Azimuth angle estimation using a combination of amplitude monopulse (AM) and phase monopulse (PM)
- Inclinometer for complete 3D orientation

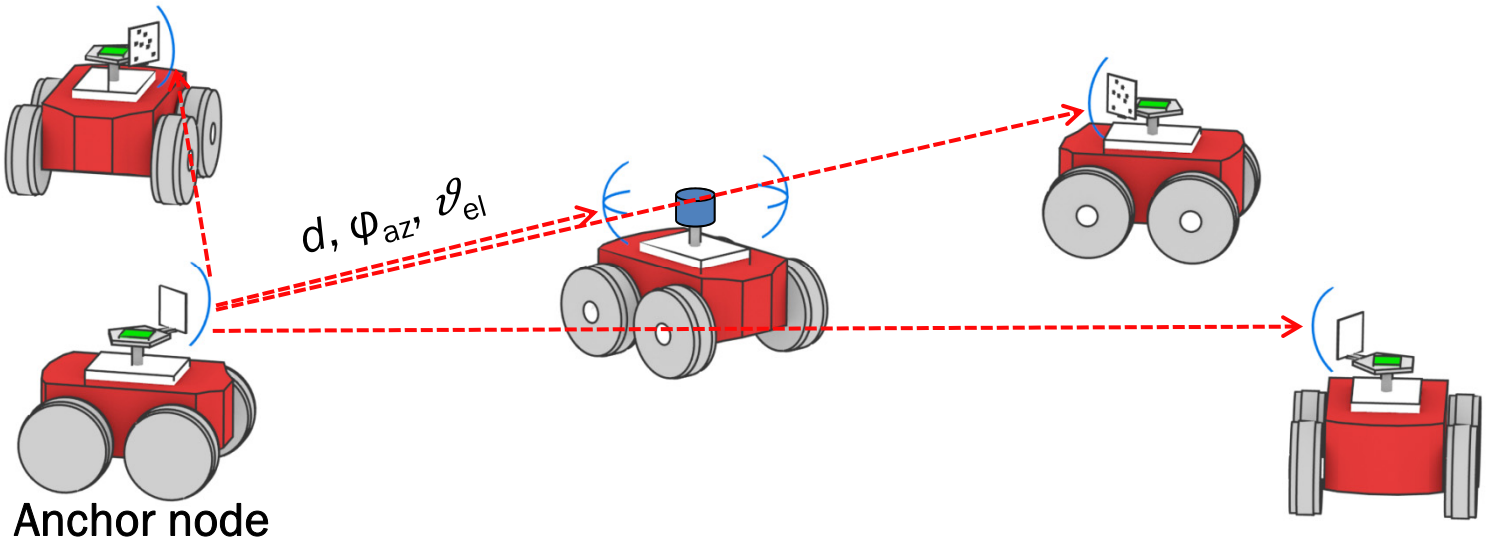


Ring antenna array



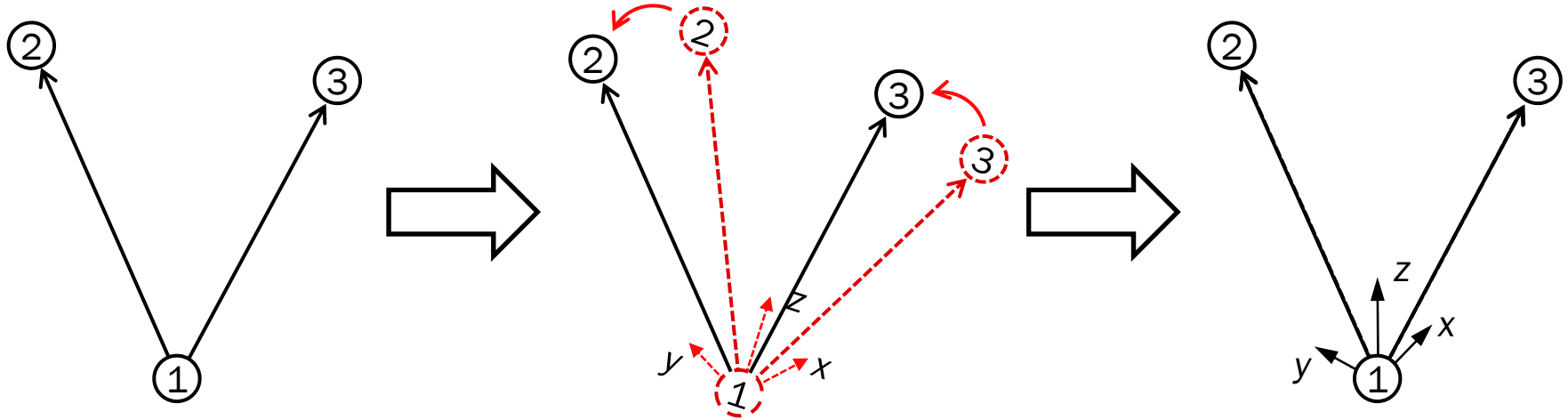
Self-Organization – 3D Position

- One node is chosen as anchor
- It measures d, φ_{az}, ϑ_{el} to other nodes
- 3D position of other nodes can be estimated
- 3D orientation of nodes still unknown



Self-Organization – 3D Orientation

- 3D position of nodes 1, 2, and 3 in anchor frame of reference already estimated → define orientation matrix R_{glo}
- Node 1 determines 3D position of nodes 1 and 2 in its frame of reference → orientation matrix R_{loc}
