

Performance of autonomous underwater vehicle positioning by acoustic communication

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Outlines

- 1 Context
- 2 State of art
- 3 Positioning innovation
- 4 Simulation results
- 5 Conclusion

Outlines

- 1 Context
Autonomous Underwater Vehicle (AUV)
Application example: The search for AF447 - Rio Paris 2009
- 2 State of art
- 3 Positioning innovation
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Context

Autonomous Underwater Vehicle (AUV)

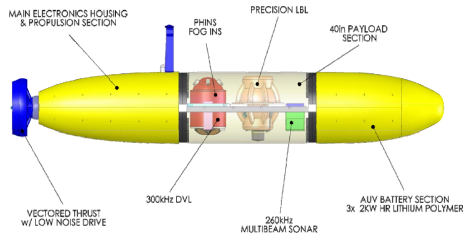


Figure 1 – Generic AUV plan

Context

Autonomous Underwater Vehicle (AUV)

- **Autonomy**
 - Long distance and long period travel
 - No human intervention underwater
 - Internal spatial positioning
 - Wireless communication
- **Applications**
 - Oceanography (bathymetry, mapping)
 - Commercial (research mission, videos)
 - Military (mine detection, sonar)

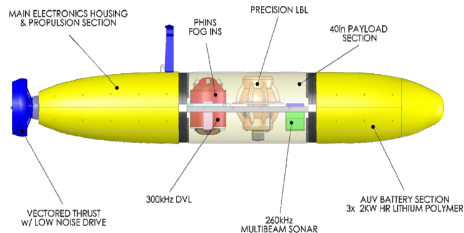


Figure 1 – Generic AUV plan

Context

Application example: The search for AF447 - Rio Paris 2009

After 2 years of research in four phases and several marine vehicles employed, the AUV REMUS 6000 locates the wreckage of the plane at 4000m depth.



Figure 2 – REMUS 6000, 3.84m of length

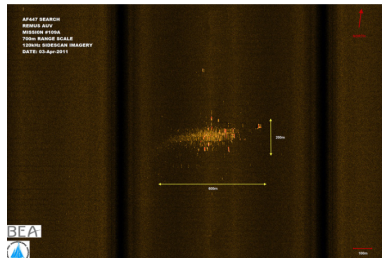


Figure 3 – Detection of debris by acoustic imaging

Figures from BEA report

Outlines

① Context

② State of art

Underwater communications

Doppler shift on acoustic communication

Positioning systems

③ Positioning innovation

④ Simulation results

⑤ Conclusion

State of art

Underwater communications

- Electromagnetic radio
 - ✓ High bandwidth at very low range
 - ✗ Large antenna and high power for longer range
- Optical
 - ✓ Ultra high bandwidth at low range
 - ✗ Ambient light and turbidity affects data rate
 - ✗ Line of sight required
- Acoustics
 - ✓ Long range, moderate bandwidth
 - ✓ Low power even at great range
 - ✗ Noise / channel dependent
 - ✗ Latency ($\simeq 1500$ m/s)

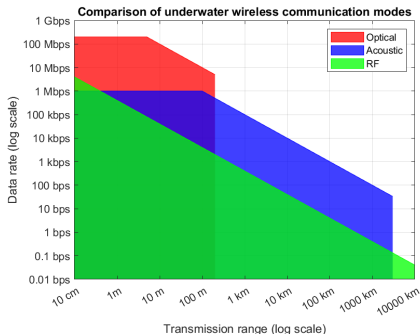


Figure 4 – Theoretical underwater communications data rates (log scale)

State of art

Doppler shift on acoustic communication

- The AUV movement imply a Doppler shift
- This shift has to be estimated and compensated to decode the communication
- Multiple delayed and distorted versions of the transmitted signal is received

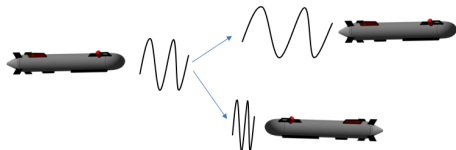


Figure 5 – Doppler shift impact on frequency

State of art

Positioning systems

No Global Navigation Satellite Systems (GNSS) available after few meters depth underwater !

- Proprioceptives sensors
 - Inertial Navigation System (INS): Low bias inertial sensors measurements filtered to an attitude estimator to get speed and position.
 - Doppler Velocity Log (DVL): Acoustic sensor that estimates velocity relative to the sea bottom.
 - INS + DVL: Adding the speed from the DVL, this system can limit the INS speed error.

