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Assessment of a last line of defense counter-UAV effector

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Abstract
There is an urgent need to develop systems that allow neutralization of the threat posed by Unmanned Aerial Vehicles. Different technologies can be assessed for different scenarios. Kinetic effectors are a viable option if collateral damage can be controlled. Present work aims to develop a systematic methodology to assess kinetic effectors in their use as Counter Unmanned Aerial Vehicle system. In particular, this work determines the ballistic limit of a specific UAV shell for a dedicated Counter Unmanned Aerial Vehicle effector, in order to understand how a potential operational use can be optimized.

1. Introduction

The commercial Unmanned Aerial Vehicle (UAV) market is becoming a mature worldwide sector [1] [2]. The misuse of UAVs, whether motivated by malicious intent or by ignorance, can lead to disastrous harm for society. Examples range from operational hindrance and financial repercussions at airports [3] [4], potential mass-casualty attacks [5], terrorism [6], wartime use [7] and are certainly not limited to a restricted number of cases [8].

Each scenario must be assessed independently with the common objective to avoid harm to society. Therefore, the common aim is to prevent the potential effects of a UAV action. A consistently used structured approach for this is the kill chain. There are several variations as *Find, Fix, Track, Target, Engage, Assess* (F2T2EA) [9] or *Detect, Identify, Respond and Report* [10] or more generally *Detection, Tracking, Identification and Neutralization* (DTIN) [11]. The former Engage phase and the latter Respond phase can be categorized as neutralization phase. An appropriate response or engagement will aim to prevent the potential effects of a UAV action. Hence, it is a phase in which the threat must be neutralized.

The scope of present work tackles this neutralization phase. '*Low, Slow and Small*' UAVs (LSS UAVs) defined by the NATO Class I Unmanned Aircraft Systems [12] category pose specific challenges that are difficult to handle with conventional air defense systems since the scenarios in which these air defense systems are used are generally different from the scenarios in which the LSS UAVs are deployed [13]. An urgent need exists to develop dedicated Counter UAV (CUAV) systems.

Currently, several technologies are being implemented to develop neutralization CUAV systems. Technologies range from directed energy weapon systems as high energy lasers and high-power electromagnetic systems, to jammers, spoofers and hacking devices, to entanglement systems (nets) and to unguided and guided kinetic effectors [14] [15]. The discussion on the benefits, drawbacks and implementation requirements of each technology can be the subject of an entire research project as there are many aspects to consider. However, the main conclusion to understand is that different technologies shall be used in different scenarios.

Directed energy weapon systems have been known for decades and currently encounter several implementation barriers [16]. Jammers, spoofers and hacking devices target the wireless communication link between UAV and remote

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controller (i.e. the operator). It means that, if no wireless communication is required for the normal action of the UAV, then jammers, spoofers and hacking devices become less effective. This case can occur in a near future since autonomous UAVs are investigated incrementally to execute a specific mission independently [17]. Entanglement systems are promising for scenarios in which collateral damage is a significant parameter. However, due to the inclusion of a physical net, the ranges at which it will travel cannot be tuned in a flexible manner. The major aspect to consider in the use of kinetic effectors is the reduction of collateral damage. If this can be controlled, kinetic effectors can handle the previously mentioned drawbacks of the other technologies, certainly in the future growing presence of autonomous UAVs.

This is the reason why present work proposes a structured and systematic methodology to assess kinetic effectors on their effectiveness against the intended target and their risk for collateral damage. As a practical example, a particular last line of defense Counter-UAV (CUAV) effector will be used.

A first step in the appropriate use of a kinetic effector is to understand its behavior during flight. In other words, the comprehension of its trajectory must be conceived. It is commonly accomplished by selecting an adequate trajectory model that is complemented with empirically determined parameters that characterize the effector [18]. One typically enters the study of Exterior Ballistics for this step.

