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Research Article

Design and Simulation of the Guidance and Control System for Gliding Munitions

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ABSTRACT

In this paper, a fixed wing, tail fin controlled gliding munition has been designed. A guidance and control system is developed for the designed model and the glide towards the target is tested in the XPLANE 11 flight simulator environment. The simulation was carried out in two stages, both in the software loop and in the hardware loop. After the munition system is released from the aircraft, it measures the angles that will enable gliding to the target coordinates with the guidance system and starts to control fin movements. It compares the instantaneous position data received from GPS with the target position data. With the LOS method, the pitch angle is found by comparing the heading angle required to reach the target and the instantaneous altitude information with the target altitude information. The angles found are compared with the information from the IMU sensor and the errors are processed in the PID controller. The output of the PID controller is converted as a PWM signal to the tail fins in accordance with the munition dynamics. The system was transferred to XPLANE 11 and scenarios with different initial conditions were tested.

Introduction

With the advancements in technology, military operations have seen the use of various weapon systems. Guided bombs, also known as aerial guided munitions, are one such system that can strike land and sea-based targets from a distance with air strikes [1, 2, 3, 4]. However, the fact that these systems do not have any propulsion engine causes their range and maneuverability to be limited [1]. Hence, the aircraft carrying the munitions has to come close to the target to execute the operation, increasing the risk of approaching enemy defense systems [5]. To minimize risk and ensure accuracy, the munition system's range, maneuverability, guidance, and control system must be designed accordingly.

The gliding munition is designed to precisely hit the target by gliding towards the target coordinates after being released from the aircraft [6, 7]. Since it doesn't have its own propulsion system, it must be released in the direction of the target coordinates with the initial speed and altitude. Figure 1 shows that the released ammunition goes through two stages. The first stage aims to maximize the glide ratio, while the second stage involves the diving phase of the munition when it gets close enough to the target.

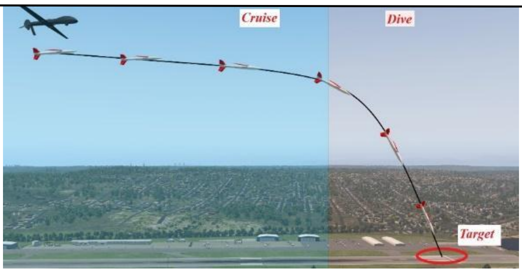

Figure 1. Release of gliding munitions from the aircraft towards the target.

The aim of this study was to design an efficient guidance and control system (GNC) that directs munitions towards their targets, while also contributing to the literature by testing the system in an alternative simulation environment. A conceptual munition model was developed to analyze and optimize the guidance and control system. The design of gliding munitions is influenced by various internal and external factors, as they are designed for a specific mission [8]. Additionally, hardware or software related problems may arise in guidance and control systems [9]. To address the complexity of the design process, a test setup was created, which involved real-time testing of a conceptual model for the software in the loop (sitl) and hardware in the loop (hitl) forms of the guidance and control system design. For this test setup, the XPLANE 11 flight simulator application developed by Laminar

Research was chosen, which allows for custom aircraft designs, real-time simulations, and data transfer [10].

Material and Method

This section addresses the theoretical foundation and essential components required to develop a Guidance and Control System (GNC) that effectively directs munitions towards their targets. The study elaborates on the integration of subsystems that form the basis of the GNC system, how these subsystems come together to create the main system, the critical electronic components necessary for the system's functionality, and the design of the conceptual model. This approach aims to thoroughly examine the aspects of the munition guidance process, thereby maximizing the designed system's capability to reach its targets.

Guidance

In order for gliding munitions to hit their target accurately, an accurate guidance angle and pitch angle are required. The Line of Sight method can be used to determine these angles.

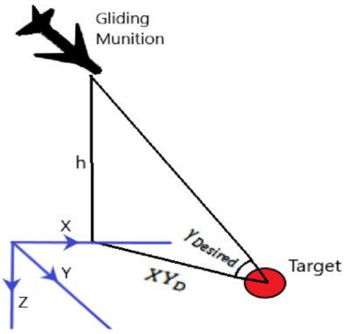

Figure 2. Desired yaw and flight path angle [11].

