

Enquiring the Accuracy of Mortar Shells via Smart Fuses with Additive Manufacturing

Papakitsos C.¹, Simos V.², Mouzakis D.E.¹, Panagiotopoulos I.¹, Nasikas N.¹, Papakitsos E.²

¹Laboratory for Mechanics and Defence Applications (LAMDA), Hellenic Army Academy, Vari, GREECE

²Department of Industrial Design & Production Engineering, University of West Attica, Egaleo, GREECE

Corresponding Author: papakitsev@uniwa.gr.

Abstract

This thesis examines the design and implementation of intelligent fuses engineered for flexible integration across diverse projectile platforms, thereby enhancing interoperability and extending the operational lifecycle of existing munitions stockpiles. The scope encompasses the complete development lifecycle, incorporating an illustrative analysis of the underlying codebase. By integrating pre-trained machine vision or infrared homing models alongside artificial intelligence methodologies, the system facilitates autonomous terminal guidance while maintaining robust resistance to electronic countermeasures. The architecture operates strictly under the “fire-and-forget” paradigm, completely precluding human intervention or external signal reliance during flight, which fundamentally differentiates this approach from conventional smart munition systems. In this respect, the usage of additive manufacturing is enquired on how to enhance the easier construction of munition parts in the field for conversion purposes.

Keywords: Autonomous munition, smart fuse, mortar shell, additive manufacturing.

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I. INTRODUCTION

Although the deployment of smart munitions originated approximately three and a half decades ago, rapid technological advancements necessitate a continuous re-evaluation of established terminology. Military regulations and academic literature, even those dating back to the 1990s, reflect definitions dictated by the technological capabilities of their respective eras. Autonomous munitions possess the capability to strike all target categories in an optimal manner, determined by user-defined criteria. The processes of target detection, localization, identification, and tracking are fully automated, operating entirely without human intervention. Consequently, these munitions enable target engagement based on the degree to which predetermined operational parameters are fulfilled, while the final decision to execute the strike remains strictly autonomous.

Modern armed conflicts, particularly those between advanced military forces in the realm of fire support, demand enhanced range and increased firepower precision. A primary advantage of smart and autonomous munitions lies in their minimal required pre-launch preparation, which significantly reduces operator training requirements. Furthermore, key characteristics of these modern munitions include an extended operational range and full compatibility with existing weaponry platforms.

Regarding their operational range, this has expanded both spatially and temporally with the introduction of loitering munitions. These autonomous systems can be deployed from existing land, naval, or aerial platforms. Loitering munitions are capable of prolonged autonomous flight within geofenced areas or along predetermined routes to detect and autonomously strike target categories in accordance with programmed rules of engagement. By combining extended loitering times with autonomous self-guidance upon target acquisition, they offer forces effective area-denial capabilities aligned with Anti-Access/Area Denial (A2/AD) doctrine.

A primary advantage of autonomous munitions lies in their operational capability within heavily contested electromagnetic (EM) environments, leveraging technologies suited for GPS-denied scenarios, such as 3D terrain matching. In this study, munition modifications are explored on how to operate independently of external data sources, including user remote guidance or any form of EM signaling, including GPS [3, 4].

Furthermore, this study focuses on the category of converted or modernized autonomous munitions. These systems comprise conventional (non-smart) munitions, currently present in large stockpiles within most national arsenals, which are rendered autonomous through the integration of autonomous sensors. The benefits of this modernization scheme are manifold. First, it offers a cost-effective life-extension for legacy weapon

platforms nearing retirement, as the integration of such munitions dramatically increases their lethality, often rendering them comparable to modern counterparts. Second, rapid technological advancement alongside the relative absence of large-scale operations among modern armed forces has created substantial conventional reserves; these assets risk operational obsolescence against adversaries equipped with autonomous systems due to the “first-hit defeat” doctrine. Finally, deploying converted autonomous munitions decentralizes advanced strike capabilities to lower tactical echelons, reducing reliance on higher-tier fire support and yielding a more lethal, timely, and responsive combat support structure.

Consequently, this study presents the core definitions adopted herein and clarifies related terminology frequently confused with smart munitions. Then, it presents the research and development process for constructing smart fuses in two cases of existing mortar shells, enquiring the feasibility of their conversion by the usage of additive manufacturing.