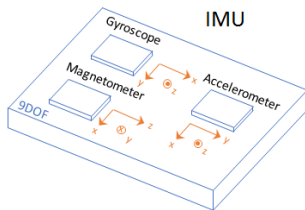


Figure 6 – Inertial Measurement Unit (IMU)

State of art

Positioning systems

No Global Navigation Satellite Systems (GNSS) available after few meters depth underwater !

- Exteroceptive systems
 - Ultrashort Baseline (USBL)
 - Range-only single beacon (ROSB)
 - GPS Intelligent Buoy (GIB) and Long Baseline (LBL)
 - Short Baseline (SBL)

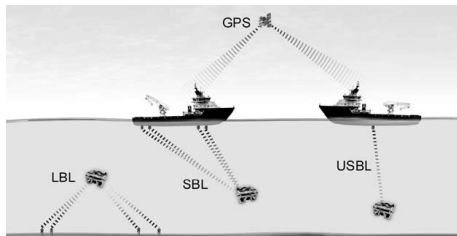


Figure 7 – Acoustic baseline positioning systems

It is common practice to use INS/DVL system with occasional acoustic alignment.

State of art

Positioning systems

Existing systems are perfect for precise mapping and bathymetry, when spacial knowledge is critical

- ✓ Great navigation accuracy for a long time
- ✗ Costly
- ✗ High operational time

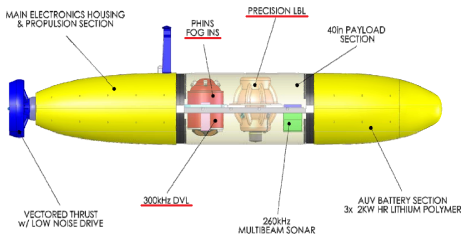


Figure 8 – INS/DVL LBL architecture

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 - System
 - What's the innovation ?
 - Estimation filters
- 4 Simulation results
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Positioning innovation

System

We are using single beacon exchanging communications with an AUV architecture. Light and low complexity.

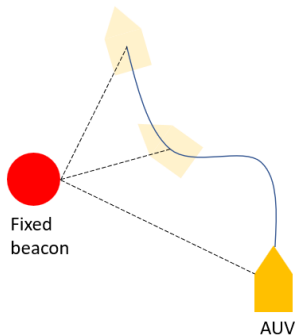


Figure 9 – Simulation architecture

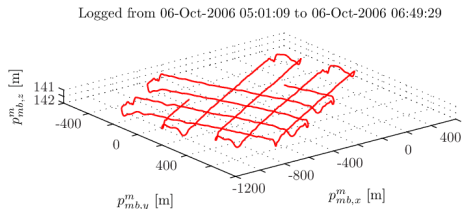


Figure 10 – Grid pattern trajectory mostly used in industry
from Hegrenæs et. Al "Model-Aided Inertial Navigation for Underwater Vehicles"

System objective

The goal is not to compete with INS/DVL Baseline system but to provide time efficient navigation system for AUV.

- Acoustic communication
- Cost-efficient Micro-Electro-Mechanical System (MEMS) IMU
- GNSS sensor
- Pressure sensor *for 3 dimensional solution*

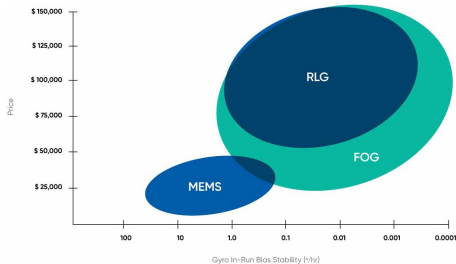


Figure 11 – Fiber Optical Gyroscope IMU and MEMS IMU comparison *from Advanced Navigation*

Positioning innovation

What's the innovation ?

Using Doppler-shift from acoustic communication compensation to do positioning.

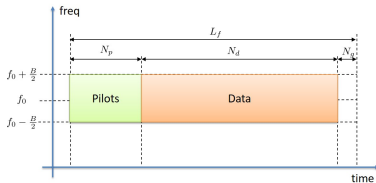


Figure 12 – Binary Phase Shift Keying (BPSK)

- N_p pilots symbols used for synchronization and channel estimation.
- N_d data PSK symbols carrying useful information
- N_g guard symbols to reduce reflections

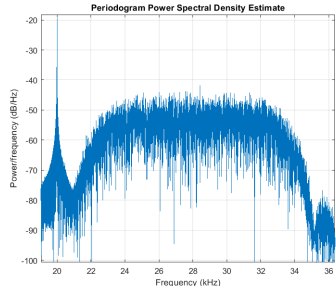


Figure 13 – PSD showing pure-tone at 20 kHz and center frequency $f_0=28$ kHz

Acoustic communication decoding

Underwater acoustic communication provide two crucial values when decoding the signal :

