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Guided Air-to-Air Hard-Launch Munitions: A Case Study in Increased Mission Effectiveness

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Guided hard-launch munitions applied to aerial platforms for air-to-air combat are shown to both increase weapon system performance as a retrofit to existing platforms and allow for more efficient new combat aircraft designs. The aeromechanics of a family of medium caliber guided hard-launch munitions are simulated with a six degree of freedom model, and the effective range of these systems is juxtaposed with conventional gunnery and missile systems. Simplified air-to-air engagements are then simulated in real atmosphere to show circular error probable against a nominal maneuvering target. Two case studies encompassing the F-15 and F-35 fighter platforms were used to illustrate the reduction in required payload weight associated with interdiction of targets using guided hard-launch systems when juxtaposed with conventional air-to-air missiles.

I. Nomenclature

B = *Mott Coefficient*
C_D = *drag coefficient*
$C_{L\alpha}$ = *derivative of lift coefficient with respect to angle of attack*
$C_{l\delta}$ = *rolling moment due to fin deflection*
C_{lp} = *spin damping moment coefficient*
$C_{M\alpha}$ = *derivative of moment coefficient with respect to angle of attack*
$C_{M\dot{\alpha}}$ = *component of pitch damping moment coefficient due to angle of attack rate*
$C_{Mp\alpha}$ = *magnus moment coefficient*
C_{Mq} = *component of pitch damping moment coefficient due to pitch rate*
$C_{NP\alpha}$ = *magnus force coefficient*
$C_{N\dot{\alpha}}$ = *component of pitch damping coefficient due to angle of attack rate*
C_{Nq} = *component of pitch damping coefficient due to pitch rate*
c = *charge mass*
D = *projectile diameter*
E = *Gurney energy parameter*
g = *gravitational acceleration*
h = *angular momentum divided by transverse body moment of inertia*
I_x = *body axial moment of inertia*
I_y = *body transverse moment of inertia*
N = *number of projectiles*
m = *projectile mass*
P_h = *probability of hit*
P_k = *probability of kill*
S = *maximum caliber area*
t = *time*
t = *thickness*
V_m = *muzzle velocity*
V = *projectile velocity with respect to earth fixed coordinates*

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v = *projectile velocity with respect to wind axis*
$\bar{x}$ = *body unit vector*
α = *angle of attack*
δ_F = *fin deflection angle*
Λ = *Coriolis acceleration*
ρ = *atmospheric density*

II. Introduction

Guided hard-launch munitions have been developed for a variety of applications to increase weapons system performance and reduce circular error probable (CEP) on target when launched from surface platforms. To date, this technology has not been implemented on aerial platforms, though it has the potential to significantly reduce the overall cost to interdict targets, increase range of gunnery systems, and act as an enabler of airframe defense. This study serves as an introduction to the modeling of these systems through exterior and terminal ballistics and provides a first estimation to the combat performance of the munitions in air-to-air engagements.

A. Guided Hard-Launch Munitions

Hard launch munitions have been fielded on aerial platforms since nearly the birth of heavier than air flight. Early incarnations of aerial gunnery in the form of handheld pistols were utilized during the Mexican Revolution in 1913 (Ref. [1]). Fixed gunnery mounts would become the staple of hard launch systems from WWI up through present day, with most aerial platforms fielding mid-caliber munitions, i.e. 12.7mm through 105mm. Guided gunnery meanwhile, has surfaced in projects across small and large caliber munitions. Early incarnations of guided hard-launch systems include programs such as the M712 Copperhead, developed in the 1970s (Ref. [2]). This wing and tail configured 155mm munition has a range of over 12 miles and is still fielded at the present date. More recent incarnations of guided hard-launch munitions have increased in capability and taken advantage of adaptive materials (such as piezoelectric ceramics) for actuation. Improvements in subcomponent design has allowed more recent systems such as DARPA's M982 Excalibur, another 155mm round, to achieve ranges in excess of 20 miles (Ref. [3]). Smaller caliber guided rounds are also possible, such as the DARPA EXACTO: a 0.50 caliber guided sniper round. Applications to aerial gunnery would include munitions between these extremes and may be designed as a retrofit to existing platforms, or as an enabling technology that will ultimately reduce the overall weight and volume of future combat aircraft.