II. DEFINITIONS

According to leading defense manufacturers, smart munitions are defined as those that utilize trajectory-correction methods at various stages of their ballistic flight toward the target. Diverse mechanisms exist both for executing these corrections and for detecting the required spatial adjustments. Broadly speaking, the definition of smart munitions incorporates a closed-loop control sequence consisting of targeting-error detection, error calculation, and the implementation of appropriate corrective force [7]. Based on the degree of human intervention within each stage of this sequence, smart munitions can be categorized into guided, smart and autonomous systems.

Guided munitions operate under the “one-munition-per-target” principle, requiring the operator to remain within the feedback loop (man-in-the-loop) to select the target and direct the projectile. This is achieved via electro-optical or infrared imaging sensors, or through target designation via a laser beam emitted by the operator or a third-party observer, enabling continuous trajectory adjustments toward the illuminated target

Smart munitions, conversely, operate on the “many-to-many” target principle. The technological advancement introduced by these munitions brought cruise-type systems to the fore, effectively removing the human operator from the control loop immediately post-launch. Utilizing satellite navigation sensors (GPS-GNSS), these munitions continuously adjust their flight characteristics to achieve terminal guidance toward targets, selected prior to launch. Consequently, they can approach designated targets with high precision without operator intervention, often leveraging unexpected approach vectors and altitudes. Furthermore, these systems execute real-time trajectory corrections by combining positional data from onboard sensors with optical imaging, matching camera feeds against pre-processed, stored target images or infra-red (IR) spectra.

Although the aforementioned definitions appear self-explanatory at first glance, they embody key dimensions that highlight the full spectrum of advantages offered by modern munitions. Primarily, they optimize the cost-benefit analysis due to their exceptionally high lethality [8]. The precision of modern munitions enables adherence to the “first-hit defeat” doctrine, allowing cost-effective systems to neutralize disproportionately valuable and expensive targets. This substantially reduces operational expenses, logistical support burdens, and collateral damage, thereby alleviating strain on supply lines and medical evacuation networks. Furthermore, their lethality complicates adversary operational planning regarding the deployment of high-value weapon systems, exposing them to precise fires at extended ranges with higher probabilities of destruction. Lastly, autonomous munitions are generally smaller and lighter, as enhanced targeting accuracy negates the requirement for large explosive payloads.

However, there are certain aspects that constitute converted autonomous munitions. Tracing the evolution of combat support munitions reveals that the initial technological leap occurred with the integration of smart sensors, which transformed conventional “iron bombs” firstly into guided and subsequently into smart munitions. The subsequent phase involved their transition toward full autonomy, enabling autonomous detection, identification, and engagement of diverse targets to achieve optimal terminal effect. The sole operational constraint accepted to maintain low conversion costs is that these munitions execute trajectory corrections of limited scope, as they lack dedicated propulsion systems unlike loitering munitions. Fundamentally, converted autonomous munitions represent existing conventional stockpiles that, through the addition of sensor suites, guidance packages, and the replacement of standard fuses with intelligent ones, are converted into autonomous systems, thereby multiplying their operational lethality.

III. FUSES

This section analyzes the structural composition and categorization of fuses utilized in indirect-fire munitions [10]. Fuses constitute the forward, typically detachable component of curved-trajectory projectiles, serving to initiate the primary explosive charge to neutralize the designated target. Generally threaded onto the nose of the shell prior to firing, they allow operators to configure firing modes via mechanical or electronic settings to control detonation upon reaching or impacting the target area. Because individual fuse models rarely

support all initiation modes, operators may need to deploy varied fuse types across different firing missions. Consequently, based on target characteristics and armor protection, the selection ranges from point-detonating and time fuses to intelligent fusing systems.

Point-detonating fuses are suitable for heavily armored targets, initiating upon impact or, via appropriate delay settings, with a micro-delay to enable the penetration of reinforced concrete fortifications. Conversely, proximity and time fuses are tailored for soft-skinned targets and exposed personnel distributed over a wide radius; consequently, they are configured to detonate at a specified height above ground level. These fuses employ diverse methodologies and sensor suites to achieve airburst functionality. Certain variants function based on elapsed flight time calculated by the Fire Direction Center (FDC) and set directly onto the time fuse, whereas others utilize electromagnetic radiation sensors to actively determine the optimal burst height above a designated area target.