In the general case, an effector is a projectile. Once the projectile is launched, it travels towards the intended target and its kinetic energy can likely be transferred to the target upon impact. Since the trajectory of the projectile is terminated upon impact, one passes into the study of Terminal Ballistics. A commonly accepted approach to study the effect of an impact of a projectile on a target is to examine if the projectile *penetrates* the target at a *given projectile velocity* [19]. In this case, the target is the UAV shell. The use of specific ballistic limits allows quantification of a velocity for which penetration occurs. One could imagine that penetration is a binary characteristic: the projectile penetrates the target or it does not. However, in practice, one relies on stochastic tools to assess penetration and its related velocity, as some projectile velocities might result in both penetration and non-penetration. Hence, the considered velocity is a statistical parameter denoted by v_x that represents the velocity for which x impacts out of 100 (i.e. x%) will penetrate the target, considering one impact is related to one shot of one projectile [20]. An accepted primary parameter is the v_{50} ballistic limit, for which 50% of projectiles will penetrate the target. It is this v_{50} that will be used in present work. The interpretation of a penetration is prone to subjectivity. Typically, an impact is accepted as a penetration when it causes a crack or hole that allows light to pass through or results in visible damage. However, since the scope of present work considers CUAV systems, an impact will be considered to be a penetration if a residual velocity can be measured. The motivation for this is that the impacting projectile should be able to transfer kinetic energy on internal components of the UAV, since a penetration of its shell solely will likely not result in the neutralization of the threat.

In the remainder of this work, section 2 will introduce the previously mentioned last line of defense CUAV system and will introduce the employed materials and methods for modeling the trajectory and for the determination of the ballistic limit on the target. In essence, section 2 will provide a structured and systematic methodology to assess kinetic effectors in their use as CUAV system. Section 3 will discuss the results specifically for the last line of defense CUAV system. Section 4 will ensure the main conclusions are captured and will highlight which aspects of the ongoing research can be expanded.

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2. Materials and methods

2.1 Weapon system

The last line of defense CUAV system of present work is a weapon system composed by the firearm and an ammunition. Their assumptions have been introduced in preliminary work [21]. For completeness, the main characteristics are presented below. The studied ammunition is fired with the firearm shown in Figure 1. It is a Benelli M4 12Ga [22].

Figure 1: Firearm of the CUAV system – Benelli M4, M1014 variant [22]

The studied ammunition, presented in Figure 2, is the 12 Gauge ADLD ammunition from the manufacturer Mary Arm [23].

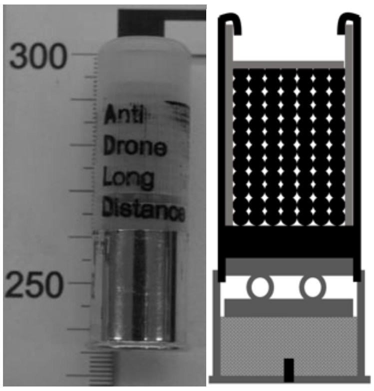

Figure 2: Photograph and schema of the ammunition [24]

An exploded view of the ammunition is provided in Figure 3. It consists of: 1) a primer, 2) a metal casing, 3) the propulsive charge, 4) a plastic wad, 5) a cork wad, 6) a number of pellets (approximately 200 pellets with a diameter of around 3mm and a mass of 180mg), 7) a shot cup and 8) a plastic casing.

