A High Accuracy Navigation System for a Tailless Underwater Glider

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Abstract — **This paper describes an integrated control system architecture with a high accuracy navigation system for an underwater glider. To optimize the glider performances, a centralized control system called "Glider Integrated Control System (GICS)" is provided: part of this system oversees the navigation function, based on an INS reference. Unlike an UAV system, in our case, some important inertial navigation error terms cannot be neglected due to the peculiar mission.**

Keywords — *Accuracy Navigation System, Tailless Underwater Glider.*
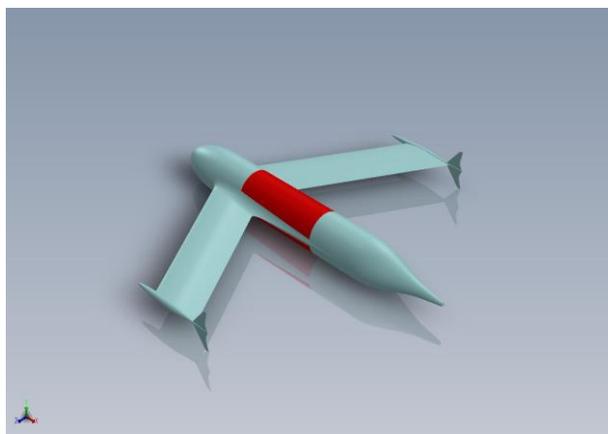
I. INTRODUCTION

Fig. 1. SQUID TUG (Tailless Underwater Glider).

An underwater glider is an autonomous drone (AUV) that moves up and down in the sea like by changing its buoyancy: it uses its hydrodynamic wings to convert the vertical motion to horizontal, moving forward with negligible power consumption [1-3]. Fig. 1 shows the example of our AUV called SQUID.

While not as fast as conventional AUVs, gliders using buoyancy-based propulsion increase the range and the duration (autonomy) compared to motor-driven vehicles, may extend the mission from hours (or weeks) to months, and to several thousands of kilometres of range. An underwater glider follows an up-and-down, sawtooth-like profile through the sea, providing data on temporal and spatial scales unavailable to previous AUVs [4-7].

II. MISSION PROFILE

An underwater glider is unable to proceed straight and level, because is motion is due to the difference between the forces of weight and buoyancy, thus converted by the wings in a smooth dive/climb trajectory [8].
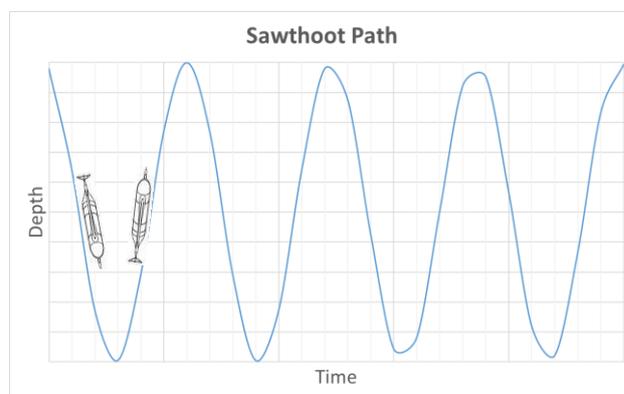

Fig. 2. Sawtooth glide path

Furthermore, unlike gliders in air, AUVs can have ascending glide slopes if the net buoyancy is positive, producing a negative sink rate.

The glider has a *buoyancy engine* that allows it to alternately change its net buoyancy between positive and negative states, thereby imparting it with the ability to string together a succession of descending and ascending glide slopes referred to as a *sawtooth glide path* (see Fig. 2) [9-12].

III. FUNCTIONAL MODES

The peculiar mission of the AUV allows us to consider it as a simple "Finite-state machine" (FSM). The fundamental normal states of the machine are essentially

two: the "diving mode" and the "rising mode". During these functional modes the glider describes the sawtooth glide path [13, 14].

The "floating mode" is used only to connect the glider with the support ship and/or used to download payload data through the Iridium communications system. The "emergency mode" is used to manage all possible problems such as dynamic instability, catastrophic failure, loss of two or more batteries, loss of the payload, etc. The only action that will be taken is to bring up the glider and prepare it to be rescued by the support ship [15-18] (see Fig. 3).
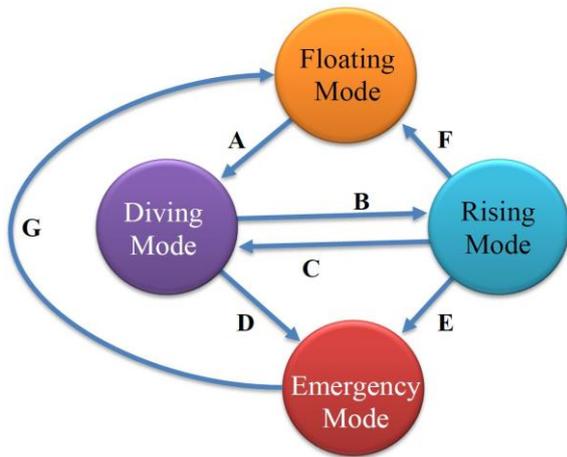

Fig. 3. Functional Modes.

