On the Accuracy of Localizing Terrestrial Objects Using Drones

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The Localization Problem

- Localization is one the most important task in a wireless sensor network
- The random deployment results in sensors initially unaware of their location
- Sensors are not expected to be GPS-enabled
- Localization algorithm: two different classes of techniques
  - *range-based*: estimations are done exploiting measurements (angles, distances) (+ precision, + hardware)
  - *range-free*: estimation is done without using any type of ranging measurements (- precision, - hardware)
- Recently published research:
  - OMNI, a range-based algorithm that uses omnidirectional antennas [3]
  - RF, a range-free algorithm that exploits the chords of a circle [2]

[3] Cristina M Pinotti, Francesco Betti Sorbelli, Pericle Perazzo, and Gianluca Dini. Localization with guaranteed bound on the position error using a drone.
In *Proceedings of the 14th ACM International Symposium on Mobility Management and Wireless Access*, pages 147–154. ACM, 2016

[2] Chia-Ho Ou and Wei-Lun He. Path planning algorithm for mobile anchor-based localization in wireless sensor networks.
IEEE Sensors Journal, 13(2):466–475, 2013

Localization Problem Applications

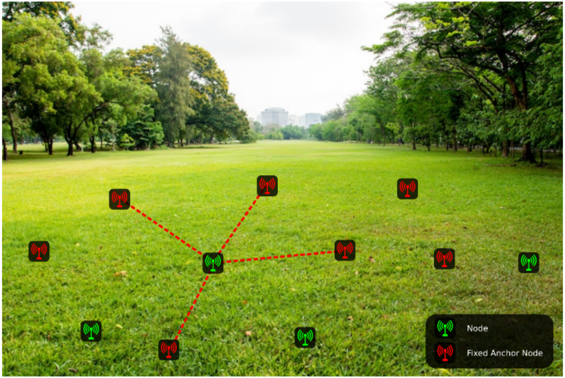
Localize people after an earthquake.

Structural Health Monitoring Problem Applications

Localize people after an avalanche.

Fixed Anchor Nodes

- Classical approach considers to use many *Fixed Anchor* nodes
- Anchor nodes are expensive and they have a high deployment cost



Fixed Anchor Nodes (blue dots).

- We consider the Localization Algorithms based on a single *Mobile Anchor* node

Our main idea

- Our idea: a **single drone** can replace many fixed anchor nodes (multiple sensors single drone)
- Challenges:
  - all the measurements are on line-of-sight and not on the ground
  - small 3D imprecision will translate into big 2D error
  - such an error increases with the drone's altitude

Drones

- Are receiving increasing attention from the research and industry community
- Can be used for military and civilian applications but now also:
  - surveillance and reconnaissance, forest fire monitoring, goods transportations, ...

- A drone can easily fly over devastated areas, enemy areas or simply lakes or rivers (impossible for a rover)
- Communication Ground-UAV Technology: short and wide range
  - wide: WiMAX, SATCOMs or cellular
  - short: Zigbee or Bluetooth
- **Special attention**: *IR-UWB* technology (wide)

UWB

- Radio technology can use a very low energy level for short-range, high-bandwidth communications over a large portion of the radio spectrum
- The technology operates on two sets of frequencies: $4.5\,\mathrm{GHz}$ and $6\,\mathrm{GHz}$
- Range:
  - up to $300\,\mathrm{m}$ line of sight
  - up to $40\,\mathrm{m}$ non-line of sight
- Uses very short pulses on the order of ps or ns
- Very low duty cycle for transmission and reception of the information

	IEEE Standard WLAN 802.11a	IEEE Standard WLAN 802.11b	IEEE Standard WLAN 802.11g	Bluetooth 802.15.1	**UWB 802.15.4a**	ZigBee 802.15.4
Operational Frequency (GHz)	5	2.4	2.4	2.4	4.5–6	2.4
Maximum Data Rate (Mbps)	54	11	54	1	> 100	0.25
Maximum Range (m)	100	100	100	10	300	50
Precision (m)		7–10		15	0.10	

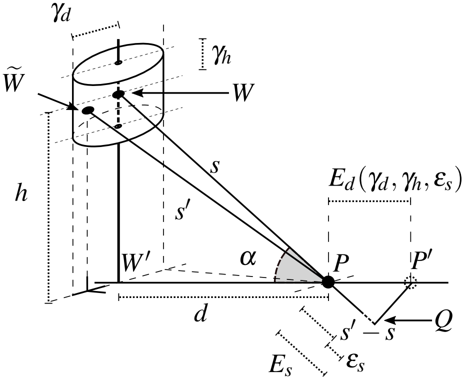
UWB capabilities compared to other IEEE standards.