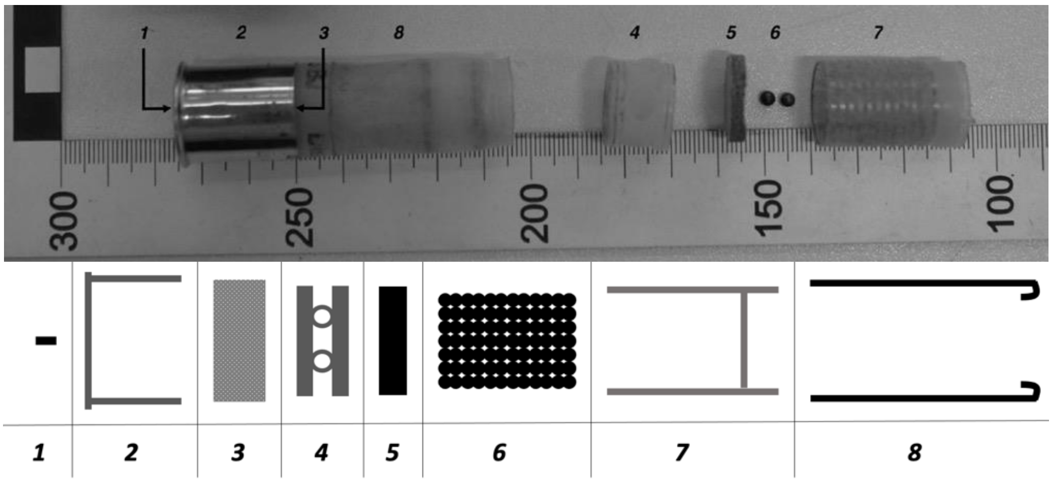

Figure 3: Exploded view of the ammunition [25]

It must be understood that the term pellet is used to represent one of the spherical objects in the shot cup, while the term projectile is used to represent all pellets and the shot cup combined. The pellets are characterized by the values in Table 1.

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Table 1: Properties for the pellets of the dedicated C-UAV ammunition

	Pellet diameter [mm]	**Pellet mass [mg]**
Sample size	24	24
Sample mean	3.10	182
Standard deviation	0.19	3.61

2.2 Trajectory modeling

The main purpose of previous work is to model the trajectory. The trajectory of the ammunition has been investigated extensively and the work results in the assessment of phases C and E of Figure 4. For the trajectory, phase A is called the firing phase, phase B is called the early flight phase, phase C is called the slug phase, phase D is called the discharge phase and phase E is called the pellets phase.

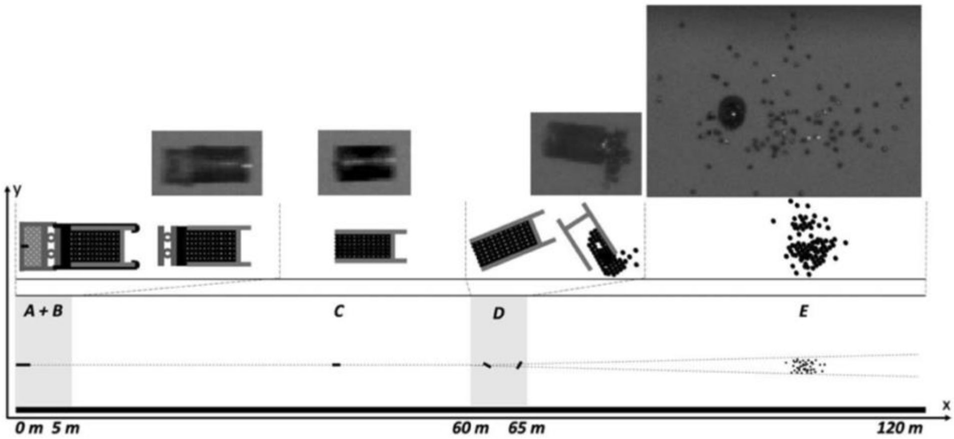

Figure 4: Schema of the trajectory phases

Since the purpose of the presented kinetic effector is to be employed as last line of defense system, short range engagement distances are envisaged. Moreover, the kinetic effector is not stabilized by rotation. With appropriate consideration of specific assumptions, a simplified trajectory model will be sufficient to represent the true trajectory for the purpose of this work. These assumptions have been elaborated in [21] and allow to conclude that the chosen trajectory model is a Point Mass Model (PMM). Additionally, the chosen trajectory model is a light weight model in terms of computational needs, which is appropriate for its intended last line of defense operational use.

