Land & Localize: An Infrastructure-free and Scalable Nano-Drones Swarm with UWB-based Localization

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### Why Nano-Drone Swarm?

#### What are Nano-drones?

- Small form factor (~10cm)
- Limited payload (~15g)
- Limited computing power budget (<100mW)

<table>
<thead>
<tr>
<th>UAV</th>
<th>Standard-sized</th>
<th>Nano-sized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size [(\varnothing, \text{weight})]</td>
<td>~50cm / ~ few Kg</td>
<td>~10cm / ~50g</td>
</tr>
<tr>
<td>Tot. Power</td>
<td>~ 100 W</td>
<td>~ 5W</td>
</tr>
<tr>
<td>Processing device</td>
<td>High-end CPU</td>
<td>Low-power MCU</td>
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Why Nano-Drone Swarm?

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Why Nano-Drone Swarm?

- Small form factor enabling indoor applications
- Ensure safe Human-Robot Interaction (HRI)
- Reduced costs
What is Localization?
• Localization is the ability of the Swarm agents to identify their positions
Localizing Nano-Drone Swarm

What is Localization?
• Localization is the ability of the Swarm agents to identify their positions

Why Localizing a Nano-Drone Swarm?
• A Wide range of indoor applications can benefit from the Nano-Drone swarm
• Localization is a key for any Nano-drone Swarm applications

Indoor Inspection
Flight Formation
Research

[*] Sniffy Bug: A Fully Autonomous Swarm of Gas-Seeking Nano Quadcopters in Cluttered Environments.” IROS 2021
# Common indoor positioning approaches

<table>
<thead>
<tr>
<th>Motion Tracking Systems</th>
<th>IMUs</th>
<th>Visual Odometry</th>
<th>Ultra Wideband [UWB]</th>
</tr>
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<tbody>
<tr>
<td>✔️ High resolution</td>
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<td>✔️ cm-level resolution</td>
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- **IMUs**:
  - High resolution
  - Low resolution
  - Light computation
  - Low power
  - Low cost
  - Costly infrastructure

- **Visual Odometry**:
  - High resolution
  - Heavy computation
  - High power
  - Medium cost

- **Ultra Wideband (UWB)**:
  - cm-level resolution
  - Light computation
  - Low power
  - Low cost
Common indoor positioning approaches

Motion Tracking Systems

- High resolution
- Light computation
- Low power
- Costly infrastructure

IMUs

- Low resolution
- Light computation
- Low power
- Low cost

Visual Odometry

- High resolution
- Heavy computation
- High power
- Medium cost

Ultra Wideband [UWB]

- cm-level resolution
- Light computation
- Low power
- Low cost
UWB-Localization & challenges

**UWB Ranging**

ToF = (t_total - t_comp) / 2

Distance = ToF × speed_of_light
UWB-Localization & challenges

**UWB Ranging**

\[
ToF = \frac{t_{\text{total}} - t_{\text{comp}}}{2}
\]

**Distance** = ToF × speed of light

**UWB Localization in Action**

\[
D_{\text{distance}} = T_{\text{ToF}} \times \text{speed of light}
\]

**Requirements**

1. **Installation** of Anchor modules infrastructure
2. Anchors’ positions must be **known**
UWB-Localization & challenges

UWB Ranging

**ToF** = \( \frac{t_{\text{total}} - t_{\text{comp}}}{2} \)

**Distance** = **ToF** \( \times \) speed_of_light

\[
D_{\text{station}} = T_{\text{ToF}} \times \frac{s_{\text{speed_of_light}}}{2}
\]

**Limit usefulness due to need for in-advanced installation of infrastructure**

Static UWB infrastructure imposes a major rigidity!

Requirements

1. Installation of Anchor modules infrastructure
2. Anchors’ positions must be known

UWB Localization in Action

Ranges \( A_i(X,Y) \)

Extended Kalman Filter

www.bitcraze.io/documentation/system/positioning/loco-positioning-system
Contribution

Infrastructure-less UWB localization systems

1. Exploiting **Drones as Dynamic Anchors** to provide anchor deployment at run-time
2. A **Self-Localization system** to compute anchor drones’ initial position
3. An open-source **UWB Software Library (USL)** enabling fast prototyping of UWB localization

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**More Flexible Systems**
UWB Software library (USL)

- An open-source Library
- High-level API
- Enable Fast prototyping
- Minimal interaction with HW-level complexities

GitHub: https://github.com/vladniculescu/uwb-software-library
Assumptions:
- Anchor installation
- Anchors’ positions must be known
Dynamic Anchor System

Assumptions:
- Anchor installation
- Anchors’ positions must be known
**Dynamic Anchor System**

1. Anchor-Drones **fly & land** to a target location

   - Navigation based only on the onboard state estimation (Optical-Flow, IMU)

2. After landing Anchor-Drones **start ranging** with MDs

   - There is an **error** between target landing point and the actual one

   - Target landing point
   - Actual landing point
Dynamic Anchor System

After landing Anchor-Drones start **ranging** with MDs

Mission-Drones are receiving **ranging information** containing Estimated Anchor Drones’ positions

There is an **error** between target landing point and the actual one
Dynamic Anchor System

- **Ideal Landing**
- **Dynamic Anchors**
- **Self-localize**

- ✔️ Installation of anchor infrastructure
- ✗ Anchors’ positions must be *known*
Dynamic Anchor System

- Installation of anchor infrastructure
- Anchors’ positions must be known

- Ideal Landing
- Dynamic Anchors
- Self-localize
How does Self-localization System work?