In Figure 2, XYD represents the distance between the aircraft and the target in the XY plane of the Earth's fixed frame. The variable h indicates the height of the missile relative to the target. According to the figure, the desired flight path angle, as determined by Equation (1), is needed for ensuring optimal trajectory alignment and effective target engagement [11].

$$\gamma_{Desired} = atan\frac{h}{XY_D} \tag{1}$$

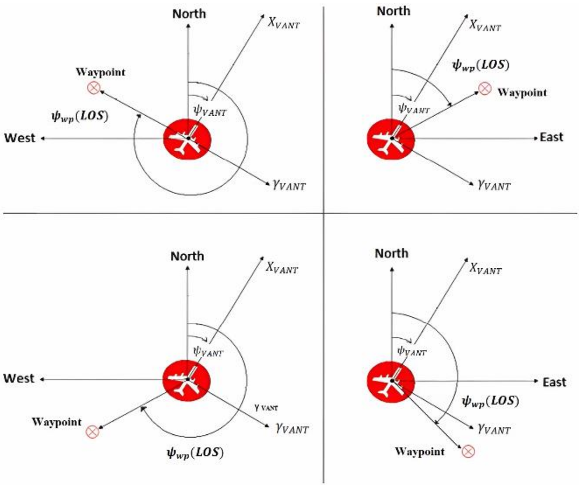

Figure 3. Line of Sight [9-10].

Equation (2) calculates the direction angle, which provides the output in an angle format ranging between 0 hand 360 degrees. However, it is necessary to convert these angles between -180 and +180 degrees while determining the trajectory of the gliding munition [12].

$$LoS = atan2\left[\frac{Lon_{Target} - Lon_{aircraft}}{Lat_{Target} - Lat_{aircraft}}\right] \tag{2}$$

Direction and flight angle values are inputted into the control system to glide towards the target.

Control

To ensure the aircraft maintains the desired roll and pitch values, the instantaneous data is compared to them. Any deviation from these values is processed using PID control. The output generated by this process is then used to control the motors of the tail flaps. The control system schematic is shown in figure 3. [13].

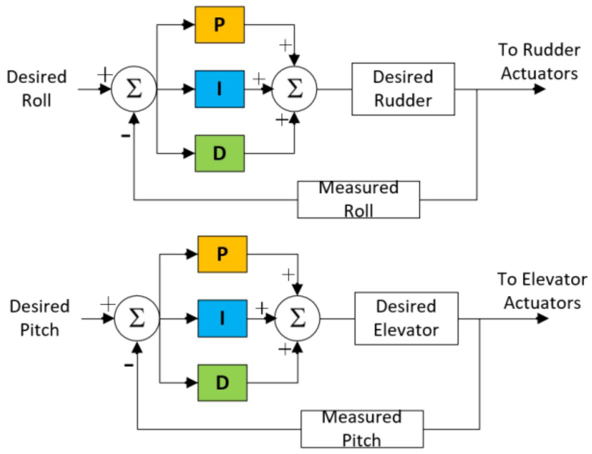

Figure 3. Block Diagram of PID Control System on UAV.

The control system shown in Figure 3 is critically important for ensuring the gliding munition progresses towards the target effectively and accurately. It corrects deviations in the munition's roll and pitch by detecting them and adjusting through a Proportional-Integral-Derivative (PID) control loop. Proportional control responds proportionally to the difference between the munition's current state and the desired target, while integral control balances cumulative errors over time, ensuring long-term accuracy. Derivative control mitigates sudden changes, contributing to system stability. Correction signals are transmitted to the fin actuators, adjusting the movements of the munition's control surfaces to achieve the desired trajectory. The accurate setting of PID control constants—Proportional (Kp), Integral (Ki), and Derivative (Kd)—balances the system response speed and stability necessary for the munition to progress towards the target in a stable and controlled manner [6, 14, 15]. The PID control system was utilized in the X study, and parameter optimization was experimentally updated. In this study, PID parameters will be experimentally determined within the simulation environment to achieve the desired performance criteria.

Guidance Navigation Control System Design

To ensure that the gliding munition reaches its target, it needs to follow a specific path while controlling its fins. To achieve this, a Guidance Navigation Control (GNC) system was developed that is based on navigation, guidance, control systems [16]. Figure 4 displays the blocks for navigation, guidance, control, flight mode selection, and data transfer of the designed GNC system.