The considered trajectory in phase C is the trajectory of the projectile, while the considered trajectory in phase E is the trajectory of a pellet. For both the projectile and the pellet, the zero yaw drag coefficient has been determined. To understand how the pellets discharge works, a pellet cone has been determined to represent the spread of pellets throughout phase E.

2.3 Ballistic limit of the UAV shell

Since the objective of the considered kinetic effector is to impact the target with a cloud of pellets, it is the ballistic limit of the UAV shell that must be determined for such a pellet. One accessible type of UAV that has been used frequently in security or safety incidents recently, is the DJI Phantom model [26]. Therefore, the ballistic limit will be determined for the UAV shell of a DJI Phantom. An example is provided in Figure 5.

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Figure 5: DJI Phantom upper shell used for determination of the ballistic limit

The setup for the test is represented in Figure 6. The weapon system, indicated by the letter W, is positioned such that its muzzle represents the origin of the system of axes. Hence $x_1 = 0$. It must be understood that the used weapon system is a laboratory cannon which allows to execute tests in a controlled manner. It is a 9mm laboratory cannon from the manufacturer Prototypa [27], built according to the CIP standard [28]. Note that the axes have been shifted to allow a better visualization in the figure.

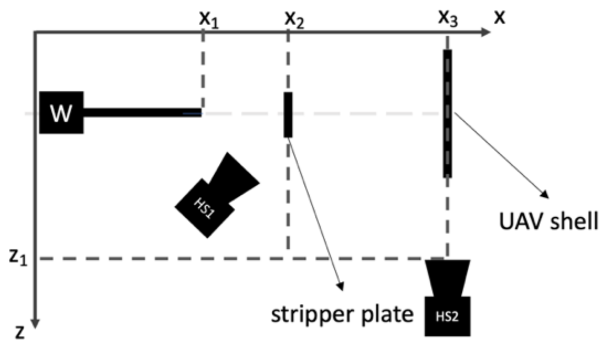

Figure 6: Test setup for the UAV shell ballistic limit

The stripper plate is required as sabots are used to carry the pellet throughout the cannon. Since the pellet diameter is in the order of 3mm, no appropriate launcher system was found that would avoid using sabots. To ensure the sabots do not influence the trajectory of the pellet, these are captured by a stripper plate that is represented in Figure 7. A high-speed camera (indicated by 'HS1') is positioned on the stripper plate merely as a means of observation to validate the correct capture of the sabot halves. The stripper plate is placed at a certain distance x_2 that must be recorded to ensure repeatability. Similarly, the UAV shell is positioned at a distance x_3 that must be recorded for repeatability.

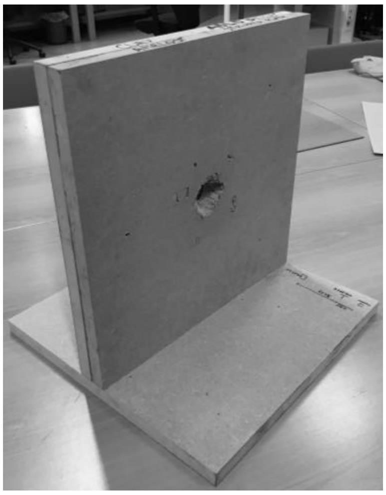

Figure 7: The stripper plate that is used to capture the sabots and that allows the pellet to pass through the hole.

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The laboratory cannon is a 9mm cannon. Therefore, the casing that is used is a 9mm casing and the sabots are 3D printed PLA+ elements that fit into the casing. Its composition is represented in Figure 8. Both sabot halves have a cavity of at least 3mm diameter that allows the pellet to be inserted in the sabots. The conical cavity on top of the sabot halves is introduced to allow the sabots halves to divert easily and rapidly during the early instances of the projectile's trajectory.