Measurement Precision

- During the localization procedure, measurement errors are unavoidable
- Drone's position is affected:
  - by the weather condition (wind, pressure, humidity)
  - by the strength of the propellers
  - by the adopted technology and
  - by the GPS error
- Can seriously impact the localization accuracy
- The instrumental inaccuracies depend on the technology:
  - Wi-Fi: error may range from 7–$10\,\mathrm{m}$
  - Bluetooth: up to $15\,\mathrm{m}$
  - Ultra-wideband: $7\,\mathrm{cm}$ precision with 99.99% reliability

The Ground Error

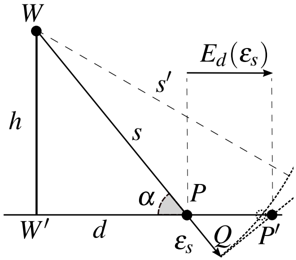
- We study the ground error E_d
- We conduct our analysis by breaking up the error into three components:
  - the *instrumental* precision ε_s
  - the *rolling* precision γ_d
  - the *altitude* precision γ_h



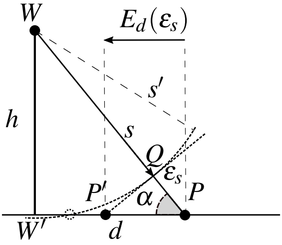
The ground error.

Instrumental component

- We investigate the impact of the instrumental error



Overestimation



Underestimation

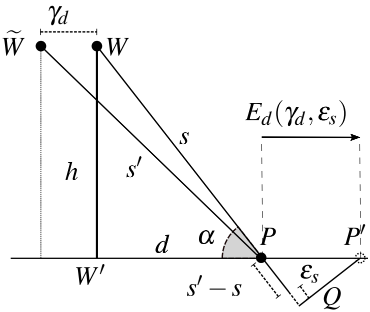
- The precision $E_d(\varepsilon_s)$ when the object is at ground distance d from the drone is given by:

$$E_d(\varepsilon_s) = \varepsilon_s \cdot \sqrt{1 + \frac{h^2}{d^2}} \tag{1}$$

- When $h \neq 0$, the error increases when d decreases

Rolling component

- When the drone is subject to a rolling (horizontal offset)



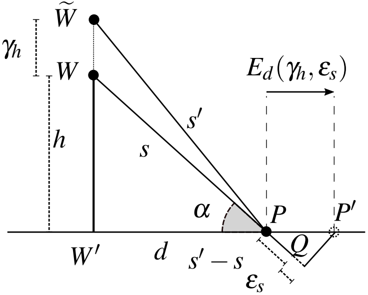
Overestimation.

- The rolling precision:

$$E_d(\gamma_d, \varepsilon_s) \approx |\gamma_d| + E_d(\varepsilon_s) \quad (2)$$

Altitude component

- When the drone is subject to an *uplift* (vertical offset)



Overestimation.

- The altitude precision:

$$E_d(\gamma_h, \varepsilon_s) \approx |\gamma_h| \frac{h}{d} + E_d(\varepsilon_s) \tag{3}$$

The Ground Precision

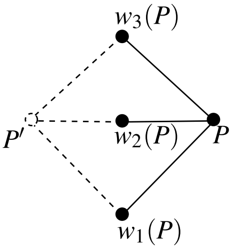
Theorem

Let ε_s, γ_d and γ_h be respectively the instrumental precision, rolling precision, and altitude precision. Bringing back the distance of the ground, the largest error E_d becomes:

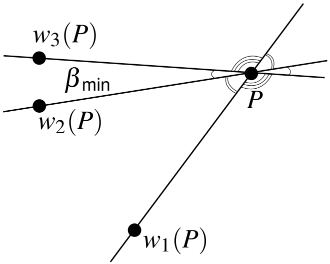
$$E_d(\gamma_d, \gamma_h, \varepsilon_s) \approx |\gamma_d| + \frac{h}{d}|\gamma_h| + |\varepsilon_s|\sqrt{1 + \frac{h^2}{d^2}} \tag{4}$$

Trilateration: Collinearity problems

- To localize we use trilateration technique:
  - for each sensor we need three measurements
- Possible localization errors:



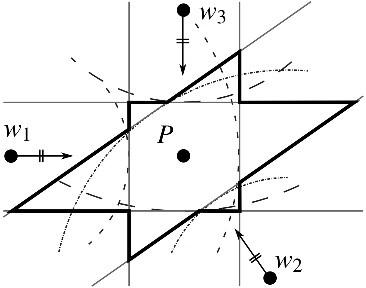
Collinear among them.



