International Doctorate School in Information and Communication Technologies

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Localization and Tracking for Indoor Environments

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Outline of This Presentation

- Technologies and Techniques for Positioning

- **Modelling** based on Experimental Measurements:
  - UWB NLOS bias modelling
  - RSS measurements modelling

- **Localization** Algorithms:
  - Low-complexity Localization Algorithms

- **Navigation** Algorithms:
  - An INS for Low-Cost IMUs
  - Turbo Filtering

- Conclusions
Technologies and Techniques for Positioning
Technologies and Techniques for Positioning

Terrestrial real-time localization systems

- Active
  - Wireless
    - Fine-grained localization
  - Proximity-based localization
    - Radio (UWB, ad-hoc networks, WLAN, Bluetooth, Zigbee)
    - Acoustic (ultrasound)
    - Radio (RFID)
    - Acoustic (ultrasound beacons)
    - Optical (infrared beacons)
  - Wired

- Passive
  - Radio (RADAR)
  - Acoustic (SONAR)
  - Optical (LIDAR, video cameras)

- INS systems
Modelling based on Experimental Measurements:
UWB NLOS bias modelling
UWB-based Localization and NLOS Bias

**Scenario:** Indoor radiolocalization systems based on Time Of Arrival (TOA) measurements between radios with fixed, known positions (anchors) and a mobile station (agent):

**Problem:**
- Non Line Of Sight (NLOS) propagation results in biased TOA estimation (obstructions slow down electromagnetic waves, so that the estimated TOA is larger than the true distance / speed of light).

**Approach:**
- A measurement campaign has been carried out to assess the correlation between NLOS bias and some features extracted from received signals.
TOA model adopted: \( \tau = \frac{d}{c_0} + b + n \)  
\[ \downarrow \]  
Real TX-RX distance  
\[ \downarrow \]  
NLOS bias (r.v.)  
Gaussian noise r.v.

**APPROACH:**
- For each measured link various features have been extracted: maximum signal amplitude, mean excess delay, rms delay spread, energy, rise time, kurtosis (the employed radios were able to store the received waveform).

**RESULT:**
- NLOS bias for TOA UWB waveforms is strongly correlated with some of the considered features; this can be exploited to *infer* and *mitigate* the bias!
Localization Algorithms

**APPROACH:**
- We have proposed *estimators* of the agent position which:
  - exploit the joint *multidimensional* pdf resulting from experimental acquisitions (histograms or multidimensional fitting polynomials have been used to represent this function);
  - exploit the TOA vectors from all available links.

**RESULTS:**
- We have found that this approach, on the average, provides performance improvements in radio localization accuracy; however, it is difficult to *consistently* achieve such improvements.
- NLOS bias *detection* is more robust than NLOS bias *mitigation* in environments characterized by strong multipath propagation.
Modelling based on Experimental Measurements:

RSS measurements modelling
Localization with RSS Measurements

**SCENARIO:** indoor radiolocalization systems based on Received Signal Strength (RSS) measurements between radios with fixed, known positions (anchors) and a mobile station (agent):

**PROBLEM:**
- **Non Line Of Sight (NLOS)** propagation results in *biased* RSS estimation. In fact, obstructions introduce attenuation which is not accounted for by the traditionally-employed free-space propagation law; this strongly degrades localization accuracy.

**APPROACH:**
- A measurement campaign has been carried out to 1) assess the attenuation in RSS due to indoor obstructions (mainly walls) and 2) develop a *map-aware* statistical model for RSS measurements.
RSS Measurement Campaign

- 169 MHz radios transmitting at +15dBm have been employed, so that the effect of signals propagating through multiple walls could be studied (up to 10 walls)

- The RSS has been acquired in many different positions inside the 2nd floor of the DII building:

![Diagram of RSS Measurement Campaign](image-url)
Based on experimental evidence, a novel map-aware statistical model for the acquired measurements has been developed:

\[ f(z|\tilde{p}) = \prod_{i\in Z} \mathcal{N}(z_i; d_i(\tilde{p}), \mu_{b,0}^{\text{RSS}}, \mu_{b,m}^{\text{RSS}} N_0(\tilde{p}, \tilde{p}_i^{\text{a}})) u_{N_0}, \]

such a statistical model represents the likelihood of obtaining a certain set of RSS measurements for a given (trial) agent position; searching for the trial position which corresponds to the maximum value of the likelihood produces an **optimal estimate** (in ML sense) of the agent position.
RSS Map-aware vs Map-unaware Model

- In the same scenario a map-aware model and a map-unaware model lead to substantially different likelihoods:

![Map-aware log-likelihood function](image1)

![Map-unaware log-likelihood function](image2)

- Anchors
- True agent position
- Peak of the likelihood
RESULTS:
A comparison between map-aware and map-unaware localization algorithms processing the RSS measurements stored in our experimental database shows that the former algorithms are, on the average, 64% more accurate (in terms of RMSE) than the latter ones:
Localization Algorithms:
Low-complexity Localization Algorithms
Algorithm Complexity as FLOPs

**PROBLEM:**
- Map-aware modelling improves accuracy in localization systems but requires more complex estimators.

**APPROACH:**
- Complexity of map-aware localization algorithms needs to be quantified. Complexity depends on a) type of estimator employed, b) models employed, c) implementation of the estimator and d) the required accuracy in computations.