Smart fusing systems and precision projectiles are categorized into two primary classifications: those that execute trajectory adjustments via Satellite Navigation (GPS), and those that deploy a parachute at a specific terminal altitude to search, detect, and engage targets by dispensing a secondary submunition (such as the US Copperhead). The latter represents an independent classification of precision projectiles rather than a mere fuse assembly, whereas the former comprises modular fuse kits designed for integration into existing conventional munitions, albeit constrained by reliance on GPS signals.

3.1 Structural Architecture

The structural architecture of fuses has remained fundamentally unchanged over time, as their initial design was tailored to fulfill precise operational requirements (Figure 1, Source: see [11]). The core functional sequence executed by a fuse encompasses arming, initiation, and the transmission of the explosive wave to the main charge, which collectively dictate its primary components and internal mechanical layout. Chronologically, these functional stages are delineated as follows.

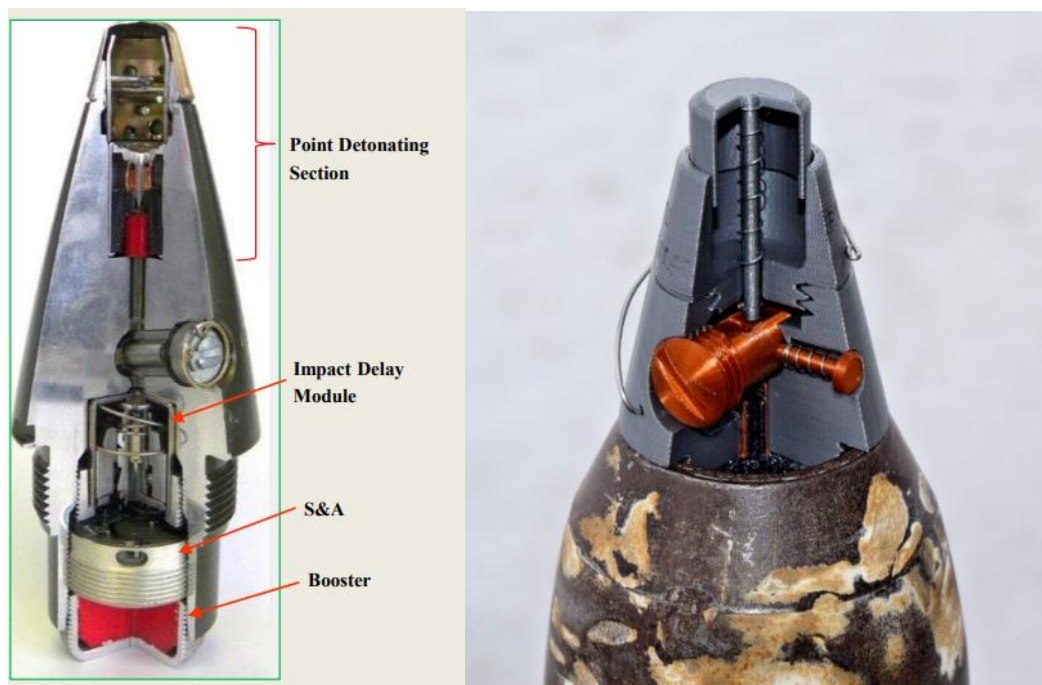


Figure 1: Illustrative 3D models of mechanical fuses

Following projectile launch (Figure 2, Source: see [12]), fuse arming is achieved through various mechanism designs. These mechanisms are typically mechanical and, depending on flight dynamics, arm the system either upon attaining a specific linear acceleration threshold during launch or via centrifugal forces generated by spin velocity induced by barrel rifling. Subsequently, initiation occurs (depending on fuse architecture) either mechanically upon direct target impact or indirectly upon fulfilling predetermined temporal or altimetric criteria, as outlined above. At this stage, the power delivery function warrants explicit mention, particularly regarding smart fuses, as it provides electrical power to onboard sensor suites. Finally, the explosive wave is transmitted to the main charge through the initiation of dedicated detonator caps.