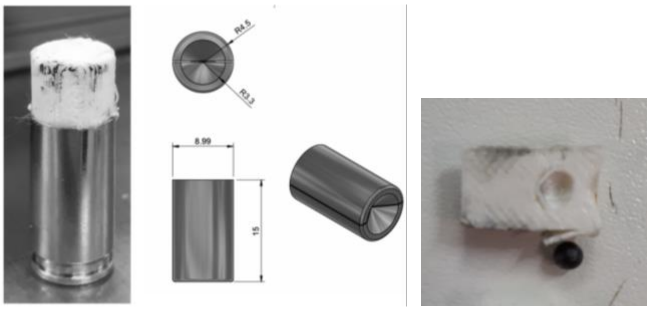

Figure 8: The combination of a 9mm casing and the 3D printed sabot halves.

To determine at which velocity the pellet impacts the UAV shell, a high-speed camera is positioned perpendicularly on the UAV shell. The high-speed camera is indicated with 'HS2' in Figure 6. After each shot, the impact will be assessed to determine if a penetration has occurred. Both high-speed cameras are Photron SA5 models [29], configured at a frame rate of 10000 fps and a shutter speed of 1/93000 seconds.

Once the setup has been finalized, an ammunition can be prepared with a certain propulsive charge mass. A direct determination of the velocity will allow, throughout all shots, to establish a relationship between propulsive charge mass and impact velocity. It is considered to be good practice to repeat the shots with a specific propulsive charge mass three times to obtain an average value for the velocity. After these three shots with one propulsive charge mass, one can pass on to increment (or decrement) the propulsive charge mass and repeat the process.

With this approach, certain velocities will lead to a penetration, while lower velocities will lead to a non-penetration. However, it must be highlighted that the '*mixed zone'* must be examined, since this will lead to the determination of the unique v_{50} value. The mixed zone indicates the velocities for which both non-penetration and penetration occur. Hence, the test must be conducted with the aim to sweep a range of velocities around a velocity value for which certain impacts result in penetration, while other impacts result in a non-penetration. This will indicate that the ballistic limit v_{50} has been found.

The dependent variable in this test is the penetration assessment and entails a binomial response (penetration or no penetration) to an independent variable, namely the pellet impact velocity. A preferred statistical method for analyzing binomial response variables is the Probit Analysis, originally introduced in [30] to calculate the standard deviation [31]. The application of the Probit Analysis will lead to an *s-curve* as schematized in Figure 9. A non-penetration is represented as a '0', while a penetration is represented as a '1'. The circles will typically be the outcome of the experiment, while the curve is the stochastically computed result by use of the Probit method.

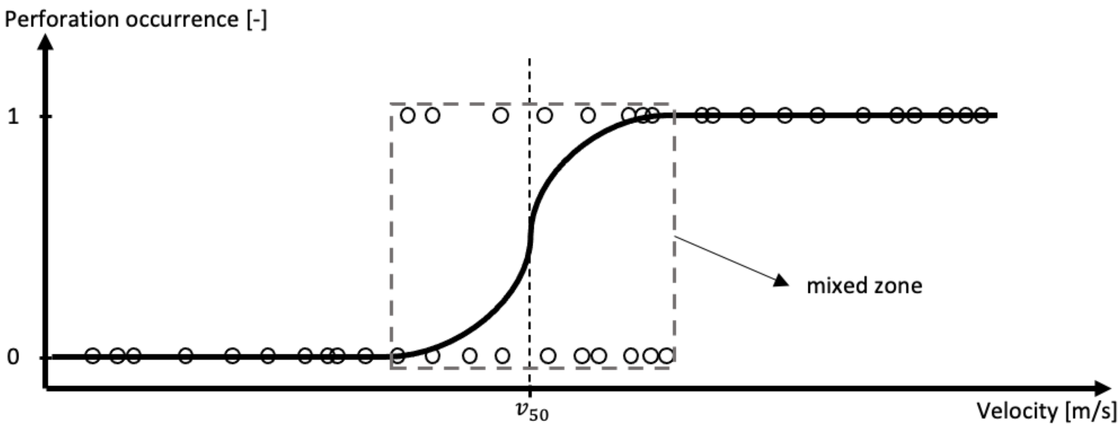

Figure 9: Typical shape of the result after processing experiment data with Probit Analysis.