The stability and control schemes for hard-launch systems are also varied. Traditional tail sets, wing and tail configurations, canards, or other lifting surfaces may be used for stability and control. Other approaches not as familiar to the fixed-wing aviation community can include body deformation (by pivoting the nose or other portions of the body), bang-bang type control with pressurized gases or charges, or nose spike actuation. Guidance to target may be achieved in a number of ways similar to existing missile systems. Direct fire engagements may implement beam riding guidance, data links, or even wired commands. Indirect fire engagements may take advantage of data links, or if larger in caliber (greater than 40mm), GPS guidance is also possible. Some of the main challenges with hard launch system is the extreme volume constraints of the weapon system and the integrity of the round during the launch event (in which a round may experience in excess of 100,000g's of acceleration). These constraints dictate much of the actuator design and is one reason why piezoelectric actuation has seen increased utility in the hard-launch community. The first of these modern hard-launch programs for aerial gunnery was the Barrel-Launched Adaptive Munition (BLAM) program of the 1990's. This effort was the first to postulate enhanced P_h, P_k and effective ranges for all aerial gunnery missions.

B. Air-to-Air Engagement

The history of aerial combat, and most relevant, air-to-air combat, is rich and extends again back to the birth of heavier than air flight. A summary of US aerial engagements following WWII may be found in (Ref. [4]). Here, the author highlights how the scope of air-to-air combat has shifted from the acrobatic dogfighting of WWII to the long range and beyond visual range (BVR) engagements of the modern theatre. To address these needs, new weapon systems must be capable of supporting both direct and indirect fire. Fighter and interceptor aircraft for this reason have used missile systems since their introduction during the conflict over Vietnam. Conventional unguided gunnery cannot match the ranges of these systems and has thus not been emphasized in US fighter aircraft in recent platforms like the F-35. By lending guidance to these systems, not only can gunnery achieve useful CEP at these extended ranges, but also ammunition is more volumetrically efficient than soft-launch systems that require onboard propulsion packages, and stow volumes including either large bomb bays or external pylons. Guided gunnery systems are in effect, the pinnacle of weapon system compression if extended ranges and range performance may be demonstrated. This has significant implications for future airframe design in modern air-to-air combat as the total weight and volume required to interdict targets with a new aircraft is greatly reduced.

III. Munition Modeling

A family of munition models including tail guided and canard guided geometries were simulated using MATLAB. A six degree of freedom model for each of the bodies was constructed using a combination of theory and empirical data found in (Ref. [5]- [6]). Energy methods were used to simulate both the launch condition and terminal ballistics. Exterior ballistics were simulated with a fourth order method simulating the six degree of freedom equations of motion.

A. Interior Ballistics

To simulate the exterior ballistics and flight characteristics of the various projectiles, the flight state of the projectile upon muzzle exit must be defined as an initial condition. During the launch event, the projectile will have significant spin and tip off angles that are not desirable in some fin-stabilized projectile designs. Obturating bands may be used to reduce the spin imparted to the munition when retrofitted into rifled barrels. Tip off angles due to barrel whip may be compensated for as the round is actively guided to target. The muzzle velocity of the system for an arbitrary round geometry and composition is estimated with a simple energy analysis. For a gunnery system with a known projectile and cartridge, the new munition system muzzle velocity may be estimated assuming same total gun energy imparted to the projectile—proportional to the square root of the mass of the projectiles. For a retrofit of guided projectiles that implement the same cartridge and expulsive charge volume, the available gun energy imparted to the kinetic energy of the round is used to estimate the muzzle velocity of the modified projectile Eq. 1.