- 3D orientation matrix R_{node1} of node 1 in anchor frame can be determined by $R_{node1} = R_{loc}^{-1} R_{glo}$



3D Position of Nodes 1,2, and 3

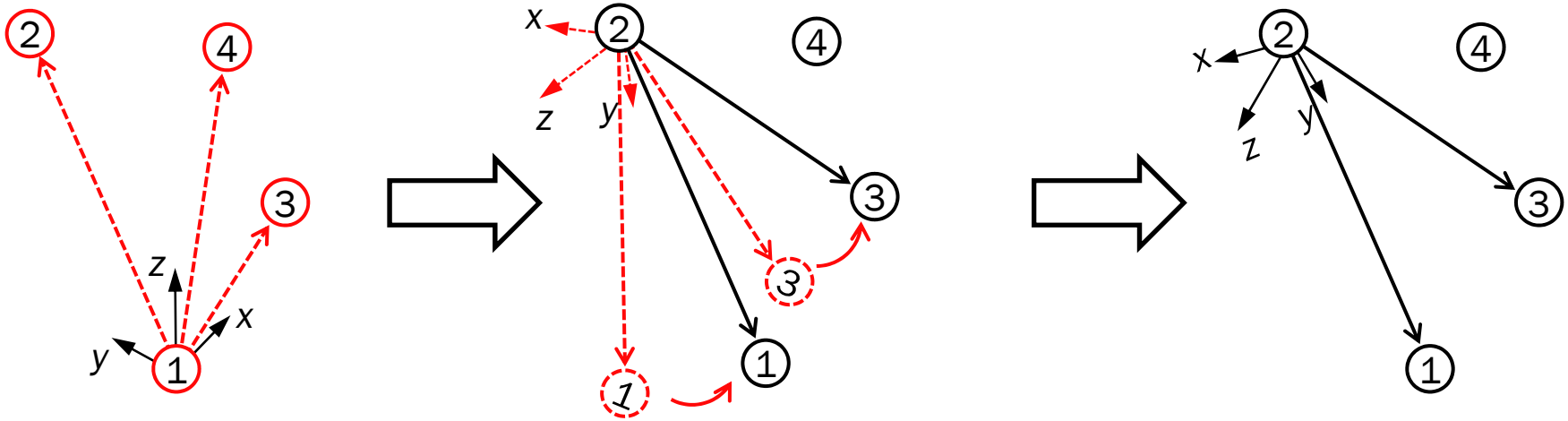
Node 1 measures to nodes 2 and 3

Node 1 can be oriented

Self-Organization Algorithm

Perform breadth-first search in search tree

- Anchor node 1 locates other nodes in 3D in its frame of reference
- Next nodes estimate their 3D orientation and improve positions from own measurements
- Repeat until all network nodes visited
- Weight nodes according to their position in search tree (lower weight further down the tree due to error accumulation)