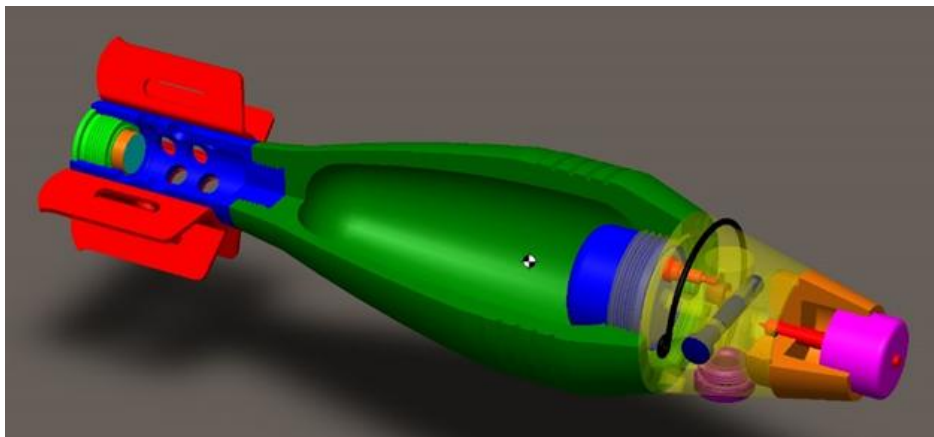


Figure 2: 3D model of a complete 60 mm mortar shell

As established, the aforementioned operational functions govern the internal structural configuration of the fuse assembly, directly informing the architecture of smart fuses regarding component layout. Specifically, the explosive train initiation mechanisms are situated at the rear of the fuse, followed sequentially by the arming mechanisms. The forward section houses the initiation electronics along with the user interface components designated for pre-launch setting configurations. The power supply module is typically integrated within the initiation section, utilizing either stored chemical energy via batteries or miniature air-driven turbines (dynamometers) positioned at the nose of the fuse assembly.

3.2 Smart Fuse

This study addresses the design and fabrication of an autonomous, smart fuse for indirect-fire projectiles. The system modifies the projectile's ballistic trajectory toward the target via control surfaces, which are regulated by a microprocessor using autonomous guidance algorithms. The fuse was developed to ensure compatibility with various projectile calibers, requiring only parameter adjustments within the correction software. Adaptation across different calibers is achieved either by integrating the core components into a 3D-printed outer shell of appropriate dimensions or by employing an adapter on the base fuse structure, thereby enhancing operational interoperability and cost-effectiveness.

The main structural and functional sub-assemblies of the fuse are structured as follows:

1. The **Outer Shell** must satisfy strict maximum cross-sectional constraints, while providing adequate internal volume for both static and dynamic components. Although sized herein for 4.2-inch mortar shells (Figure 3, Source: C. Papakitsos), the geometry can be scaled to other calibres. Its compact length and minimal electronics mass aim at preserving the overall projectile centre of gravity.



Figure 3: The outer shell for 4.2-inch mortar projectiles

2. The **Microprocessor Unit** should be positioned centrally. Two modules have been tested: a Raspberry Pi Zero 2 W board (Figure 4a, Source: [7]) for the mortar shell of 81 mm, and Arduino Micro (Figure 4b, Source: C. Papakitsos) for the mortar shell of 4.2-inch. They are evaluated for high performance-to-mass ratio, Python compatibility, and sufficient computational power to execute machine learning algorithms for target recognition. Larger calibre applications can accommodate higher-performance processing units.