Convention:
- ADs placed in unknown positions
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- AD0 act as the origin of the coordinate system
- AD0 - AD1 form x-coordinate
- AD2 considered the positive y-coordinate
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2. The ADs take off and hover at 0.5m
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3. ADi does ranging with AD(i+1)..N
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4. ADs send all measurements to AD0
5. AD0 builds the distance matrix D and runs Multi-Dimensional Scaling (MDS)

\[
D := \begin{pmatrix}
    d_{1,1} & d_{1,2} & \cdots & d_{1,M} \\
    d_{2,1} & d_{2,2} & \cdots & d_{2,M} \\
    \vdots & \vdots & \ddots & \vdots \\
    d_{M,1} & d_{M,2} & \cdots & d_{M,M}
\end{pmatrix}
\]

Runs on AD0

MDS

Anchor Drone Positions AD0, AD1, ...

Has all range measurements
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5. AD0 builds the distance matrix D and runs
6. AD0 sends the coordinates to AD1..N

Sends back the coordinates
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7. ADs know their relative position
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5. AD0 builds the distance matrix $D$ and runs
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7. ADs know their relative position
8. ADs fly toward the target landing point
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5. AD0 builds the distance matrix D and runs
6. AD0 sends the coordinates to AD1..N
7. ADs know their relative position
8. ADs fly toward the target landing point
9. Ranging starts and the MDs start flying
In-field Results

Experiment Setup
• 4 Anchor Drones
• 4-8 Mission Drones
• 3 times flying around a 1.5[m] radius circle
• ~1 m/s velocity

Evaluation Metrics
• Localization RMSE
• Control RMSE

Nano-Drone Platform

- Crazyflie 2.1
- UWB deck
- Flow deck v2
In-field Results

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Estimate → Error

Ideal → Estimation → Ground-truth
In-field Results

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Image diagram illustrating error comparison between Ideal, Estimation, and Ground-truth trajectories.
In-field Results

Experiments with 4/8 MDs and 4 ADs:
- Flexibility at the cost of a higher localization error

[1] Fixed 6x Anchor module setup using Bitcraze’s UWB localization firmware as the baseline
In-field Results - self-localization

Experiments with 4/8 MDs and 4 ADs:
- Flexibility at the cost of a higher localization error
- Self-Localization runs on-board in 5 sec

[1] Fixed 6x Anchor module setup using Bitcraze’s UWB localization firmware as the baseline
Results - Impact of AD self-localization

Experiments with 4/8 MDs and 4 ADs:
- Flexibility at the cost of a higher localization error
- Self-Localization runs on-board in 5 sec

Localization Error is contributed by
- UWB Error (also on static anchors)
- Anchors’ Landing Error

[1] Fixed 6x Anchor module setup using Bitcraze’s UWB localization firmware as the baseline
Results

Fixed 6x Anchor module setup using Bitcraze’s UWB localization firmware as the baseline

[1]
Results

Baseline setup using Bitcraze’s UWB localization firmware as the baseline.

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[1] Fixed 6x Anchor module setup using Bitcraze’s UWB localization firmware as the baseline.
Results

- Ideal
- Estimation
- Ground-truth

After removing the shift:

- Self-localize Dynamic Anchors
- Dynamic Anchors
- Ideal Landing
- Baseline

Estimated landing point vs Actual landing point

Anchor Position Error

Norm of shift vector [cm]

C-RMSE [cm]

[1] Fixed 6x Anchor module setup using Bitcraze's UWB localization firmware as the baseline
Results

Higher localization error in dynamic anchor systems is mainly impacted by a shift vector. However, the control error always remains low to enable drones to precisely follow the commanded trajectory.

[1] Fixed 6x Anchor module setup using Bitcraze's UWB localization firmware as the baseline.
Results

Flight Formation*

Longitude inter-drone distance always bounded below 13.7% i.e., ±15.6 cm

[*] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9812050
**Setup**

- 4 ADs and 8 MDs
- Dynamic Anchor Deployment
- MDs fly in a 1.5[m] circular trajectory

**Dynamic Anchors**

- Anchor-drone
- Mission-drone
Conclusion

Leveraging Nano-drone as Dynamic Anchor to eliminate the need for a static UWB infrastructure

Most challenging configuration 8x MD

<table>
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<tr>
<th></th>
<th>Ideal Land</th>
<th>Dynamic Anchor</th>
<th>Self Localize</th>
</tr>
</thead>
<tbody>
<tr>
<td>l-RMSE</td>
<td>19.4</td>
<td>24.2</td>
<td>36.4</td>
</tr>
<tr>
<td>c-RMSE</td>
<td>13.1</td>
<td>11.0</td>
<td>12.1</td>
</tr>
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Longitude inter-drone distance always <15.6 cm
Thank you for your attention!

Mahyar Pourjabar

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