A. Floating Mode

The drone is afloat: firstly, it acquires position coordinates from the GPS system and sends it through the Iridium system. Then wait for any support boat and turn on Wi-Fi for any download of new commands or software update.

B. Diving Mode

The drone is diving: it proceeds at constant speed until it reaches the programmed maximum depth.

C. Rising Mode

The drone is rising: it proceeds at constant speed until it reaches the programmed minimum depth.

D. Emergency Mode

This Mode is a sort of "panic button" of the system: if an unrecoverable attitude is detected, the system automatically goes to this emergency mode: the buoyancy is set to the maximum and the trim is placed in the maximum lift in order to reach the surface as soon as possible.

E. Transition Conditions

A - The drone receives the command to submerge and to reach the programmed maximum depth.

B - The drone has reached the programmed maximum depth.

C - The drone has reached the programmed minimum depth.

D - An unrecoverable attitude is detected by Attitude System Control.

E - An unrecoverable attitude is detected by Attitude System Control.

F - The drone has ended the mission and receives the command to emerge to wait for new communications.

G - The buoyancy is set to the maximum and the attitude is trimmed on the maximum ascend ratio.

The functional modes status and the transition modes are managed by the Glider Integrated Control System.

IV. GLIDER INTEGRATED CONTROL SYSTEM (GICS)

The Glider Integrated Control System performs the Attitude and Navigation Control and the Data Handling & Control, including Payload and Communications management functions [19-23].

The GICS architecture (see Fig. 4) is built around a central processing unit, the Glider Central Unit (GCU), and includes several remote terminal units that interface the payload and Glider equipment [24]. The functions performed by GICS are the following:

• Attitude determination and control.

• Buoyancy and other propulsion components control.

• Telemetry data acquisition, formatting and encoding.

• Command detection, decoding, distribution and actuation.

• Battery management.

• Payload Management.

Fig. 4. GICS general arrangement.

Except for the communications, all other functions are performed when the drone is in autonomous operation [25-29].

V.   NAVIGATION SYSTEM

The navigation system is composed by a Strapdown INS (Inertial Navigation System) system corrected by the GNSS (Global Navigation Satellite System receiver using the GPS, GLONASS, Galileo or BeiDou systems) data every time the vehicle enters in the "floating mode" [30].

All inertial navigation systems suffer from integration drift: small errors in the measurement of acceleration and angular velocity are integrated into progressively larger errors in velocity, which are compounded into still greater errors in position [31].

Since the new position is calculated from the previous calculated position and the measured acceleration and angular velocity, these errors accumulate roughly proportionally to the time since the initial position was input. Therefore, the position must be periodically corrected by input from GNSS (GPS and other) satellite navigation systems [32] when the AUV is in the floating mode.

The benefits of this technology are lower cost, reduced size and greater reliability compared with equivalent platform systems [33][34][35]. As a result, small, lightweight and accurate inertial navigation systems may now be fitted to small AUV [36].

The general arranging of an INS is quite simple (see Fig. 5): the output of a 3-axis accelerometer is rotated (axis transform) with the attitude angles supplied by 3 gyrometers: after a double integration we have the position offset with respect to the initial point.

The major penalties incurred are a substantial increase in computing complexity and the need to use high dynamic range sensors capable of measuring much higher rates of turn [37].
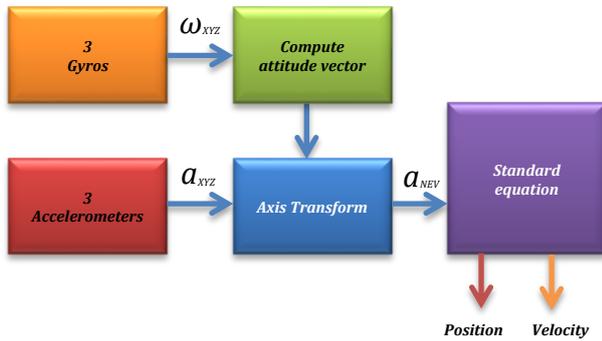

Fig. 5. Strapdown INS unit block diagram.

