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An Unmanned Underwater Vehicle Defence System

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Abstract. Nowadays, military threats are very close to us and cover terrestrial, aerial, and maritime attacks. This research defines a submarine defence system capable of monitoring and controlling a certain perimeter, based on submersible drones known as Unmanned Underwater Vehicles (UUV) and a grid of stations fixed to the seabed, which provides positioning acoustic signals as well as full-duplex digital communication using underwater acoustic modems. The novelty is the proposed 3D grid system with each Positioning Grid Element (PGE) being an Ultra-Short Baseline (USBL) low or medium operating range device and the processing

1. Introduction

Maritime defense areas are often underwater to secure economical units or military sites. Several systems are already being developed and implemented, for example Underwater Port Security System (UPSS) that is an anti-frogman technique of US Maritime Safety And Security Teams which integrates two main modules: Underwater Inspection System (UIS) and Integrated Anti-Swimmer System (IAS).

The Underwater Inspection System (UIS) is scanning the underwater environment with a real time 3D sonar which can be mobile or fix, detecting small objects and mines.

One system that detects and tracks divers is Integrated Anti-Swimmer System (IAS). However, IAS uses sound shocks to disrupt the driver with at least disorientation effect.

Tracking and maintaining the position of the UUV on the desired track is the most important feature, and this is because disturbances in the Inertial Navigation System (e.g., due to ocean currents) are difficult to be measured in order to compensate them [1,2].

2. State of the art

Unmanned Underwater Vehicles can be divided into two categories: Remotely Operated Underwater Vehicles (ROV) which are remotely controlled by an operator and Autonomous Underwater Vehicles (AUV) which sail independently on an established route without the direct influence of any operator.

Of course, there are often hybrid UUVs, which have the ability to switch from ROV system configuration to an AUV one, when the situation requires it, and switching is possible.

A Russian-made UUV, which uses solar panels for battery charging, GPS functions for positioning and satellite communication for control and tracking, produced since 1990 and called the Solar Autonomous Underwater Vehicle (SAUV) has launched long-term exploration missions.

The widespread use of UUVs in research missions is illustrated by the 2016 incident when an underwater drone being about to be recovered by the USNS Bowditch inspection ship of the US Navy was confiscated by a Chinese military ship in the South China Sea. The drone was returned a few days later, with the Pentagon confirming that the drone was unarmed and used only for exploration.

3. Characteristics of the system

The proposed system is designed to survey into maritime area with a maximum depth determined by the acoustic transmitter.

The most important general characteristics of UUVs are defined by:

- Positioning system
- Communication system

The main specific features proposed for defense are:

- Well limited survey area
- Monitoring only inside area of interest
- Rapid reaction to events detected in the monitoring area

3.1 Navigation system

Several dedicated positioning tools are necessary for UUV navigation. For the surface navigation the global positioning system is used for absolute localization [3,4,5].

The Attitude and Heading Reference System (AHRS) is imported from aircraft industry together with Global Navigation Satellite System (GNSS) receiver and an Inertial Navigation System (INS) platform. Moreover, while immersion the Ultra-Short Baseline (USBL), Doppler Velocity Log (DVL) and Fiber Optic Gyroscope (FOG) instruments compute the relative positioning by using Extended Kalman Filter (EKF).

The obtained data is then combined with the sound speed correction using the USBL algorithm, to then adjust Multibeam Echosounder (MBES) to the formation and direction of the beam.