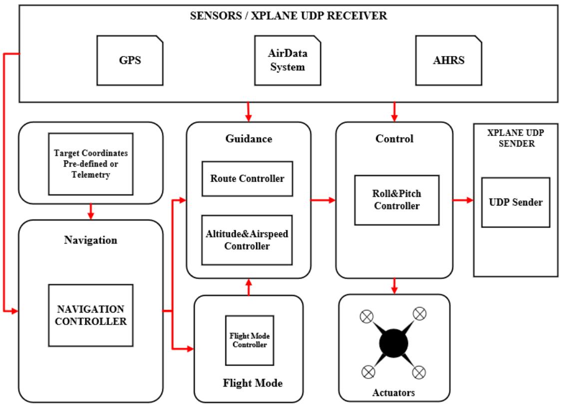

Figure 4. The GNC system architecture.

The data shown in Figure 4 is obtained through sensors or the XPLANE 11 UDP Receiver block. The system outputs are sent to the aileron actuators or the XPLANE 11 Sender block. In the Navigation block, GPS data is received instantly and compared with the target coordinates. The desired heading angle value is then found and sent to the route controller, while the distance to the target value is sent to the flight mode selector. The flight mode is selected based on the distance to the target, speed, and altitude. When the munition enters the area determined by its location and condition, the transition from the first phase, where the glide rate is kept at maximum, to the second phase, involving diving to the target, is realized.

The Guidance block consists of two subsystems - the Route Controller and the Altitude&Speed Control block. The desired heading parameter is the input to the Route Controller, which calculates the roll angle required to achieve the desired heading angle and transmits its output to the main control block. The Altitude&Speed control block receives speed, altitude, and flight mode as input. When operating under the first mode, it sends the required pitch value to the main control block to ensure minimum altitude loss by maintaining the altitude and speed ratio. When operating under the second mode, it sends the required pitch value to the main control block according to the distance and altitude to the target to perform the dive. The Roll&Pitch control block processes the required flight angles provided as input by the PID controller and generates outputs. The fin actuators of the munition or the XPLANE 11 UDP Sender block receives PWM signals as output. This structure allows for sitl and hitl simulations, ensuring the gliding of the ammunition system to the target.

Electronics

A gliding ammunition electronic system has been designed to ensure gliding, route creation, and tracking. The STM32F407VGTX board was preferred as the main controller due to its easy accessibility, low cost, and high number of ports that enable modifications to be made in future studies [17]. For target and instantaneous coordinate calculations, Radiolink SE100 GPS was chosen, while Waveshare 10 DOF IMU Sensor was preferred to calculate the angular and speed states of the aircraft [18, 19]. The smart munition has four servo motors for the rear fins and one servo motor for the front wing. The tail servos ensure that the gliding munition stays on the flight path to reach the target coordinate, while the front wing's servo is used to open the initially closed wing after it is released from the aircraft. For aircraft-ground station communication, the LORA SX1278 telemetry model was preferred. Figure 5 shows the electronic schematic of the gliding ammunition [20].

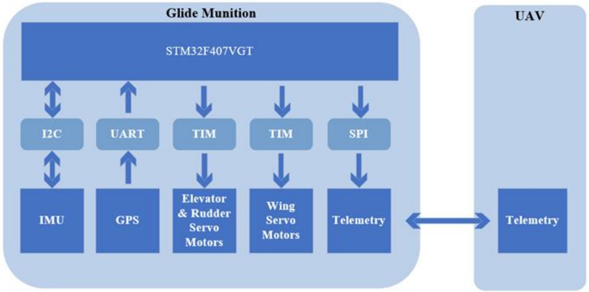

Figure 5. Electronic schematic of gliding ammunition.

Munition Model

A design concept was developed for an ammunition structure that could accommodate the guidance and control system. The design takes into consideration the containment of both the electronics and the warhead, as well as the range and glide rate parameters. Despite the complexity of the control mechanism associated with the x configuration for the tail fin design, it is preferred due to its high lift-to-drag ratio [21], which is crucial for gliding systems. Figure 6 shows the 3D design of the structure.

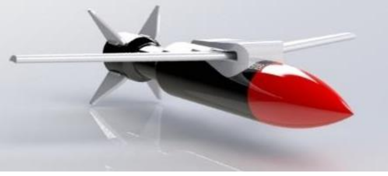

Figure 6. Gliding munition Model.

Simulation

This article reports on a simulation experiment that was conducted using the XPLANE 11 flight simulator application. The GNC system was tested using MATLAB SIMULINK's SITL function. The communication between the Simulink-created system and the XPLANE 11 application is shown in Figure 7, which utilizes the XPLANE fixed wing UDP Sender & Receiver blocks [10].