A. INS Errors Assessment

The essential General Error Equations block diagram representation of the error model is given in Fig. 6. The diagram shows the Schuler's loop and other cross-coupling terms which give rise to longer-term oscillations (see Fig. 6) [38].

An inertial navigation system over long periods has 3 type of errors which propagate of time and are characterized by three distinct frequencies:

Schuler's oscillation

The Schuler's oscillation has a period of:

$$\omega_s = \sqrt{\frac{g}{R_0}} \qquad T \approx 84.4 \text{ min}$$

and is present in both horizontal channels [39].

Focault's oscillation

The Foucault's oscillation has a period of:

$$\omega_f = \Omega \sin L \qquad T = \frac{2\pi}{\Omega \sin L} \approx 30 \, h$$

and can be considered a modulation of the Schuler's oscillation [40,41].

24 h Oscillation

The 24 h Oscillation has a period of:
$$\omega_e = 15°/h \qquad T = 24 \, h$$

and it is obviously equal to the period of rotation of the Earth [42].
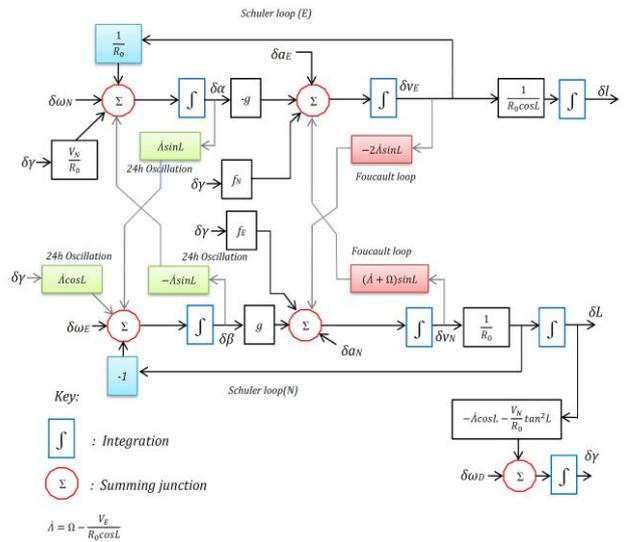

Fig. 6. INS Errors Assessmen.t

Generally, the full error model in the previous section is required to assess the performance of inertial navigation systems operating for long periods of time: for our glider applications, flight times are typically of the order of 2-3 days rather than weeks [43, 44].

Unlike an UAV system, in our case, the inertial navigation error terms cannot be neglected: an aerial drone has a rather limited mission time and therefore all long-term oscillation periods can be absolutely deleted in the

calculation of the position. In our case, however, they cannot be neglected but not only: they also have a considerable weight, as they would critically contribute to the overall error.

All of these fixes help minimize the INS platform error: however, at every denomination, the error is cancelled due to the connection to the GNSS system, as seen in Fig. 7. The GNSS measurements are used to update the *Kalman's* filter estimates the INS position, velocity and attitude errors [45]. These errors are then subtracted from the indicated position, velocity and attitude provided from the INS forming an optimal estimate of the true position [46].
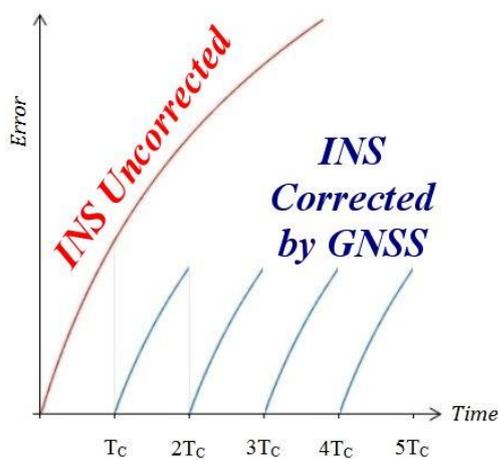

Fig. 7. INS Error drift in time: corrected and uncorrected.

VI. PAYLOAD MANAGEMENT

The GCIS delivers the properly conditioned power for all the necessary services. It also collects all the scientific data produced by the payload itself [47-50]. The system also frequently monitors the payload "health": if a serious failure occurs, emergency mode is immediately commanded and therefore the emersion of the vehicle as it misses the primary purpose of the mission [51-53].

VII. CONCLUSIONS

A centralized control system called "Glider Integrated Control System (GICS)" was invented for the glider management. GICS monitors the buoyancy and attitude control (subject of another paper), handles the payload by taking care of the entire data package that it provides and of all communications with the "outside world".

The most important part is the navigation control, based on an INS system that controls the glider trajectory and ensures that the various dive/rise cycles of the mission are carried out correctly.

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