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3. Results and discussion

3.1 Trajectory model

The construction of the trajectory model has been validated by executing several tests to observe agreement between theory and experiment, as elaborated in [21]. It results in the trajectory shown in Figure 10. Hence, the model and experiment agree when a model barrel elevation is fixed on -0.05° and a muzzle velocity of 396,48 m/s.

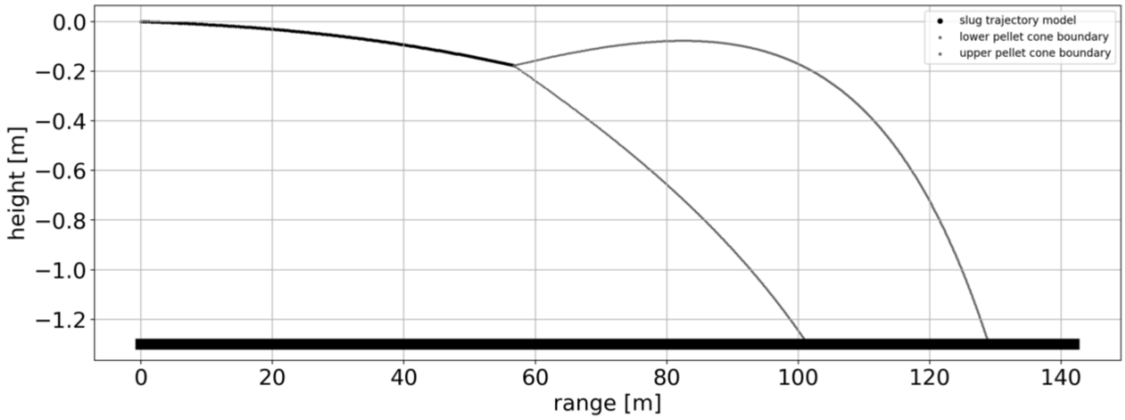

Figure 10: Result of the PMM with a barrel elevation of -0.05° and a muzzle velocity of 396.48 m/s [32].

The use of the previously introduced pellet cone allows to determine that potential impacts of pellets on ground vary, in orders of magnitude, between 100 and 130m when the projectile is shot with the parameter values discussed above.

3.1 Ballistic limit of the UAV shell

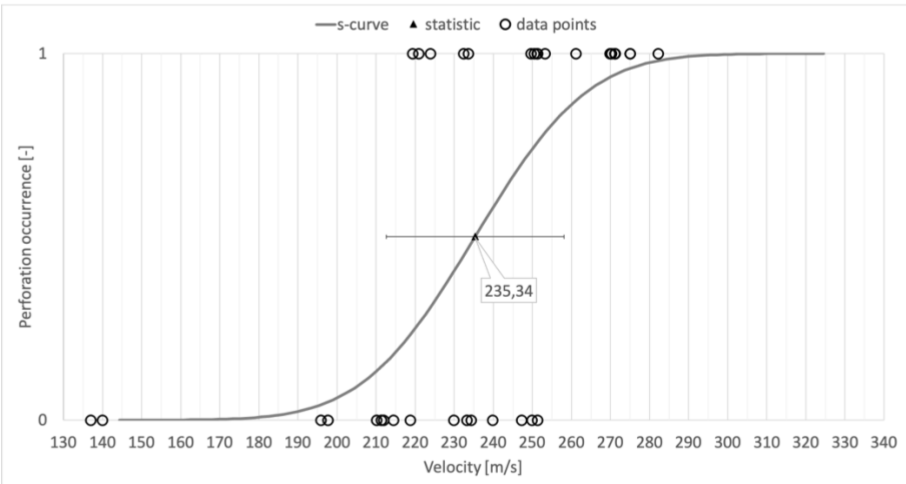

Figure 11: Results of the determination of the ballistic limit v_{50} of the UAV shell

The experimental determination of the ballistic limit v_{50} of the UAV shell results in the graph of Figure 11. The graph shows the experimental data points, relating a velocity value of a shot with an assessment of penetration. After applying the statistical computations elaborated in the section on Materials and Methods, it leads to the curve visualized as a solid line. A total of 24 shots has been executed on a total of 4 UAV shells. The pellets used for these shots are characterized by the properties in Table 1.