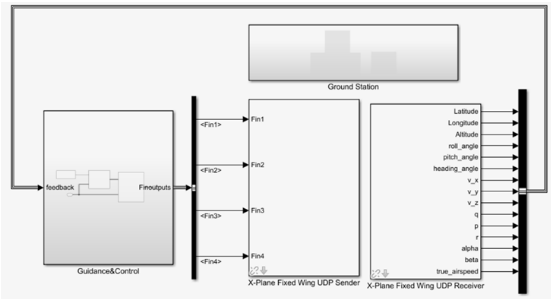

Figure 7. XPLANE 11 Sender&Receiver Blocks and GNC system.

To simulate the HITL (Hardware-in-the-Loop) scenario, a prototype was created using a 3D printer, and the necessary electronics were installed. The electronic system and the computer were connected via USB TTL for serial communication. Furthermore, the Plane Maker tool was utilized to create the ammunition structure in the XPLANE 11 simulation environment. Figure 8 illustrates the experimental setup formed by the SITL and HITL systems.

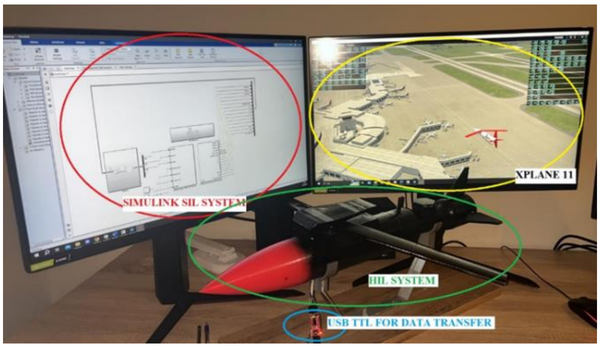

Figure 8. Experimental setup.

After several rounds of testing, the PID parameters were experimentally established as indicated in the table below:

Table 1. PID Parameters

Controller	K_p	K_i	K_d
Roll Controller	1.6	0.02	0.05
Pitch Controller	1.5	0.1	0.01

The simulation phase began with setting up the experimental environment and creating a flight application model. Figure 9 displays the flight control screen and a simulation sample output.

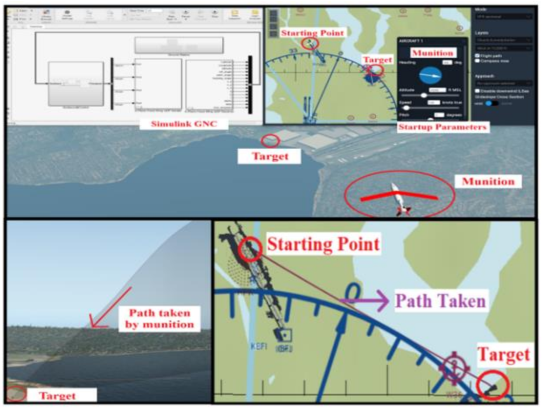

Figure 9. Flight display and munition trajectory.

Figure 9 illustrates the release of the gliding munition towards the target at a particular altitude and speed as specified in the mission description. The release scenario were tested in 2000 m and 150 heading degree with 60 knot releasing speed.

Simulation Results

The simulation test conducted reveals the glide path of the munition released from an altitude of 3600 meters and a heading angle of 150 degrees, as visualized in Figure 10. In the scenario, the trajectory followed by the gliding munition is depicted with a black-purple line to enhance visibility. This graphical representation not only highlights the precise route taken by the munition towards its target but also underscores the importance of visibility in tracking and analyzing the effectiveness of the munition's glide path. The use of a distinct color scheme aids in clearly distinguishing the trajectory amidst various environmental and operational variables, facilitating a more intuitive understanding of the munition's performance throughout its descent.

Figure 10. Glide path of munition released at 3600 m and 150 Heading Degree.

Figure 10 shows the glide path of the gliding munition towards the target point when released from an altitude of 3600 metres and a heading angle of 150 degrees.

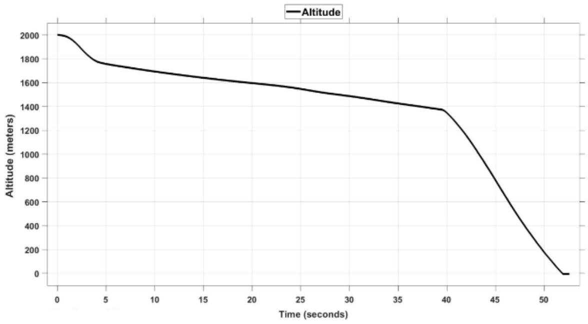

Figure 11. Altitude graph of munition released at 2000 m.