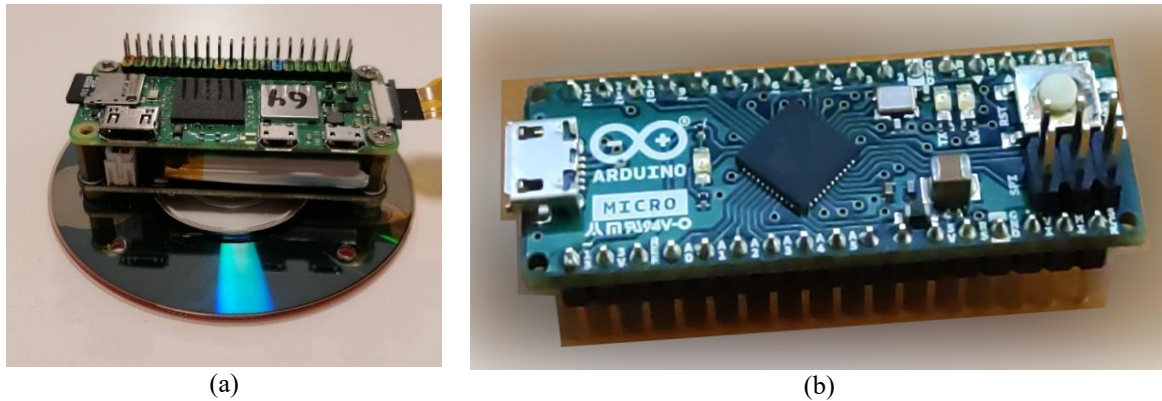


Figure 4: The microprocessor units

3. The **Sensor Suite** (Figure 5a, Source: [7]) is mounted at the forward section (Figure 5b, Source: C. Papakitsos) to ensure uninterrupted data acquisition. The suite may comprise an optical or IR sensor for target detection, a gyroscope for attitude tracking, and an accelerometer to supply arming data. Incorporating an optical sensor requires stabilizing the projectile along its spin axis. Another infrared distance sensor was evaluated but temporarily excluded due to structural design complexity.

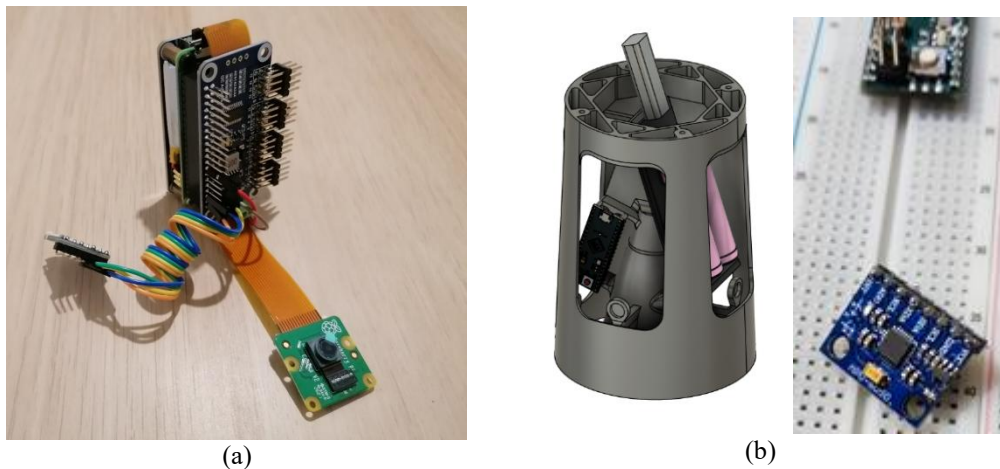


Figure 5: The sensor suite

4. The **Control Mechanisms** are composed of four independently actuated control surfaces featuring some proper aerofoil profile (Figure 6a, Source: C. Papakitsos), accordingly, to minimize adverse aerodynamic effects. These surfaces can be mounted either on folding or not mechanisms, in the former case designed to deploy post-muzzle exit. In addition, stabilization fins maybe required if absent in the original shell, as in the 4.2-inch mortar shell (Figure 6b, Source: C. Papakitsos).

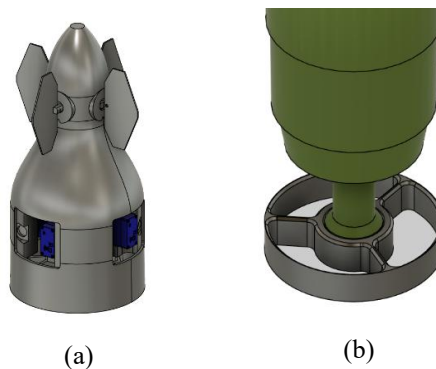


Figure 6: The control mechanisms

5. The **Actuation Systems** should consist of four independent servomotors, driving each control surface (Figure 7, Source: C. Papakitsos). Simultaneous actuation presented a power delivery challenge, requiring mitigation against voltage drops that could cause microprocessor failure. Independent control was deemed essential to execute simultaneous three-axis attitude corrections (pitch, yaw, and roll), while maintaining level flight to optimize guiding-sensor data acquisition.

