DME/DME NAVIGATION USING A SINGLE LOW-COST SDR AND SEQUENTIAL OPERATION

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Taher Jalloul, Omar Yeste, Ajib Wessam, René Landry Jr., Claude Thibeault
AGENDA

1. Introduction

2. Sequential DME/DME

3. Tests and performances

4. Conclusion
Benefits of SDR for aviation

• Today’s avionics facing few problem related to increasing:
  – size, weight, power and cost

• SDR technology is a solution that offers:
  – Reprogrammability & reconfigurability
  – Scalability
  – Reduced number of parts
Context of the work

AVIO-505 project:

– “Software defined radios for highly integrated system architecture”

• Objectives:
  – Integration of navigation, communication and surveillance systems under a single universal reconfigurable platform
  – Demonstrate the capabilities and performance of SDR in aerospace
  – Address new regulatory initiatives (NextGen)

• Partners:
  – Academic: ETS Montreal, Ecole Polytechnique Montreal, UQAM
  – Industrial: Bombardier, MDA, Marinvent Corporation, Nutaq
DME new interest

• FAA launches APNT program to maintain aviation operations in the event of GPS unavailability or outage

• One of the proposed APNT systems is an optimized DME Network based on DME/DME navigation
Objective of the work

• Proof of concept: DME/DME implementation into low cost SDR

• Initial operability

• Testing and measuring DME/DME implementation in a laboratory environment
DME overview

• Pulse-ranging navigation system composed by an airborne interrogator and a ground station transponder
• Frequency range: 962-1213 MHz
Sequential DME/DME

- DME-DME: Aircraft determines position by 2-way ranging towards 2 or more using scanning DME
- Implementation platform (ZeptoSDR) equipped with a single transceiver

-No simultaneous distance acquisition
-Solution: Sequential DME/DME
  - Getting the distances sequentially from each DME station
  - Position calculation
Principle of operation
Algorithm for distance calculation

- \( i \) the iteration to compute the position and \( j \) the index of the station
- The aircraft is moving: the three first distances are not correct to compute the position
- The three distances measured respectively at \( t_{i1}, t_{i2} \) and \( t_{i3} \) should be extrapolated to \( t_{i4} \) (the measuring time of the fourth distance)

\[
\text{for } i \text{ from } 2 \text{ to } \infty \text{ do}
\]
\[
\text{for } j \text{ from } 1 \text{ to } 3 \text{ do}
\]
\[
a_{ij} \leftarrow \frac{d_{ij} - d_{i-1j}}{t_{ij} - t_{i-1j}};
\]
\[
b_{ij} \leftarrow d_{ij} - a_{ij} \cdot t_{ij};
\]
\[
d_{ij} \leftarrow a_{ij} \cdot t_{i4};
\]
\[
\text{end}
\]
\[
\text{end}
\]

\textbf{OUTPUT:} Distances calculation at the instant of acquiring the fourth distance
Position computation

\[
\begin{align*}
\sqrt{(x_r-x_1)^2 + (y_r-y_1)^2 + (z_r-z_1)^2} &= d_1 \\
\sqrt{(x_r-x_2)^2 + (y_r-y_2)^2 + (z_r-z_2)^2} &= d_2 \\
\sqrt{(x_r-x_3)^2 + (y_r-y_3)^2 + (z_r-z_3)^2} &= d_3 \\
\sqrt{(x_r-x_4)^2 + (y_r-y_4)^2 + (z_r-z_4)^2} &= d_4
\end{align*}
\]

Where \((x_r, y_r, z_r)\) is the aircraft coordinates

\((x_i, y_i, z_i)\) station \(i\) coordinates and

\[
\Delta d = \begin{bmatrix}
\Delta d_1 \\
\vdots \\
\Delta d_4
\end{bmatrix} \quad \Delta x = \begin{bmatrix}
\Delta x_r \\
\vdots \\
\Delta z_r
\end{bmatrix} \quad H = \begin{bmatrix}
a_{x1} & a_{y1} & a_{z1} \\
\vdots & \vdots & \vdots \\
a_{x4} & a_{y4} & a_{z4}
\end{bmatrix}
\]

\[
\Delta d_i = \hat{d_i} - \hat{d_i} \\
ap_{xi} = \frac{x_i - \hat{x}}{\hat{d_i}} \\
ap_{yi} = \frac{y_i - \hat{y}}{\hat{d_i}} \\
ap_{zi} = \frac{z_i - \hat{z}}{\hat{d_i}}
\]

Where
SDR platform: Nutaq’s ZeptoSDR

• Main components:
  – Radio420X: High quality radio module
  – Xilinx Zynq FPGA (pass-through mode)
  – Dual ARM Cortex-A9