Figure 11 displays in detail the altitude profile of the gliding munition released from 3600 meters during its operation. This graph demonstrates how the munition loses altitude in response to air conditions and aerodynamic effects and how altitude control is achieved while it glides towards the target.

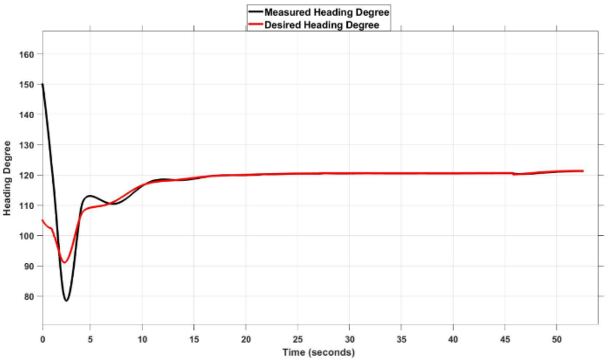

Figure 12. Heading degree graph of munition.

Figure 12 shows the changes in heading angles that a gliding munition, released with a 150-degree initial heading angle, needs to achieve and actually achieves throughout its mission to accurately reach the target. This graph helps to understand which angular adjustments are applied to direct the munition towards the target and how accurately this process is managed.

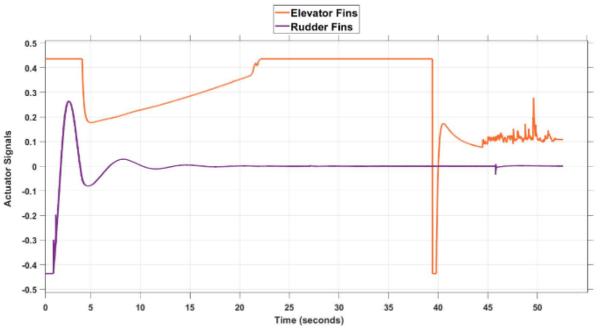

Figure 13. Elevator and Rudder Fin Actuator Signals.

Figure 13 focuses on the actuator signals for the elevator and rudder fins, integral components that facilitate the munition's maneuvering capabilities. The control mechanism receives these fundamental signals and converts them into appropriate motion commands for the munition's complex control surfaces in the 'X' configuration, namely the elevons and ruddervators. This conversion process is carefully calibrated according to the munition's aerodynamic profile and the maneuvering requirements of the mission scenario, ensuring that the munition can be precisely directed towards its target.

Findings

During the experimental phase, the munition was analyzed in a scenario. The result demonstrated that the munition accurately hit the target in test scenario. In particular, the munition successfully hit the target at an altitude of 3600 metres and with a heading difference of approximately 30 degrees, demonstrating that the GNC system provides the desired results in this area and that the XPLANE 11 application can be used to develop and test this system. These results show that the guidance and control system design is effective and suitable for various operational scenarios, and that the XPLANE 11 application can continue to be used in future studies during the simulation phase.

Conclusions

This study tests a GNC system operating on a gliding munition. Specifically, a PID controller based on the Line of Sight theory is tested in a simulation environment. The testing is performed as SITL between the GNC system developed in the SIMULINK environment and the XPLANE 11 application.

The results of the simulation tests indicate that the gliding munition system can hit the target with a high degree of accuracy, as long as it has sufficient altitude and is operating in suitable weather conditions. The lack of an engine on gliding munition systems means that they must exhibit efficient control behavior, which was demonstrated in this study through the designed GNC system.

In addition to the simulation testing, the prototype production of the gliding munition was completed, and its electronic systems were integrated. A communication link was established using serial communication between the prototype's electronic system and XPLANE 11, facilitating tests on the electronic hardware in SIMULINK and guiding future research. The tests were conducted to determine if communication and control could be effectively maintained through the Hardware in the Loop (HITL) format during simulation, and successful results were obtained. Future studies will implement the full scenario over the hardware to further validate the system's capabilities.

Future studies should focus on optimizing the conceptual design of the model for the mission and improving the response of the controller to ensure precise hits even in harsh weather conditions. Overall, this study represents an important step towards the design and performance improvement of gliding munition systems. A new GNC system has been designed and demonstrated to be testable in Xplane 11. Further studies will be conducted to meet the requirements of the defense industry and to improve operational effectiveness.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

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