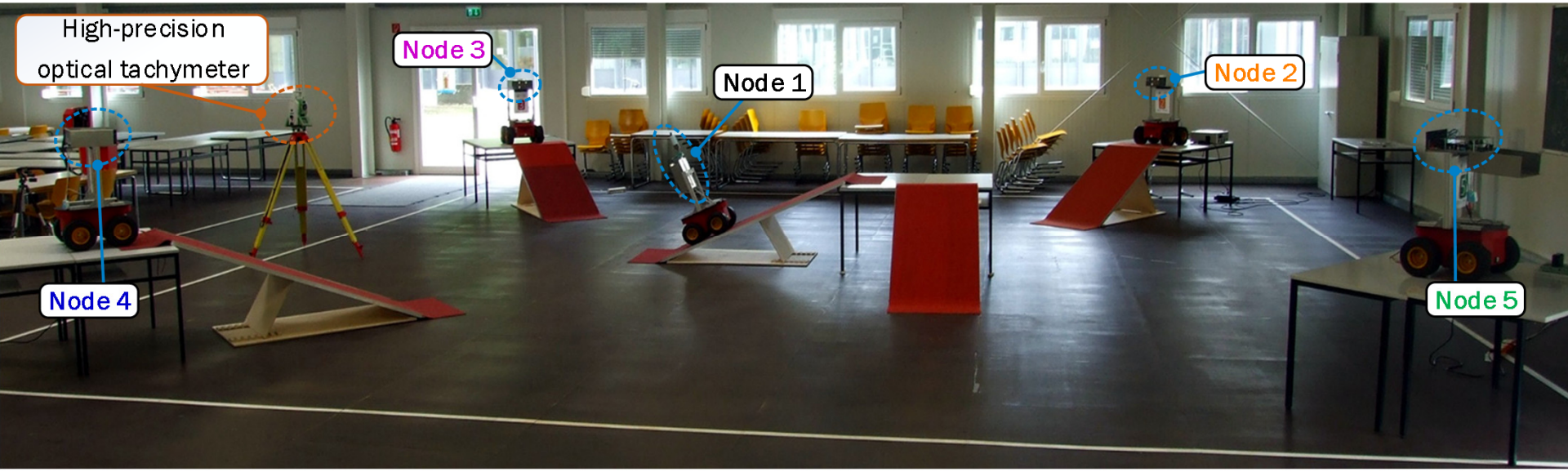


Determine 3D Position

Determine rotation matrix

Rotate node, continue with next node

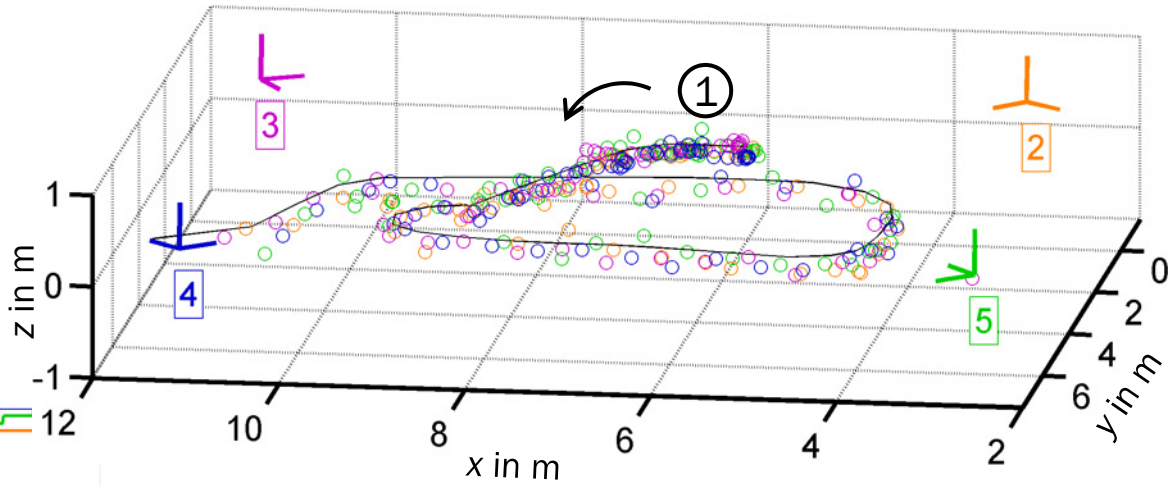
Measurement Scenario

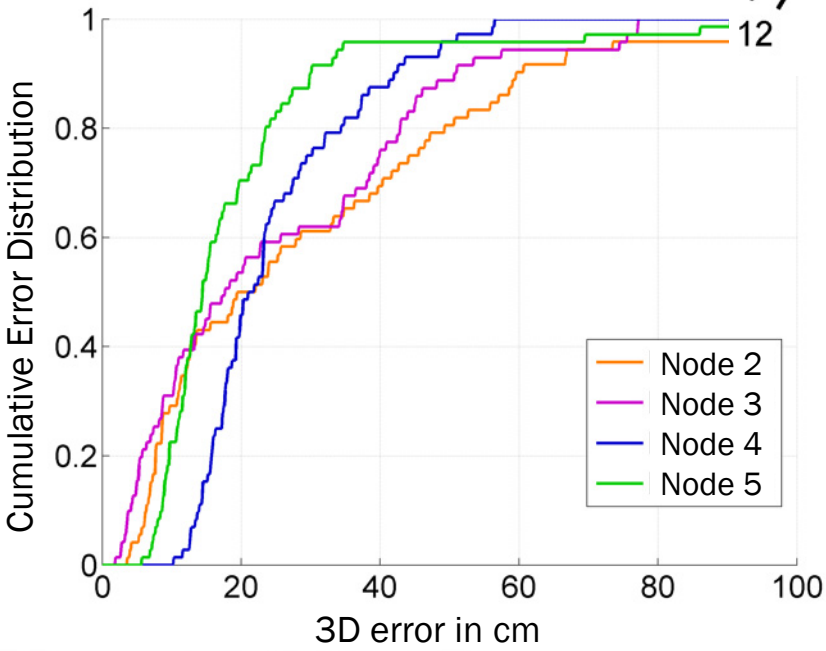


- 5 mobile robots
- 5 tables / ramps to test different heights / slopes
- Evaluation: Keep nodes 2…5 static, move node 1
- High-precision optical tachymeter as reference