- Computational complexity is difficult to analyse and quantify whenever non-linear algebra is involved (e.g., this occurs when the RSS statistical modelling described above is used).

- We decided to adopt a mixed simulation/analytical approach which allows to count the different types of floating-point operations (FLOPs): multiplications, divisions, square roots, etc. and weight them differently.
Based on our complexity results, two novel low-complexity localization algorithms have been developed:

1. **A distance-reduced domain (DRD) estimator**: it is based on the fact that localization can be split in two phases: a) a raw (map-unaware) estimation reducing the search domain and a b) fine (map-aware) estimation.

2. **A probability-reduced domain (PRD) estimator**: it is based on the fact that complexity can be reduced by: a) evaluating the likelihood in selected points of a given map and b) shrinking the search domain around the most-likely positions found in step a).

In addition, for localization algorithms involving the search for minima in non-convex functions, several state-of-art direct-search optimizers have been tested: active-set, iterative grid search, iterative compass search.
**RESULTS:**

**Accuracy (RMSE)**

- DRD and PRD variants offer an accuracy close to that of map-aware algorithms but require a lower complexity (on the average 13 times smaller).
Navigation Algorithms:
An INS for Low-Cost IMUs
**CONTEXT:**

- **Inertial measurements units (IMUs)** based on MEMS are low-cost sensors which can be used in **Inertial Navigation Systems (INS)** for indoor/outdoor pedestrian dead-reckoning.

- MEMS IMUs provide 3-axis acceleration and angular velocity measurements, which can be used to perform **dead-reckoning**, i.e., position estimation sequentially integrating estimated velocities and accelerations.
Error Mitigation for Map-unaware INSs

**PROBLEM:**
- Outputs of low-cost IMUs’ accelerometers and gyroscopes are affected by several sources of errors (random noise, time-variant biases, etc). Such measurements are continuously integrated in an INS, so that even small errors quickly affect the estimate of the agent position.

**SOLUTION:**
- The INS was implemented in a real-time system using an Extended Kalman Filter (non-linear filtering technique).
- In our system model biases of the sensor are part of an hidden state and thus can be tracked together with the pedestrian position and dynamic state (orientation, velocity, acceleration, etc):

\[
\begin{align*}
x_k & \triangleq [p_k, v_k, a_k, q_k, a^b_k, \omega^b_k, \omega^b_k, b^a_k, b^\omega_k]^T,
\end{align*}
\]
Map-awareness Reduces Drifting

**PROBLEM:**
- Any INS based only on accelerometers/gyroscopes suffers from a slow drift between the true position and the INS-estimated one.

**SOLUTION:**
- Map-awareness may remove such a drift, thanks to the constraints that the map puts on the agent movements.

- Similarly to radio localization algorithms, map-awareness introduces strong **non-linearities** in the filtering algorithms, forcing a transition from semi-linear (EKF) to non-linear (e.g., PF) tracking algorithms.
A Novel Filtering Technique for Non-Linear Systems

**PROBLEM:**
- Traditional non-linear filtering techniques (PF, RBPF, UKF, etc) have a computational complexity which is **prohibitive** for large state vectors (in our case, dimensionality = 25)

**APPROACH:**
- Turbo-like filtering:

![Diagram of filtering techniques](image)
RESULTS:

- Turbo-like filtering has been employed to track a pedestrian equipped with a foot-mounted IMU.

- This resulted in a prototype of indoor localization system for pedestrians with sub-meter accuracy.
**Results:**

- The map-aware INS employing turbo-filtering is capable of **correcting the drift** that substantially affects a map-unaware INS.

- The computational complexity of the map-aware INS is roughly **1.5 times** the complexity of map-unaware INS.
Thanks for your attention.

Questions?
Publications

Journal Publications (published & submitted)

1. **Montorsi, F.; Vitetta, G. M.**; "On the Performance Limits of Pilot-Based Estimation of Bandlimited Frequency-Selective Communication Channels," *IEEE Transactions on Communications*, vol. 59, no. 11, Nov. 2011;


3. **Montorsi, F.; Mazuelas S.; Vitetta, G.; Win M. Z.**; "On the Performance Limits of Map-Aware Localization," Accepted for publication in *IEEE Transactions on Information Theory*


5. **Montorsi, F.; Pancaldi, F.; Vitetta, G.**; "Reduced-Complexity Algorithms for Indoor Map-Aware Localization Systems," Submitted to *IEEE Transactions on Wireless Communications*

Conference Publications (published)


2. **Montorsi, F.; Mazuelas S.; Vitetta, G.; Win M. Z.**; "On the Impact of A Priori Information on Localization Accuracy and Complexity," Accepted for publication in *IEEE International Conference on Communications 2013*

3. **Montorsi, F.; Pancaldi, F.; Vitetta, G.**; "Map-Aware RSS Localization Models and Algorithms Based on Experimental Data," Accepted for publication in *IEEE International Conference on Communications 2013*

4. **Montorsi, F.; Pancaldi, F.; Vitetta, G.**; "Design and Implementation of an Inertial Navigation System for Pedestrians Based on a Low-Cost MEMS IMU," Accepted for publication in *IEEE International Conference on Communications 2013 - Workshop on Advances in Network Localization and Navigation*