- Range between the station and the AUV
- Relative speed of the AUV
 - Includes water current speed, AUV speed and beacon speed
 - Can be converted to total speed of the AUV if its heading is known

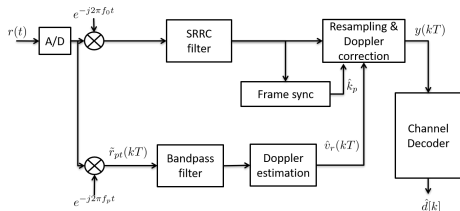


Figure 14 – Receiver demodulator

Positioning innovation

Estimation filters

Having these measurements estimation, the last important part of our algorithm is the estimator

There's few possibility. Here are the more relevant to our system :

- Classical Kalman Filter and its extended version
- Unscented Kalman Filter
- Particle Filter
- Maximum A Posteriori Filter

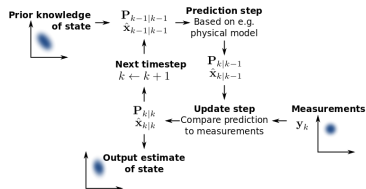


Figure 15 – Concept of Kalman filter

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 - Parameters
 - Results - 2D position estimation with Unscented Kalman Filter
 - Analysis
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Simulation results

Parameters

- Grid-pattern trajectory during 22 minutes
- Distance traveled : Around 1200 meters
- AUV speed between 2 and 4 knots
- Filter used : Unscented Kalman Filter (UKF)
- 200 iterations
- No GNSS fix but 2 meters noise at initial state
- Observation equation : $y = (v_r \quad d_{est} \quad \theta_{heading})^T$
- Communication frequency : 0.25 Hz
- IMU measurement frequency : 4 Hz
- Noises :
 - Distance estimation noise : Normal distribution between -6 and 6 meters
 - Relative speed noise : Normal distribution between -0.4 and 0.4 meters per second
 - Heading noise from the IMU : Normal distribution between -10 and 10 degrees

Simulation results

Results - 2D position estimation with Unscented Kalman Filter

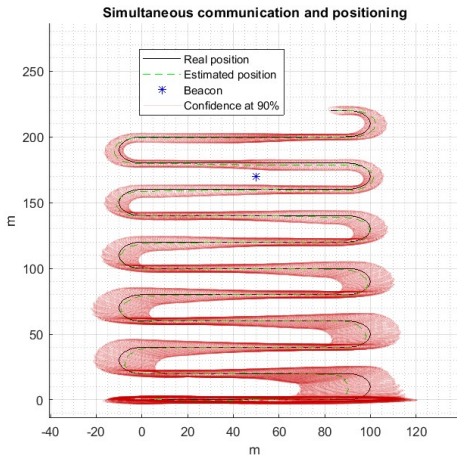


Figure 16 – Fixed beacon located at the same direction of straight lines

Simulation results

Analysis

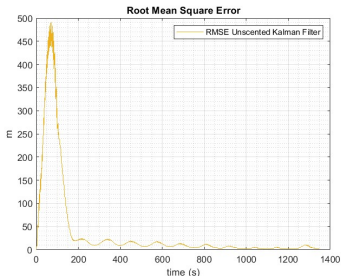


Figure 17 – RMSE, image of the confidence

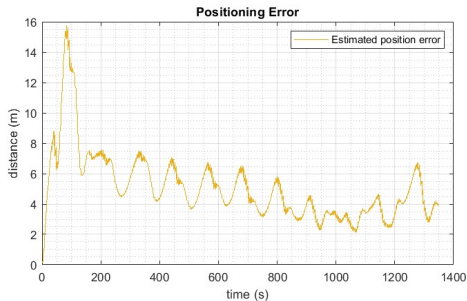


Figure 18 – Position error at each time

Mean position error : 5.02m

Percentage of the traveled distance error : 0.417%

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 - About the results
 - Future works

Conclusion

About the results

Convincing positioning error results in simulation using realistic noises

- PHINS/DVL LBL position error is around 0.03% of the traveled distance
- USBL position error is from 1% for its simplest configuration to 0.06% of the traveled distance when in full configuration

Conclusion

Future works

In July 2022, a sea experimentation with the same parameters as the simulation has been made

- Post-processing and algorithm fitting to real world
- Current estimation
- Navigation with control correction
- Using straight lines to enhance estimation

In the future we can totally imagine multiple AUV positioning

Do you have any questions?