The conditions to validate a shot are that the pellet should impact on the flat surface of the UAV shell, that the pellet trajectory should not be influenced by sabots, that the impact should not occur near the borders of the shell and that the impact should not occur near another impact. The distance to border or other impact should be quantified in future work. Since the flat surface of a shell is relatively limited, 4 shells were needed to allow 24 valid shots. From the test

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results, it appears that the pellets of the ammunition presented in the introduction with the characteristic data introduced in Table 1 will penetrate the UAV shell in 50% of the shots at a velocity of 235,34 m/s. This result can be used to determine effective ranges for the studied kinetic effector. This velocity value can be associated with a range value through the trajectory model and will allow to determine for which ranges the kinetic effector can be implemented as a last line of defense CUAV system.

4. Conclusion and future work

This study presents the continuation of the trajectory modeling of a multi-projectile Counter UAV 12 Gauge ammunition in its use as last line of defense CUAV system. It is necessary to characterize how the ammunition behaves against a representative UAV model. A commonly used UAV model is the DJI Phantom family. In order to neutralize the threat, posed by the UAV, the studied kinetic effector must penetrate the UAV shell and perforate it in order to impact the internal components. Another option is for the kinetic effector to impact the propellers or motors, which are typically not covered by a shell.

The chosen trajectory model is a light model in terms of computation resources, which is required for the considered operational use of the presented kinetic effector. With specific assumptions, it allows to represent the trajectory sufficiently for the operational use. In present work, the ballistic limit of the UAV shell has been determined.

To study the use of the presented kinetic effector for its use as last line of defense CUAV system, it is necessary that several aspects are investigated. Firstly, the ballistic limit of the UAV shell should be assessed on the trajectory model to determine for what range value it is reached. Another future aspect to consider may be the fact that there are a couple of reasons why the penetration assessment on UAV shells does not provide a satisfactory solution. Firstly, procuring UAV systems, or even only the shells, solely for a penetration assessment can be a costly endeavour. Secondly, since UAV shells typically have complex shapes, each shot can impact the target under a different angle, hence resulting in different types of impacts. Additionally, the UAV shell has structural reinforcements to optimize material use. These challenges can be solved by use of an *equivalent plate* that represents the UAV shell *sufficiently*. Since it is mainly used for the penetration assessment, the equivalent plate should be characterised by same order of v_{50} value as the UAV shell. This will certainly be the case if one selects the same material as the UAV shell and if one allows minor differences in v_{50} values due to the difference in UAV shell shape and equivalent plate shape. Therefore, the selection of an adequate equivalent plate, after characterization of the UAV shell will allow to execute ample penetration assessments on the equivalent plate instead.

The v_{50} principle is applicable for the assessment of collateral damage as well. The purpose of assessing collateral damage is to understand the effect of an impact on human beings. The approach to investigate this is elaborated in a NATO standard [33]. It employs a skin surrogate based on a cloth of chamois leather, foam and gelatine [34] [35]. The standard provides a definition of penetration as well. With this skin penetration assessment, an impact is considered to be a penetration when the impact results in visible damage on the gelatine.

Once the ballistic limit of the equivalent plate and the ballistic limit of the skin surrogate are determined, they may be associated to a range value at which the pellets reach this velocity, similarly as for the ballistic limit of the UAV shell. Given the likely difference between these values, one can determine a zone characterized by two range values for which 50% of pellets will not penetrate the UAV shell anymore while still being a danger for skin penetration.

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