Measurement Results – Raw Data

- Node 1 starts on table and drives down and around ramp
- Nodes 2...5 static

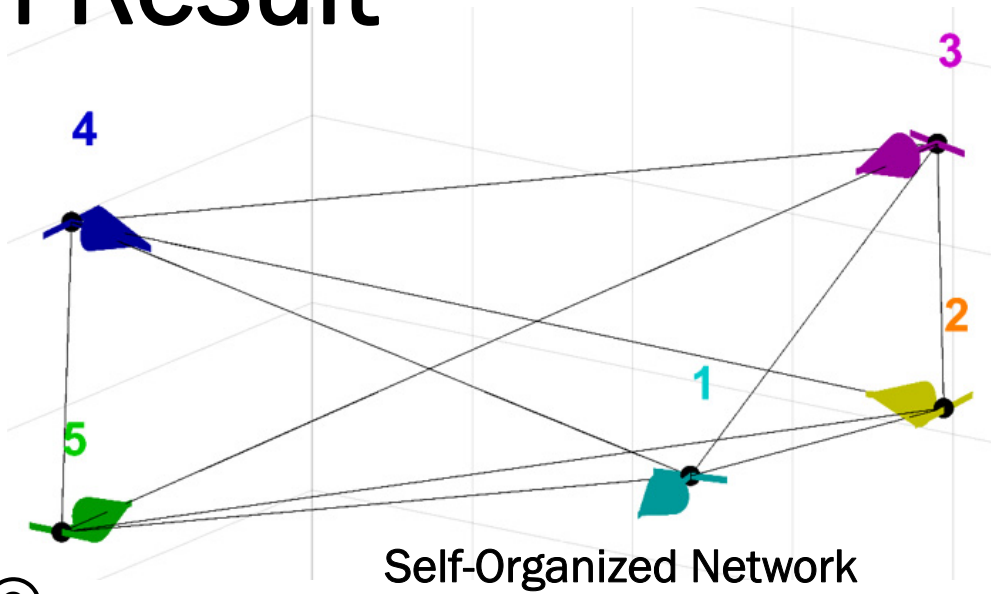




- RMS-Error
  - Range 9-19 cm
  - Azimuth 0.7°-1.9°
  - Elevation 0.8°-1.1°
- 68.3 % of measurements have 3D error <19-39 cm
- 95.4 % of measurements have 3D error <34-74 cm