$$V_m = \sqrt{m_{conventional}/m} * V_{m,conventional} \tag{1}$$

B. Exterior Ballistics

The exterior ballistics of the system are modeled as an axisymmetric aerodynamic body following the methods of (Ref. [7]- [8]). The six degree of freedom equations of motion for an axisymmetric fin stabilized projectile in flight are given in Eq. (2) and Eq. (3).

$$\begin{aligned}\frac{d\bar{V}}{dt} = 1/(2m)\{&-\rho v\bar{v}SC_D + \rho SC_{L\alpha}[v^2\bar{x} - (\bar{v}\cdot\bar{x})] - \rho SDC_{Np\alpha}\left(I_x/I_y\right)(\bar{h}\cdot\bar{x})(\bar{x}\times\bar{v})\\ &+\rho vSD\left(C_{Nq} + C_{N\dot{\alpha}}\right)\left(\bar{h}\times\bar{x}\right) + 2m\bar{g} + \bar{\Lambda}\}\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{d\bar{h}}{dt} = 1/2\{&\rho vSD^2C_{lp}\left(\bar{h}\cdot\bar{x}\right)\bar{x}/I_x + \rho v^2SD\delta_F C_{l\delta}\bar{x}/I_y + \rho vSdC_{M\alpha}(\bar{v}\times\bar{x})/I_y\\ &+\rho SD^2C_{Mp\alpha}\left(\bar{h}\cdot\bar{x}\right)(\bar{v} - [\bar{v}\cdot\bar{x}]\bar{x})/I_x + \rho vSD^2\left(C_{Mq} + C_{M\dot{\alpha}}\right)\left(\bar{h} - \left(\bar{h}\cdot\bar{x}\right)\bar{x}\right)/I_y\}\end{aligned} \tag{3}$$

Stability derivatives and coefficients are found using the theoretical and empirical methods provided in (Ref. [5]- [6]) and vary based on projectile geometry and control surface specification. A fourth order Runge-Kutta method was used to integrate the equations of motion to simulate range performance.

C. Intercept Simulation

Terminal ballistics and guidance requirements for a given projectile geometry were modeled with a simplified intercept scheme against targets representative of aircraft and missile systems. A simple planar engagement was assumed, and the projectile exposed to real atmosphere in Simulink with a Von Kármán turbulence model (Ref. [9]). To minimize miss radius in an intercept, the projectile is fired along an unguided ballistic arc in a gross maneuver before guiding in terminal phase (fine pointing) to intercept along the flight path of the target as shown in Figure 1. An ideal control law developed in (Ref. [10]) was used to find the normal accelerations required to impact the target at a specified intercept angle, 180 degrees. From these normal force requirements, the deflections of control surfaces and bandwidths required to achieve intercept are determined for a given projectile geometry.