Collinear with the sensor.

Trilateration Error

- Due to the ground errors the 3 circumferences do not intersect at a single point
- They delimit a small *star* area



- The furthest vertex (worst case) is at distance $\frac{E_d}{\sin\left(\frac{\beta_{\text{min}}}{2}\right)}$ from P
- A good localization aims at a large value of β_{min}

Localization Error

Theorem

Given the precisions ε_s, γ_d and γ_h, the maximum localization error is obtained as:

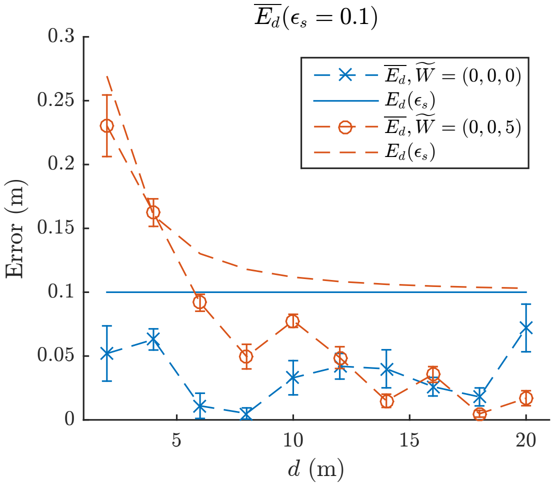
$$E_L(\gamma_d, \gamma_h, \varepsilon_s) = \frac{E_d(\gamma_d, \gamma_h, \varepsilon_s)}{\sin\left(\frac{\beta_{min}}{2}\right)} \tag{5}$$

Experimental Evaluation: Settings

- We propose two sets of **real experiments**:
  - First: we test the goodness of the approximation of the instrumental, rolling and altitude errors
  - Second: we use the drone that hovers in a field close to Assisi, Italy

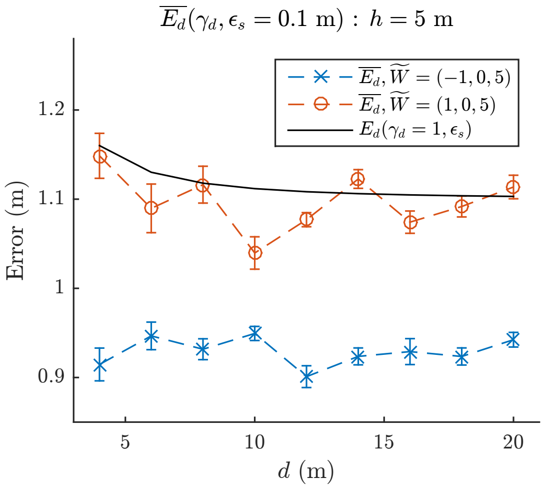
Our settings during experiments with the drone.

Experimental Evaluation: Instrumental Ground Error



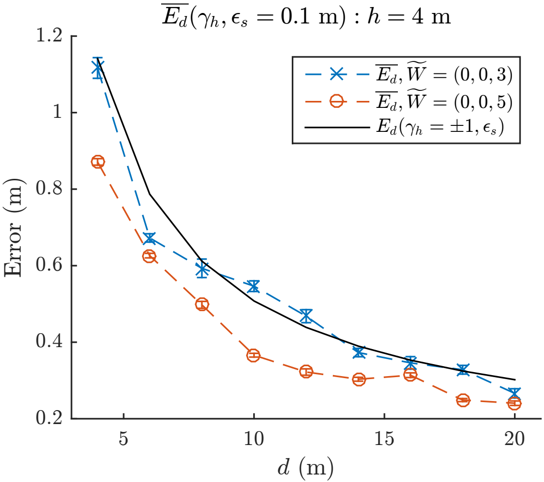
Ground Error: The experimental Instrumental error.

Experimental Evaluation: Rolling Ground Error



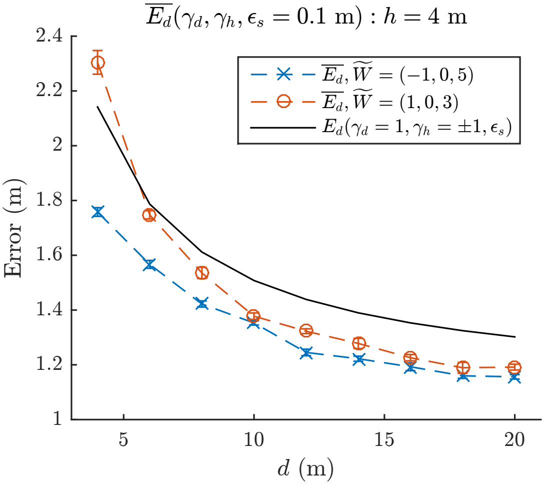
Ground Error: The experimental Rolling error (when $W = (0, 0, 5)$).