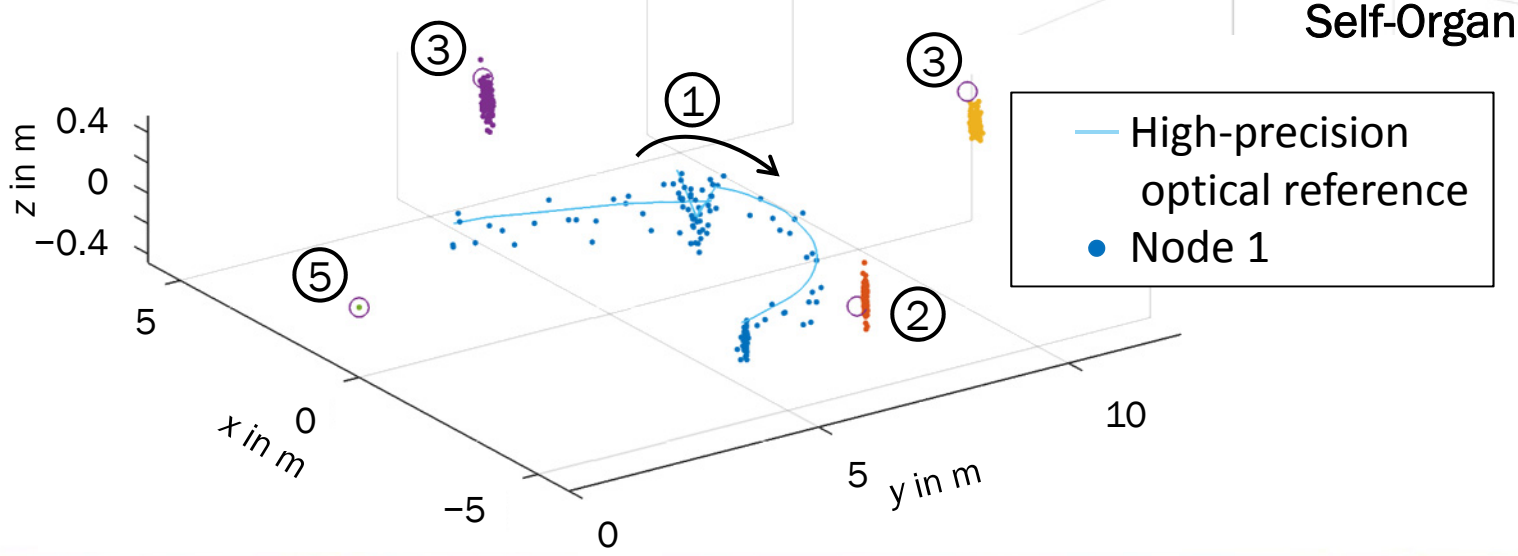
Self-Organization Result

- Node 5 is anchor node
- Apply breadth-first search algorithm
- Determine 3D position and 3D orientation of all network nodes



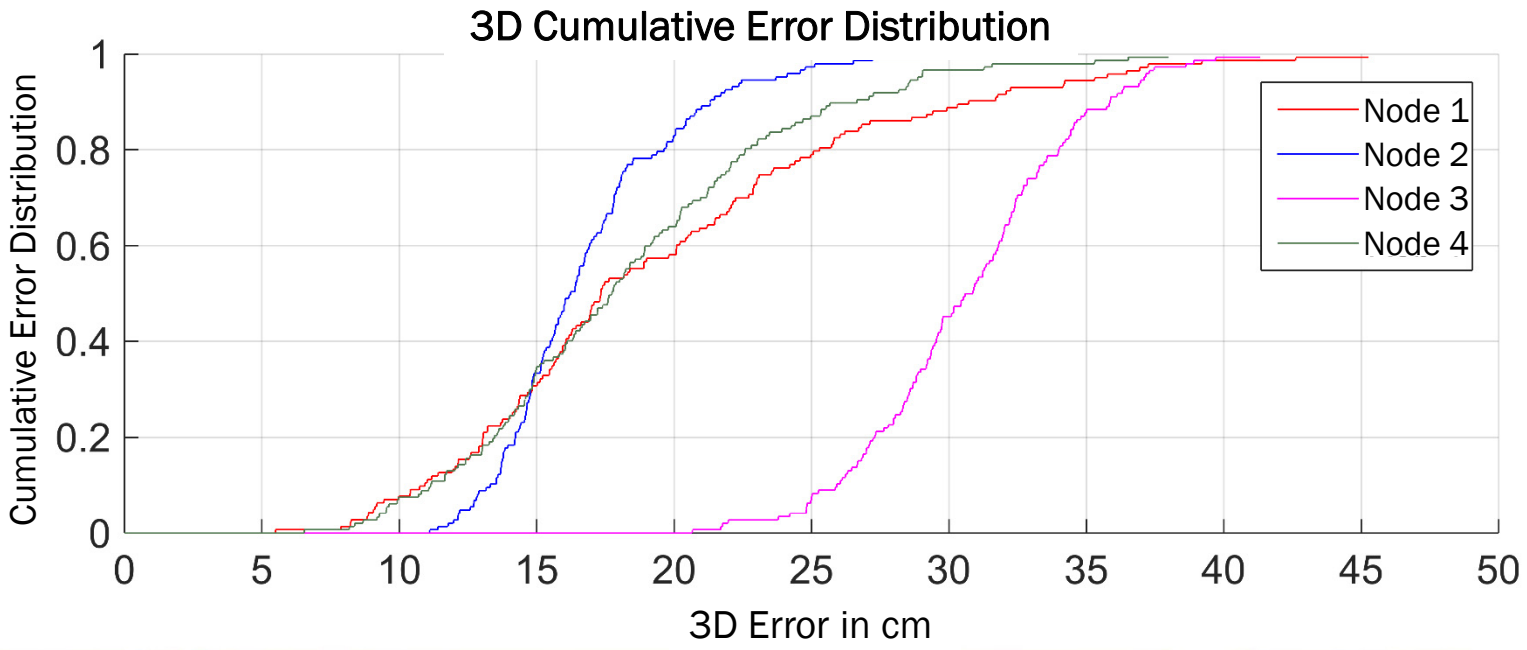
Self-Organized Network

Measurement Result



Self-Organization Result

- 68.3 % of estimated 3D positions have error <18-32 cm
- 95.4 % of estimated 3D positions have error <24-37 cm
- Unfortunately no reference for 3D orientation available