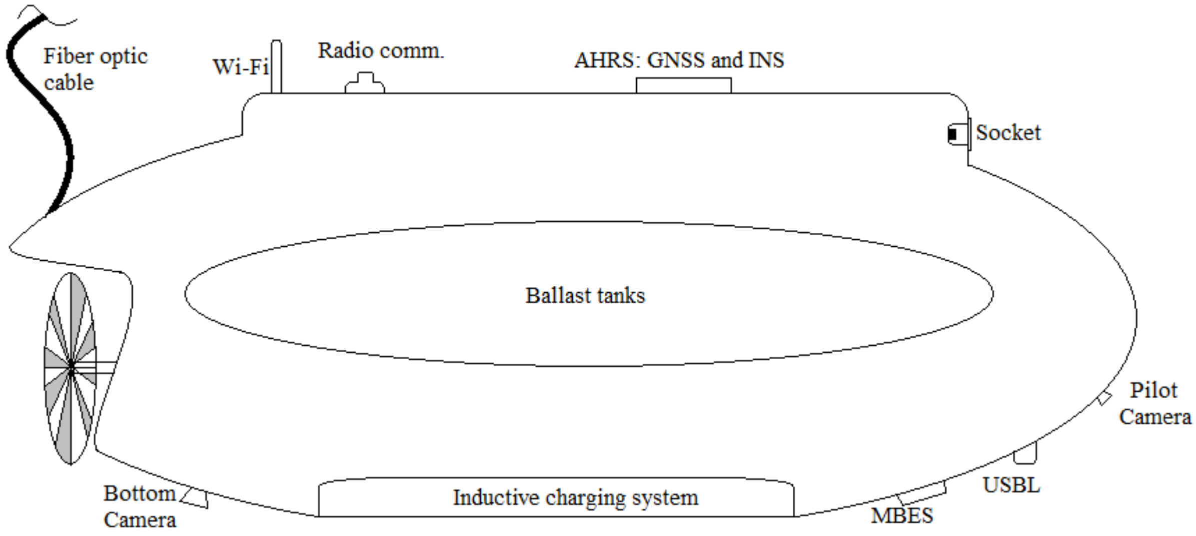

Figure 1 – Main UUV components

The necessary survey tools are optical cameras (Bottom and Pilot), MBES, a standard instrument for temperature and conductivity and one for sound speed and pressure measure.

3.2 Communication system

For the ROV configuration navigation mode the system is tethered for remote only propose with an optical cable that could be of maximum 500 m length because its weight. Because narrow hostile environments typically require seabed inspection at a medium cruising speed, ROV mode is suitable because commands and data are communicated in real time to / from the surface host system.

In the case of large areas, the cruising speed must also increase and the AUV navigation mode becomes feasible in safe conditions. For this type of navigation, the survey path can be programmed either by setting some crossing points to be positioned in areas without obstacles or in areas with known topography.

However, a better solution is a fix grid design based on Positioning Grid Element (PGE), which use acoustic transmitter or acoustic modem, located on the seabed to send AUV position control signals, for clear delimited areas of monitoring.

With specific sensors of the board's instruments (e.g., acoustic modem) the action radius for communication in real-time is over 100m for a good quality data transfer resolution.

The data and commands transferred over acoustic USBL channels between the AUV and PGE are then communicated to the host main station via the fixed infrastructure.

A PGE with communication functionality has an underwater acoustic modem that uses full-duplex digital communications and self-adaptive algorithms and is characterized by nominal bit rate (usual ~ 13 kbit / s), bit error rate (less than 10^{-10}), time synchronization, attenuation, data delay, stratification, underwater noise, and multi-path effect.

3.3 Well limited survey area

Monitoring for defence is done by delimiting the area to be inspected. The chosen solution is the use of a grid of communication elements that allow the transmission to UUV of underwater positioning signals or full-duplex digital communication between UUV and the base station via PGE.

Thus, the use of two types of PGE significantly reduces the cost of the UUV positioning grid by eliminating acoustic modems for grid elements used only for AUV positioning. However, if continuous communication with the submarine is desired, then more elements of the grid should allow communication with the AUV.

Figure 2 and 3 shows the general architecture of a UUV positioning grid.

