Sensor Fusion for UWB and Wifi Indoor Positioning Systems

March the 3rd, 2005

Frédéric EVENNOU
What positioning is used for?

Many applications require positioning information
- In city driving
- Emergencies (E911, E112)
- Finding your friends (buddy finder applications)
- Visiting an area or a museum

Many solutions exist
- GPS
- GSM network (Cell-ID, TDOA, AOA)
- Video
- Ultra-sound and infra-red

Some weaknesses remain
- Poor accuracy
- Dependant of the environment
Contents of this presentation

- Indoor positioning with WiFi
  - Basic WiFi positioning
  - Improving WiFi positioning
    - The Kalman filter
    - The particle filter
    - Particle filter on a Voronoi diagram

- Indoor positioning with UWB technology

- Accuracy augmentation with sensor fusion
Basic indoor positioning with WiFi (1)

- WiFi access points are present in more and more public area
- Time information is not available in standard commercial WiFi products
- The available information is the signal strength from the different access points
  - Use of a propagation model \( P_{\text{received}}(d) = P_{\text{received}}(d_0) - 10 \cdot \alpha \cdot \log \left( \frac{d}{d_0} \right) \)
  - Triangulation
  - Use of the fingerprinting method
- Simple propagation model does not match the indoor complex propagation
Basic indoor positioning with WiFi (2)

- Use of a database containing the signal strength footprints
- Constraint
  - Building the database
- Closest neighbor algorithm:
  - Search in the database
  
  \[ X = \arg \min_{x_k, y_k} \left( \sum_{l=1}^{N} \left( P_{\eta_l} (x, y) - P_{\eta_l} (x_k, y_k) \right)^2 \right) \]
- Problem:
  - Signal strength fluctuations over the time
    - Position extracted from the database fluctuates all the time
The Kalman filter

- Estimates the state of a system
  - Prediction of the next state
  - Correction by a new measurement
- Minimization of the covariance of the posterior error
- Appliance conditions: linear laws
  - Hard to model all the situations
- Advantages:
  - Gives a linear trajectory
  - Can be run on handheld devices
- Drawbacks
  - Some wall crossings remain
  - Signal strength fluctuations remain
The particle filter (1)

Filter based on a set of "particles" exploring the space of possibilities

Each particle has a weight.
  - The weight is the probability to find the particle at a given position

The weight includes:
  - The history of the particle
  - The structure of the building
  - The signal strength measurements
  - Other information (ex: INS)

 Leads to the distribution law associated to the mobile's presence probability density
The particle filter (2)

The weight of a particle is defined as follows

$$w_k^i \propto w_{k-1}^i \cdot \Pr\left[Z_k \mid X_k^i\right] \cdot \Pr\left[X_k^i \mid X_{k-1}^i\right]$$

The prior law is the movement law:

- Use of gaussian noises to model the acceleration

Taking into account the structure of the building

- If a particle crossed a wall:  \( \Pr[x_k \mid x_{k-1}] = P_m \)
- If a particle did not cross a wall:  \( \Pr[x_k \mid x_{k-1}] = 1 - P_m \)

The posterior law:

$$\Pr\left[z_k \mid x_k\right] = N(z_k, d_c)$$

- Gaussian law
The particle filter (3)

Problem
- Degeneracy of the filter
  - Particles with a too low weight need to be re-introduced in the interesting area

Solution
- Triggering a resampling step

Consequence
- Loss of a part of the diversity of the filter
- The filter can collapse (if all the particles remain trapped in a room)

Criterion
- Search of the particles having the highest weights
- Add a noise to get locally some diversity (Epanechnikov, Gaussian kernels)
The particle filter (4)

- Some interesting results
  - Accuracy improvements
  - Fewer wall crossings

- Inconvenient
  - Requires a large number of particles
    - High processing work load
    - Cannot be implemented on limited processing devices
Complexity reduction

Reduction of the number of particles
- Reduction of the space to explore
  - The Voronoi diagram could be a solution
- Automatic building of this diagram
- Avoid the particles be trapped
- No checking for the wall crossings

<table>
<thead>
<tr>
<th></th>
<th>Database</th>
<th>Kalman filter</th>
<th>Particle filter</th>
<th>Voronoi filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elapsed time per Measurement</td>
<td>1</td>
<td>1.2</td>
<td>175</td>
<td>44</td>
</tr>
<tr>
<td>(ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run on a laptop</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Run on a PDA</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Principle & overview of our UWB system