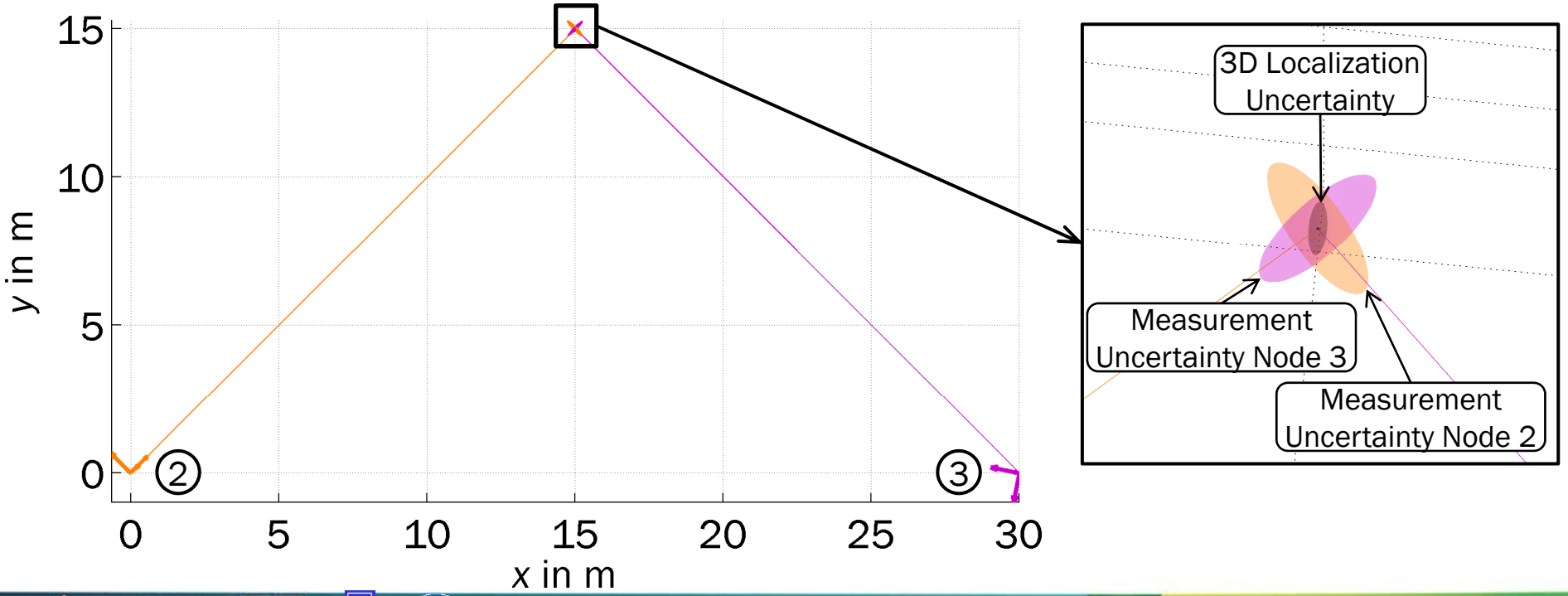


Extended Kalman Filter

- After self-organization, keep 4 nodes static (reference nodes)
- Extended Kalman filter to track mobile node in anchor node frame of reference
- Update step
  - Reference nodes' measurements: d, φ_{az}, θ_{el}
    → Estimate 3D position of mobile robot
  - Inclinometer measurements: β_{pitch}, γ_{roll}
    → Estimate pitch and roll angles of mobile robot
  - Mobile node measurements: d, φ_{az}
    → Estimate yaw angle of mobile robot
- Propagation step
  - Model 3D translational and angular acceleration as normally distributed noise
  - Estimate mobile robot 3D translation and rotational velocity from sensor measurements
  - No IMU used to keep solution generic also for legged robots

