Techniques for the Application of Radar in Off-Road Robotics

M. Sc. Paul Fritsche

http://www.rts.uni-hannover.de
Motivation

Why we want to use RADAR in Field Robotics?

<table>
<thead>
<tr>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immune against rain, snow, dust, smog, sunlight</td>
<td>Wide beams, bad angle resolution</td>
</tr>
<tr>
<td>Ability to penetrate certain material</td>
<td>Bad distance resolution</td>
</tr>
<tr>
<td>High range</td>
<td>Slow scan speed</td>
</tr>
<tr>
<td></td>
<td>Optical effects</td>
</tr>
<tr>
<td></td>
<td>Almost impossible to determine target shape</td>
</tr>
</tbody>
</table>
Motivation

Why we want to use RADAR in Field Robotics?
Motivation

What can we do with radar?

- Detect objects
- Object tracking
- Mapping
- Sensorintegration
1. Range and velocity estimation

\[ f_s - f_e + f_{Dopp} \]
1. Range and velocity estimation

![Diagram of Range and Velocity Estimation](image)

- **Modulator**
- **VCO**
- **Frequency Mixer**

Mathematical expressions:

- $f_s - f_e + f_{Dopp}$
- $P_s \rightarrow G_s$
- $P_e \rightarrow G_e$
- $R \rightarrow \lambda$
- $\sigma$
1. Range and velocity estimation

Voltage-Controlled Oscillator (VCO)
1. Range and velocity estimation

\[
P_e = P_s \cdot \frac{G_e G_s \lambda^2 \sigma}{(4\pi)^3 R^4}
\]
1. Range and velocity estimation

Sending and Receiver Antenna

\[ P_e = P_s \cdot \frac{G_e G_r}{(4\pi)^3 R^4} \]
1. Range and velocity estimation

Object | RCS ($\sigma$) in $m^2$
---|---
Car | 10
Garage door | 100
Ship | 1000
Human | 1
Corner reflector 15cm | 13

$$P_e = P_s \cdot \frac{G_e G_s \lambda^2 \sigma}{(4\pi)^3 R^4}$$
1. Range and velocity estimation

Distance estimation

\[ R = \frac{cT f_d}{2\Delta f} \]
1. Range and velocity estimation

Distance and velocity estimation

\[ f_d = \frac{|f_{d1} - f_{d2}|}{2} \quad f_{Dopp} = \frac{|f_{d1} + f_{d2}|}{2} \]
1. Range and velocity estimation

Distinguish accuracy and resolution!

Points inside a resolution cell merge to one object

\[ \Delta R = \frac{c}{2\Delta f} \]
2. Imaging methods

Imaging Methods

- Beam focusing and mechanical pivoting
  - Parabolic reflectors
  - Group antennas
  - Luneburg lens
  - Lenses

Quelle: https://de.wikipedia.org/wiki/L%C3%BCneburg-Linse
Quelle: http://www.brennpunkt-srl.de/UMTSParabolStickBlock.html
2. Imaging methods

- Lateration

Distance equations for m sensors and n objects:

\[
\begin{align*}
(x_{S1} - x_{O_i})^2 + (y_{S1} - y_{O_i})^2 &= d_{i1}^2 \\
(x_{Sj} - x_{O_i})^2 + (y_{Sj} - y_{O_i})^2 &= d_{ij}^2 \\
&\vdots \\
(x_{Sm} - x_{O_i})^2 + (y_{Sm} - y_{O_i})^2 &= d_{im}^2
\end{align*}
\]
Data association and convert the distance equations to a linear system of equation for every object $i$:

$$
\begin{pmatrix}
2 \cdot (x_{S1} - x_{Sm}) & 2 \cdot (y_{S1} - y_{Sm}) \\
2 \cdot (x_{S2} - x_{Sm}) & 2 \cdot (y_{S2} - y_{Sm}) \\
\vdots & \vdots \\
2 \cdot (x_{Sm-1} - x_{Sm}) & 2 \cdot (y_{Sm-1} - y_{Sm})
\end{pmatrix}
\begin{pmatrix}
x_{O1} \\
y_{O1}
\end{pmatrix}
= 
\begin{pmatrix}
(x_{S1} - x_{Sm})^2 - (y_{S1} - y_{Sm})^2 - d_{i1}^2 - d_{im}^2 \\
(x_{S2} - x_{Sm})^2 - (y_{S2} - y_{Sm})^2 - d_{i2}^2 - d_{im}^2 \\
\vdots \\
(x_{Sm-1} - x_{Sm})^2 - (y_{Sm-1} - y_{Sm})^2 - d_{i,sm-1}^2 - d_{im}^2
\end{pmatrix}
$$

System gets overdetermined if number of sensors $m + 1$ is higher then the dimension of the operating space.
2. Materials and Methods - Lateration - Scanner

Wrong data association can result in ghost targets. Condition for the appearance:

$$\Delta R < \frac{d_{\text{Ant}}}{2}$$

Ghost targets can be resolved by discretizing the observation space into a finite set of possible object positions and calculating a mean square error E for them.

$$E(x,y) = \sum_{j=1}^{m} \left[ \min_{d_{ij} \in OL_j} (d_{ij} - d(x,y)) \right]^2$$
2. Materials and Methods - Lateration - Scanner

Wrong data association can result in ghost targets. Condition for the appearance:

\[
\Delta R < \frac{d_{Ant}}{2}
\]

Ghost targets can be resolved by discretizing the observation space into a finite set of possible object positions and calculating a mean square error \( E \) for them.

\[
E(x, y) = \sum_{j=1}^{m} \left( \min_{d_{ij} \in Ol} (d_{ij} - d(x, y)) \right)^2
\]
2. Imaging methods

Sensors are placed close as possible to each other, but facing slightly to different directions with $\varphi$.

\[
ASR = \frac{\Delta}{\Sigma} = \frac{P_{e1} - P_{e2}}{P_{e1} + P_{e2}}
\]
2. Imaging methods

Quelle: A Target Shape Estimation Algorithm for Pulse Radar System Based on Boundary Scattering Transform, Sakamoto, T. and Sato, T.
2. Imaging methods

IBST:

\[ x = X - Y \frac{dY}{dX} \]

\[ y = Y \sqrt{1 - \left( \frac{dY}{dX} \right)^2} \]

Quelle: A Target Shape Estimation Algorithm for Pulse Radar System Based on Boundary Scattering Transform, Sakamoto, T. and Sato, T.
3. Summary

- Beam focusing (Applied in scanner setups, suitable for mapping, sensor integration with Laser)
- Lateration (Suitable for object tracking, sensor integration with camera)
- ASR (Suitable for tracking and further beam sharpening)
- IBST (Mapping?)
Thank you for your attention!