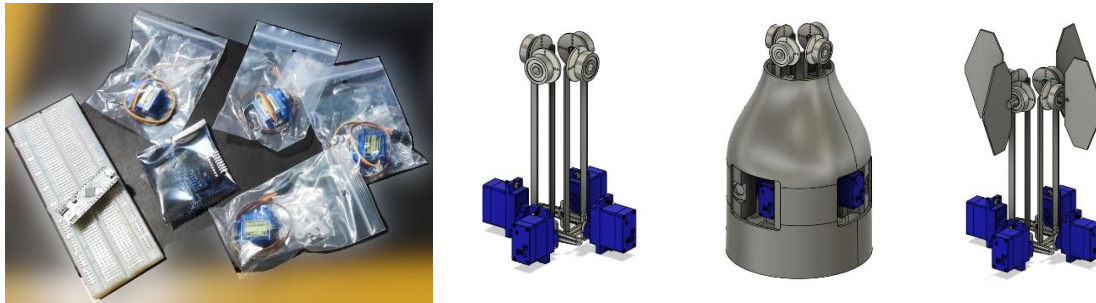


Figure 7: The actuation systems

6. The **Power Supply Unit** must be located in the lower section. Two modules have been tested: a 3.7 V rechargeable LiPo battery (Figure 8a, Source: [7]) for the mortar shell of 81 mm, and two rechargeable 18650 3000 mAh batteries (Figure 8b, Source: C. Papakitsos) for the mortar shell of 4.2-inch. Despite limited energy capacity, their chemical discharge characteristics support the high current draw required for concurrent servo operation, though extreme environmental conditions and long-term storage present potential operational limitations.



Figure 8: The power supply units

7. The **Arming and Fusing Mechanisms** are situated at the base of the assembly. These subsystems were not developed in this study, as interoperability requirements dictate the integration of standard conventional mechanisms.
8. The **User Interface** is designed as an electronic switch configuration, actuated via a rotating selector ring. This enables manual input for target classification (for machine learning model selection) and detonation mode parameters (adjusting sensor search ranges).

To clarify the operational framework of the smart fuse, its functional cycle is categorized into three sequential phases: data acquisition (sensor input), processing, and output of corrective control commands. A representative execution cycle is defined as follows:

- a) **Shell Launch:** The initial firing sequence follows conventional mortar operations without modification. Ballistic parameters (including azimuth, elevation, and propellant charge configuration) will be determined identical to those for standard, unguided shells.
- b) **Muzzle Exit and Initialization:** Following muzzle exit, minimal or no control interventions are applied during the initial flight phase. Intervening at peak velocities would demand excessive actuator power and may adversely distort the ballistic trajectory, impairing accuracy. During this stage, the control surfaces deploy wherever necessary and lock into position, while the sensor suite and core electronics are fully powered.

- c) **Zenith Reach and Guidance:** Guidance interventions initiate when the gyroscope detects a predetermined pitch angle relative to the horizon, signalling that the shell is approaching its trajectory peak. Attitudinal pitch measurement via gyroscopic sensing can be selected over barometric altimetry to reduce system design complexity. Utilizing a PID control algorithm, the actuators adjust the control surfaces to stabilize and level the airframe. This roll-and-pitch stabilization should be maintained for the remainder of the flight to preserve the optical sensor's horizon alignment. Concurrently, a pre-trained computer vision model for the 81 mm shell initiates target search [7]. Upon target detection, the flight computer generates real-time surface deflection commands to keep the target centred within the visual field until impact.

Secondary functions encompass the arming and fusing mechanisms. Although essential for warhead detonation, these processes do not govern the autonomous guidance algorithms and rely on standard existing architectures [5].