• Features
  – Remote and embedded operation
  – GNU Radio support

GNU Radio
Test set-up

- Laptop ZeptoSDR
- IFR-6000
- Ground station
- PC Simulator
- Flight simulator
- Aircraft SDA

Connections:
- Ethernet Gigabit connection
- RS232 connection

GNU Radio

Ubuntu

2014-09-19
Test set-up

• Flight simulator: providing the distance to each station and the aircraft position to be compared with the ones calculated
• The IFR6000 avionics ramp test set representing the ground stations in the DME/DME positioning system
• The ZeptoSDR connected to a laptop representing the DME airborne
System performance

\[ \sigma_{\text{Position}} = \text{GDOP} \cdot \sigma_{\text{Distance}} \]

\[ \text{GDOP} = \sqrt{\text{trace}(H^T H)^{-1}} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \]

\[ \text{HDOP} = \sqrt{C_{11} + C_{22}} \]

\[ \text{VDOP} = \sqrt{C_{33}} \]

Where \( C = (H_{enu}^T \cdot H_{enu})^{-1} \) and \( H_{enu} = \begin{bmatrix} \cos(EL_1) \cdot \cos(AZ_1) & \cos(EL_1) \cdot \sin(AZ_1) & \sin(EL_1) \\ \vdots & \vdots & \vdots \\ \cos(EL_4) \cdot \cos(AZ_4) & \cos(EL_4) \cdot \sin(AZ_4) & \sin(EL_4) \end{bmatrix} \)
Distance accuracy

- Distance measurement accuracy better than 20 m for moderate and high SNR
- The accuracy is small enough to assess DME compliance with minimum operational performance standards (MOPS)

Figure  Distance RMSE vs SNR
Simulated Scenario

- Scenario from the simulated flight
- High value of the VDOP due to the same altitude for the ground stations
- The four DME stations located at distances 53 Km, 96 Km, 71 Km and 99 Km
- The observed standard deviations of the range accuracy are 10.2 m, 5.4 m, 5.6 m and 18.0 m, respectively

Figure: GDOP = 14.76, HDOP = 4.75, VDOP = 13.97
Static Positioning Accuracy

- Different accuracies for the east and north coordinates, where $\sigma_N = 56.05\, \text{m}$ and $\sigma_E = 9.23\, \text{m}$

- The difference explained by decomposing the HDOP into the east and north components, which will be denoted the East DOP (EDOP) and the North DOP (NDOP), where EDOP = 0.66 and NDOP = 4.70

- Vertical position errors

Figure: Distribution of the computed position
Results

• Existence of a bias in the position estimates, being 8.6 m towards Est and 79.0 m towards North

• This bias is the result of biased range measurements, which in turn are due to the conjunction of two effects:
  – A frequency independent bias due to residuals during DME calibration step at the beginning of operation
  – A frequency dependent bias caused by the group delay of the different hardware involved

• Vertical position errors in the order of several hundreds of meters
  – Marginal influence on horizontal position
Dynamic positioning

[Graphs showing dynamic positioning data]
Dynamic Positioning Accuracy

**Direct computation**

**Smoothed positioning**

![Graphs comparing direct computation and smoothed positioning](chart.png)
Results

- The bias increased to 552 m towards East and 189 m towards South
  - Distance correction algorithm
  - Poor synchronization between flight simulator and DME

- The standard deviations are $\sigma_N = 100$ m and $\sigma_E = 32$ m:
  - Velocity accuracy
  - Variable GDOP
  - Smoothed positions' accuracy is $\sigma_N = 41$ m and $\sigma_E = 24$ m
Conclusion

• The new sequential DME/DME concept was introduced to develop a DME/DME positioning system in the ZeptoSDR platform

• The position accuracy is dependent on the stations geometry and the distance measurement errors, which is highly accurate

• To get the best performance from the system, station geometry should be controlled

• Integration of DME/DME navigation with other navigation systems, such as GNSS, is also an interesting future research and would help to reduce the position bias
Future Work

• The interrogator performs the complete search/tracking procedure before switching to the next ground station channel in a positioning rate of about 0.2 Hz

• Accelerate the process by decreasing the interrogator dwell time at each frequency to the minimum allowed (about 20 ms)
  – Improved accuracy

• Stations selection for optimal geometry based on availability can be investigated in the future

• Implementation of more advanced position smoothing and distance computation methods to increase accuracy
Questions?

Thank you

For more information about LASSENA or AVIO-505 project: renejr.landry@etsmtl.ca