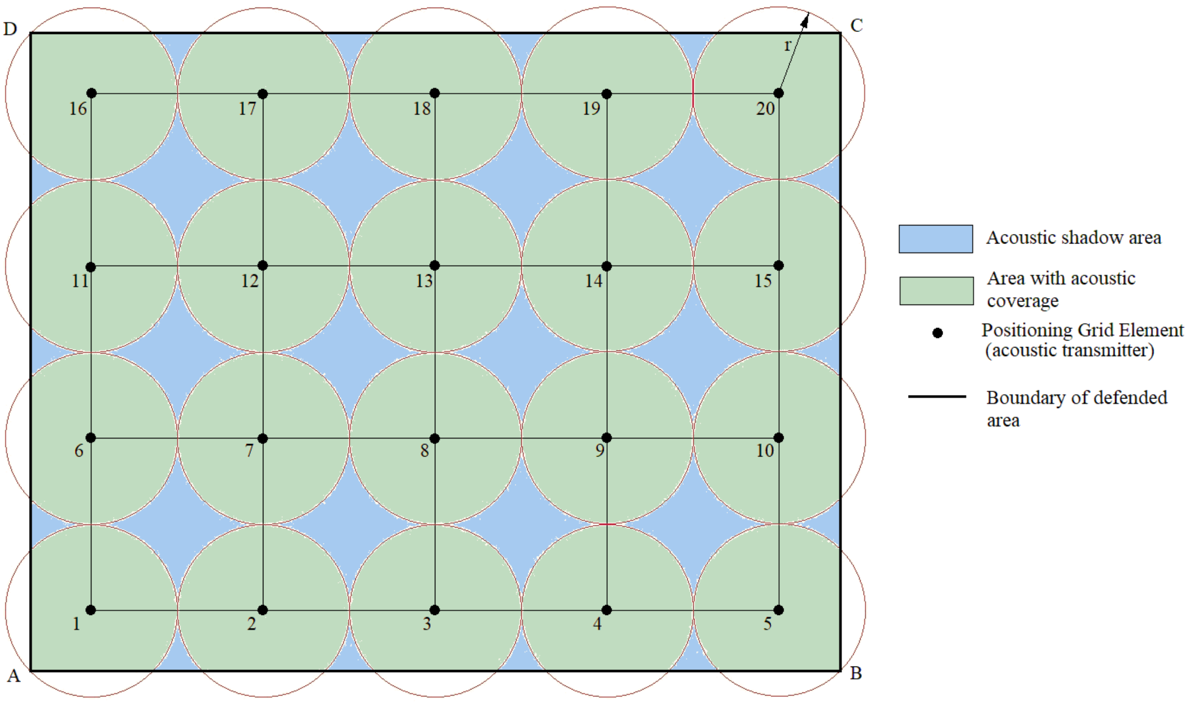

Figure 2 - Horizontal projection of the underwater positioning grid
("r" being the useful radius of propagation of the acoustic wave)

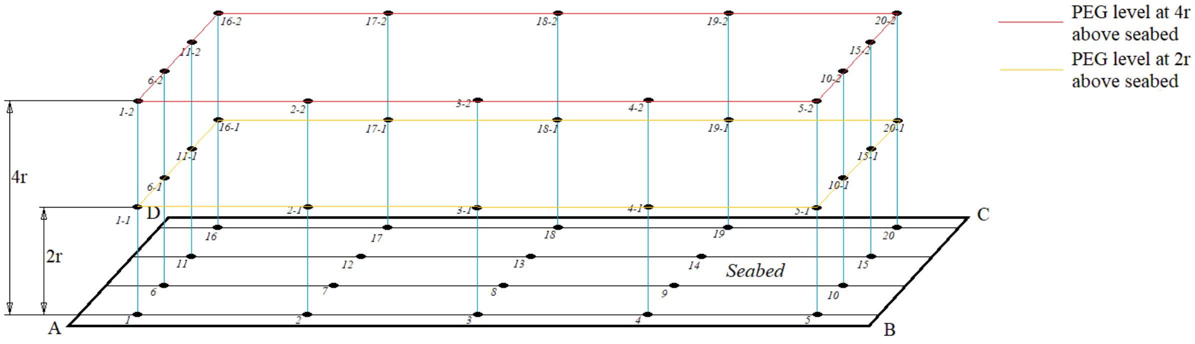

Figure 3 – Spatial extended grid over the transmitter range

Every element of the positioning grid will send an acoustic signal which will contain the index of the PEG encrypted. Thus, the UUV by decoding the received signal, will be able to correctly determine its position in absolute coordinates.

3.4 Positioning System

The proposed positioning system is an Ultra-Short Base Line acoustic positioning system that is simple, accurate and more efficient type [13] comparing with Long Baseline or Short Baseline. Even for USBL method several factors have negative influence on the positioning results, e.g., environmental interferences or acoustic signals multi-path propagation that can provide wrong inputs for the next processing procedures. For the positioning accuracy several methods were proposed [14,15].

The method proposed for positioning processing is using Kalman filters synchronized with every Positioning Grid Element (PGE), where the accuracy is computed with minimum mean-square error estimator.