IV. CONSTRUCTION

During the initial design phase of the fuse, processor selection posed a critical challenge due to strict volumetric constraints. The physical dimensions of the microprocessor directly correlate with its computational capacity, thereby complicating software integration. Furthermore, given the diameter of the targeted shell calibers, alternative mounting orientations (i.e., transverse versus axial relative to the flight line) were evaluated. This spatial configuration directly influences fuse height, affecting total projectile length and overall aerodynamic stability. To minimize alterations to the shell's center of gravity and ballistic profile, an architecture that maintains a low-profile fuse geometry should be selected. Accordingly, different overall configurations have been constructed and assessed for the 4.2-inch mortar shell (Figure 9, Source: C. Papakitsos).



Figure 9: Different overall configurations for the 4.2-inch mortar shell

A further engineering constraint involves the control surface deployment mechanism. The primary approach considered stationary servomotors coupled to the fins via mechanical linkages. An alternative design integrated the control surfaces directly onto the servomotors, rotating the entire actuator assembly into the operational flight position.

Mechanical operations involve control surface deployment during the unfolding sequence, as well as continuous actuation adjustments during trajectory correction [2, 6]. The deployment mechanism encompasses

two primary phases: initial unfolding and mechanical locking into the flight position. Accordingly, two candidate mechanical configurations were evaluated:

- i. **Torsion Shaft Folding Mechanism:** Control surfaces are stowed parallel to the shell's longitudinal axis. Upon deployment, they lock along the unfolding axis, with steering actuation transferred from the servomotors via mechanical linkage arms. Despite its increased design complexity, this approach minimizes axial length requirements, maintaining a compact fuse profile.
- ii. **Full Actuation Assembly Rotation Mechanism:** The control surface deflection axis aligns directly with the servomotor output shaft. Unfolding requires the rotation of the entire servomotor assembly to which the fin is mounted. While this design provides superior structural rigidity and mechanical simplicity, it exhibits two key disadvantages: it demands greater internal volume to accommodate the rotating servomotor housing, and the absence of mechanical leverage increases load demand on the actuator, impacting response latency and torque endurance.

In overall, the modification of adding a newly designed smart fuse to existing ammunitions, particularly as exhibited herein in the case of the 4.2-inch mortar shell, poses significant technical and operational considerations. The former ones include ballistic and construction issues. In terms of ballistics, the addition of the extra parts of the smart fuse shifts the centers of gravity and pressure, thus affecting the smooth trajectory of the shell. To compensate for this shift and achieve aerodynamic stability, the addition of ballast might be necessary; yet, this extra weight will certainly reduce the range of the shot. In terms of construction, the materials for the additive manufacturing of the smart fuse must withstand the temperature and the forces exerted during firing. This necessity affects the selection of proper materials, as well as their usage in specific positions of the construction; therefore, different materials in different places inevitably complicate the manufacturing process. Finally, regarding operational considerations, the usage of smart fuses on mortar shells intended for soft targets is of questionable efficiency and cost-effectiveness. Unlike hard targets (e.g., armoured vehicles or naval vessels), training a smart mortar fuse through machine vision to strike soft targets, mostly stationary, is impractical at least, due to their variety of image traces. Even IR homing doesn't work well in this case. Therefore, the development of smart mortar munitions seems worthwhile for intended hard/moving targets, as it appears so far.

V. CONCLUSION

Certain constraints were identified during various development phases of this study, driven primarily by system complexity, and specific technical limitations. Nevertheless, the factors that delineated the scope of this implementation are explicitly detailed below.

Experimental numerical simulations of the fuse were conducted through specialized computational fluid dynamics (CFD) software, to generate reliable aerodynamic data [1, 9]. Consequently, empirical tuning of the Proportional-Integral-Derivative (PID) control parameters governing control surface actuation were preliminary performed. Notwithstanding several limitations, the implemented approach yields actionable insights regarding the feasibility of autonomous fuse integration and offers a scalable framework applicable to a broader range of conventional ballistic munitions.

Transitioning from the proof-of-concept prototype to a fully mature production model revealed substantial engineering challenges. Design analysis indicated that full-scale deployment requires long-term strategic architectural decisions that are planned for the next stages of this research.

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