Objectives
- Comparison of timing position vs. Signal strength fingerprinting
- Study of the capabilities of UWB radio impulse for device positioning

Technique: Time Difference Of Arrival
- Computation of way differences
  \[ [(t_i-t_0) - (t_{ref}-t_0)] \times c = (t_i - t_{ref}) \times c \]

System's overview
The challenge

_Fighting the multipath (indoor environment)_

- Delay spread > 100 ns
- ISI is possible: chip duration = 200 ns

_Finding the direct path_

- Better accuracy

![Diagram showing TX and RX with LOS and NLOS signals with correlation result graphs showing error]

Distribution of this document is subject to France Telecom’s authorization
D13 - 18/03/2005
Signal processings (1)

- **Use of the CLEAN algorithm to detect that path**
  - Based on the Generalised Maximum Likelihood algorithm (iterative algorithm)
  - Hypothesis: \( r(t) = \sum_i c_i w(t - \tau_i) \)
  - Stop criterion: \( \arg\min \left[ \| r(t) - \hat{f}(t) \|^2 \right] \)

- **Limitation:**
  - Ignorance of the pulse shape at reception
  - Use of the energy detection
  - Minimization of the False Alarm (\( P_{\text{FA}} \)) and the Missed path detection (\( P_{\text{MP}} \))
Signal processings (2)

- **$P_{MP}$** depends on the channel's statistics
  - $\frac{\tau_{direct} - \tau_{max}}{\alpha_{direct}}$
  - $\frac{\alpha_{direct}}{\alpha_{max}}$

- **$P_{FA}$**: probability that the noise be over $s$ during the window $w$
  - Depends on the processing at reception

- **Criterion**: choose $\nu$ such as the direct path be not missed and $s$ minimizing $P_{FA}$ and $P_{ND}$

- **Simulations with the 802.15.3 channel models**

- **Limitations**:
  - **$P_{FA}$**: requires the maximum correlation peak value for normalization
  - **$P_{MP}$**: channel's statistics; measurement campaign
Positioning system

- Always an NLOS situation
- Covered area 20*20 m
  - Two kinds of positioning areas
Comparison of different strategies

**Strategies**
- Adaptive threshold
- Fixed thresholds
- Maximum peak detection
Sensor fusion (1)

The particle filter is a convenient tool:

- **Calculate** \( \Pr[z_k | x_k] = \Pr[z_{k, \text{WiFi}}^k, z_{k, \text{UWB}} | x_k] \)
  - Hypothesis
    - Assume the WiFi and UWB measurements are uncorrelated
      \( \Pr[z_k | x_k] = \Pr[z_{k, \text{WiFi}} | x_k] \cdot \Pr[z_{k, \text{UWB}} | x_k] \)
    - Each probability density is assumed to be gaussian
  - The best of each sensor must be kept
    - WiFi: 2 m accuracy
    - UWB: 50 cm accuracy

**Constraint:**

- Area availability of each technology
  - WiFi: coverage over the building
  - UWB: coverage over a 20*20 m area
Sensor fusion (2)

- No special criterion for the WiFi measurement
  - Accuracy is estimated to be about 2m

- Need a special criterion for the UWB measurement
  - Accuracy depends on the signal to noise ratio
    - The lower it is, the harder the first path detection will be
      - Poor accuracy

- Confidence index will be introduced by the variance of each gaussian law

\[
\sigma_{UWB} = \begin{cases} 
\sigma_{WiFi} & \text{if } SNR_{low} < \min[SNR_i] \leq SNR_{high} \\
\frac{\sigma_{WiFi}}{4} & \text{if } \min[SNR_i] > SNR_{high} \\
\infty & \text{if } \min[SNR_i] \leq SNR_{low}
\end{cases}
\]
Performances of sensor fusion
Summary

- **Indoor positioning is promising in comparison with actual outdoor techniques**
  - Better accuracy (2 m)
  - Infrastructure are most of the time installed
    - Low cost (network + interface on the mobile device)

- **UWB leads to encouraging positioning results**
  - Accuracy (50 cm)
  - But short coverage area (20*20 m area)

- **Combination of positioning technologies is necessary**
  - To know the position of the mobile in a room
  - Resynchronize the poorest technology
  - UWB + WiFi positioning require a network-based solution
    - Higher processing capabilities