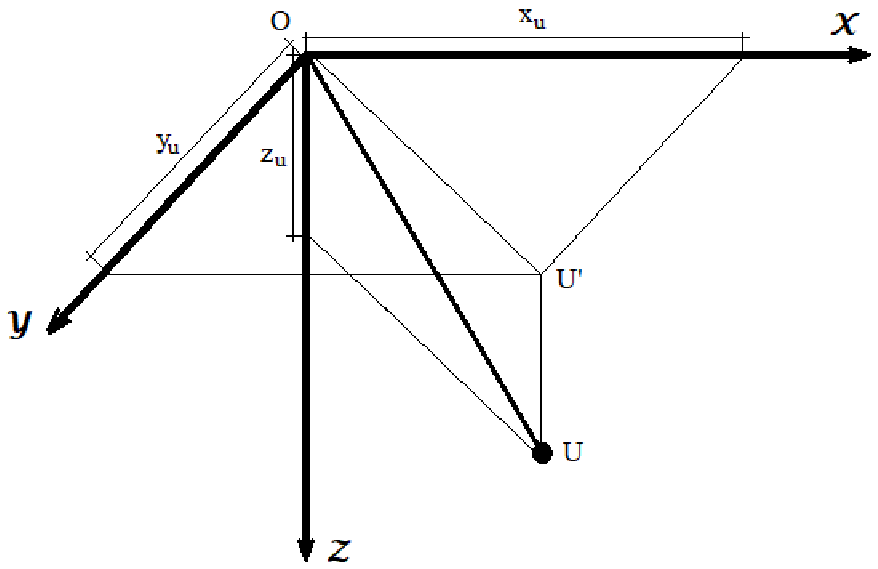

Figure 4 – UUV positioning

The underwater position of UUV is the point U(x_u,y_u,z_u) from the figure 4. To define the $\overline{OU}$ vector needs:

$$\cos \widehat{UOX} = \frac{x_u}{\overline{OU}} \quad (1)$$

$$\cos \widehat{YOU} = \frac{y_u}{\overline{OU}} \quad (2)$$

$$\overline{OU} = \sqrt{x_u{}^2 + y_u{}^2 + z_u{}^2} \quad (3)$$

And we obtain the angle $\widehat{U'OX}$:

$$\widehat{U'OX} = arctg\left(\frac{y_u}{x_u}\right) = arctg\left(\frac{\cos \widehat{YOU}}{\cos \widehat{UOX}}\right) \quad (4)$$

$$z_u = \sqrt{\overline{OU}^2 + \overline{OU'}^2} \quad (5)$$

The equation for the difference of phase ϕ_x between UUV and adjacent PGEs on *x*-axis at equidistance δ with acoustic signal wavelength τ is:

$$\phi_x = \frac{2\pi \cos \widehat{UOX}}{\tau} \quad (6)$$

and

$$x_u = \frac{\tau\, \phi_x\, \overline{OU}}{2\pi\delta} \quad (7)$$

The equation for the difference of phase ϕ_y between UUV and adjacent PGEs on Y axis at equidistance δ with acoustic signal wavelength τ is:

$$\phi_y = \frac{2\pi \cos \widehat{YOU}}{\tau} \quad (8)$$

and

$$y_u = \frac{\tau\, \phi_y\, \overline{OU}}{2\pi\delta} \quad (9)$$

And finally, considering two closest PGEs by the UUV at distances *p* and *q*, using the projection of the $\overline{OU}$ vector on the *x*-axis we have:

$$\Delta x_p = \frac{\Delta\, \phi_x(\tau\, \overline{OU})}{2\pi p} \quad (10)$$

and

$$\Delta x_q = \frac{\Delta\, \phi_x(\tau\, \overline{OU})}{2\pi q} \quad (11)$$

Our future work will analyse the Kalman filtering method from numerical perspective and the acquisition and performance for the phase difference method.

3.4.1 Monitoring only inside area of interest

The software architecture of the telematics control unit (TCU) will be designed to prevent the AUV from crossing the boundary. Even if the position signal is missed and the vehicle is out of the area's borders (detected by the INS unit), the TCU will automatically retract the AUV path back to the area of interest. Thus, AUV will deliver information only about dedicated area.

3.4.2 Battery power management

An energy docking station will be used for energy management, to which the UUV will be connected to charge the batteries.

The UUV batteries will be charged by automatic coupling of the vehicle (using magneto-inductive transfer) or by physical coupling to the surface docking station.

In the case of relatively isolated monitored areas or for which monitoring is confidential, an underwater inductive charging station coupled with a PGE will charge the AUV batteries.

3.4.3 Rapid reaction to events detected in the monitoring area

The proposed positioning grid and data transmission will allow real-time monitoring of events in the area of interest and as such will lead to a rapid reaction in order to apply the countermeasures required for the reported events.

For example, the appearance of divers, the detection of mines or even other underwater objects foreign to the environment.

4. Conclusions

The grid for the automatic positioning of the UUV is a system that allows the inspection on the area of interest with autonomous underwater vehicles having a positioning error in the order of centimetres.

In addition to positioning, the grid elements allow real-time communication with the surface monitoring station via PGE which also allows a quick reaction to the reported events.

The functional autonomy of the AUV is theoretically unlimited (thanks to the integrated PEG inductive charging station), practically limited only by the maintenance times necessary for the AUV.

Future research will focus on the design of the telematics module and the addition of robotic arm tool capable of capturing / annihilating underwater mines or being able to perform various underwater activities of civil interest.

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