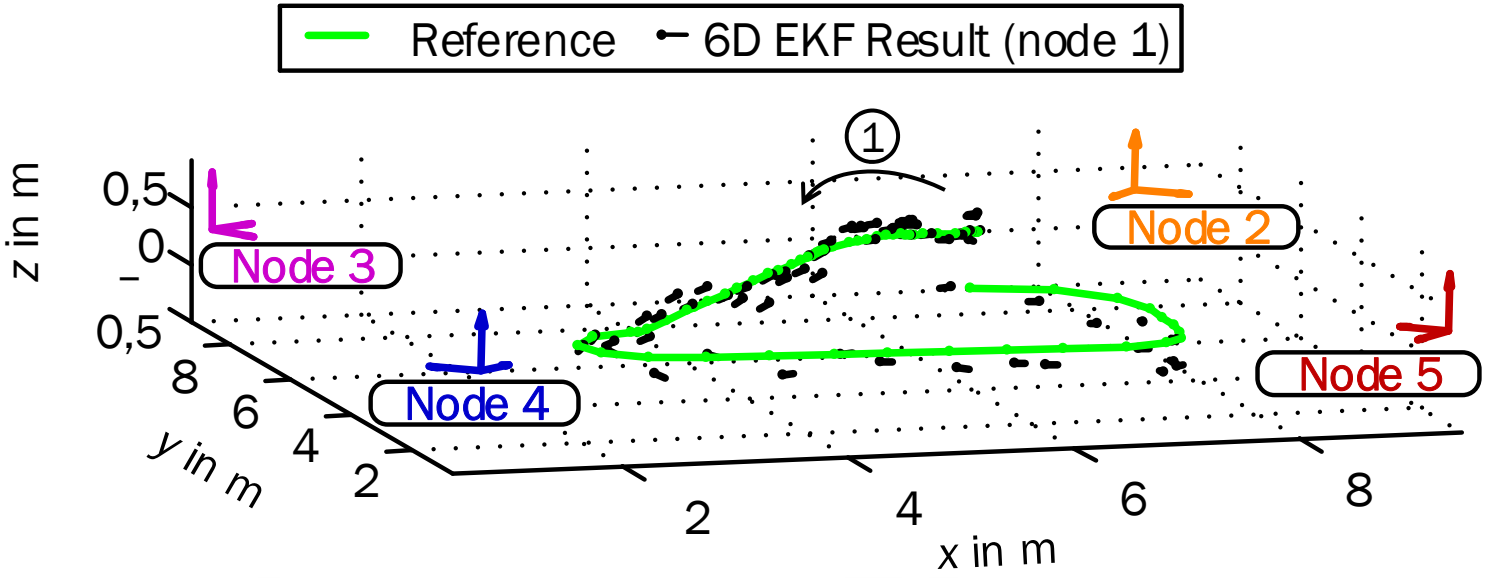
Localization Uncertainty

- Node 2 and 3 measuring to a target
- Longitudinal uncertainty independent of distance; Lateral uncertainty dependent on distance
- Resulting 3D localization uncertainty dependent on network constellation



EKF Result

- Phase 1: All nodes static, self-organization
- Phase 2: Nodes 2...5 static, node 1 mobile
- 68.3 % of errors <16.8 cm, 95.4 % <33.6 cm



Summary

- FMCW 24 GHz localization system using RTOF and DOA using sparse antenna arrays
- 6D network self-organization – Extremely challenging task due to very high degree of freedom
- Self-organization of static nodes using breadth-first search algorithm
- Extended Kalman filter used for subsequent localization of mobile node
- Verified using a mobile robot swarm of 5 nodes

Thank you for your attention!