Experimental Evaluation: Altitude Ground Error



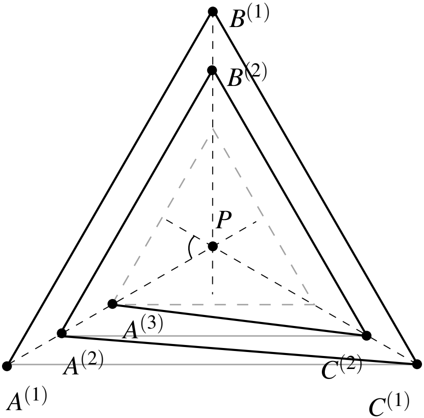
Ground Error: The experimental Altitude error (when $W = (0, 0, 4)$).

Experimental Evaluation: Combined Ground Error



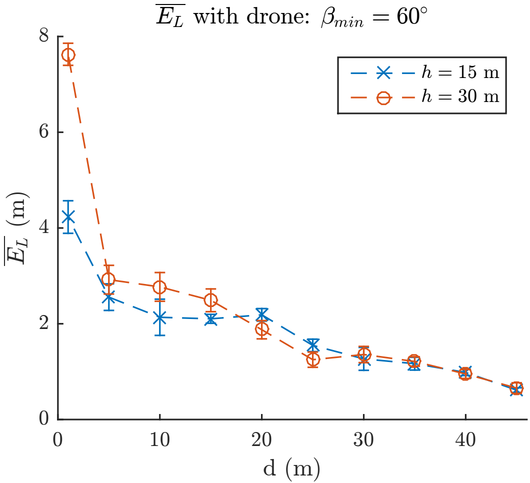
Ground Error: The experimental combined error (when $W = (0, 0, 4)$).

Experimental Evaluation: Trilateration Error (1)



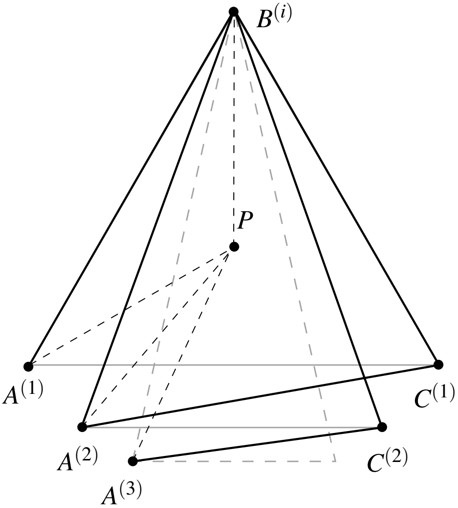
Same minimum angle.

Experimental Evaluation: Trilateration Error (2)



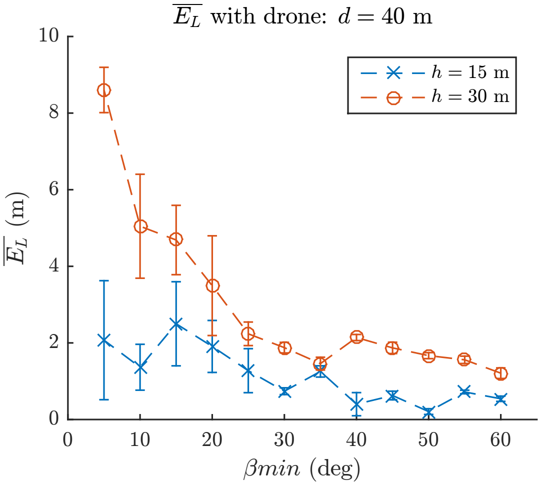
Trilateration Error: d varies.

Experimental Evaluation: Trilateration Error (3)



Same distance.

Experimental Evaluation: Trilateration Error (4)



Trilateration Error: d varies.

Lessons

- We takeaway two lessons from this analysis
- To limit the ground error:
  - all the waypoints used to measure the same node must be at a sufficiently large ground distance from the node itself (d_{min})
  - they must not be collinear among themselves nor with the node (β_{min})

Thank you for your attention!