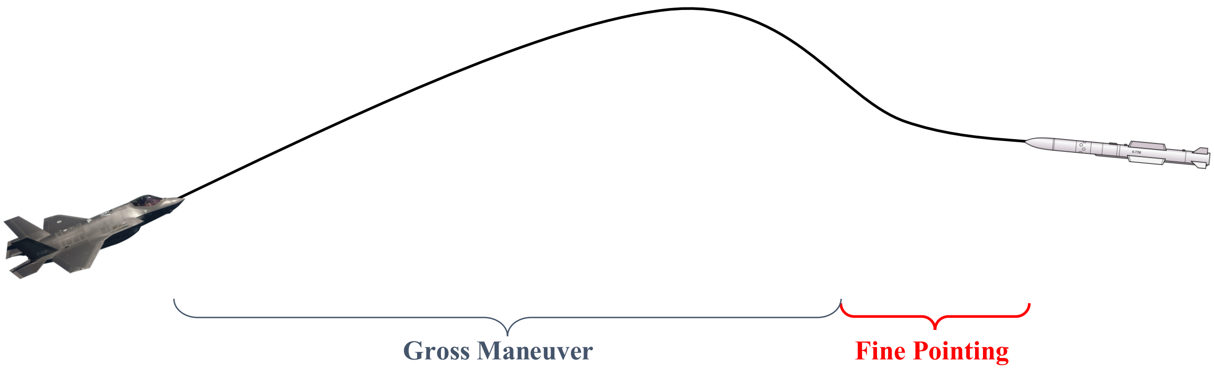

Figure 1: Interception Path

When intercepting a target, the probability of kill, P_k, is scaled from a known 20mm PGU-28 P_k value when interdicting lightly armored targets (Ref. [11]). The mass ratios of the projectile to the PGU-28 and the target to a nominal fighter aircraft are used to scale the quantity assuming lethality is directly a function of the kinetic potential of the round or mass of high explosive (HE) onboard the munition. The number of rounds to achieve a desired P_k level against conventional targets (aircraft and other lightly armored vehicles) may then be estimated for a given munition type, geometry, and target mass.

Proximity detonation is also possible when engaging smaller targets such as hostile missiles. In this interception scenario, when the munition achieves a prescribed standoff range, the frangible round is detonated, scattering a debris field in the flight path of the target. The lethal radius for a munition of a given HE composition was estimated with energy analysis using the Gurney method (Ref. [12]). The velocities of the metallic fragments given a mass ratio of metallic to explosive composition is given in Eq. 4. A cylindrical detonation pattern is assumed, and the flight path of the fragments projected forward into the flight path of the oncoming target is used as a probabilistic measure of target impacting debris.

$$V_{frag} = \sqrt{2E}(m_{metalic}/c + 0.5)^{-0.5} \tag{4}$$

Fragment size within the blast may then be estimated with the semi-empirical Mott formulation. The number of fragments of a given size N_m is determined from a distribution factor M_k as a function of munition geometric characteristics [12].

$$N(m) = M_0/2M_K^2 * \exp\left(-\sqrt{m}/M_K\right) \; ; \quad \text{where: } M_K = Bt^{\frac{5}{6}}D^{\frac{1}{3}}(1 + t/D) \tag{5}$$

The number of projectiles required to achieve a certain level of lethality or conversely the probability of kill given the number of impacts of a particular fragment size and the relative lethality of each, P_{kh}, may then be readily expressed as follows.

$$P_k = 1 - \exp\left(-NP_{kh}\right) \tag{6}$$

IV. Performance Analysis

The proposed family of guided hard-launch munitions were simulated first as a retrofit on existing airframes engaging in air-to-air combat. The investigation into range performance of a fin stabilized munition when fired from an F-15, F-35, and AC-130 aerial platform was used to juxtapose the potential of these rounds to meet modern aerial combat range requirements. The terminal engagement performance of these rounds was then simulated against a Su-35 and Mach 4 air-to-air missile (AAM). The number of rounds required to interdict each of these targets was investigated for both platforms accounting for environmental effects and miss radius.

A. Indirect Fire

The indirect fire support mission enabled by guided hard-launch munitions implementation was studied on two platforms with a series of tail stabilized munitions as shown in Figure 5. This geometry was scaled for use in the 25mm GAU-22/A and 20mm M61 Vulcan respectively. The effective range of these munition types was measured when fired from 305 m (1,000 ft) and 18,300 m (60,000 ft) in altitude MSL.

As shown in Figure 2, the range of the hard-launch systems match that of shorter range AAM (like the AIM-9) and exceeds the ranges of most air-to-air victories achieved to date by the US (Ref. [4]). This technology acts as an enabler for guided gunnery to enter into the beyond visual range (BVR) engagement scenario that modern fighters such as the F-35 Lightning II are designed to meet. Conventional unguided gunnery on the other hand, is limited to direct fire engagements generally less than 3,200 m (2 mi) in range.

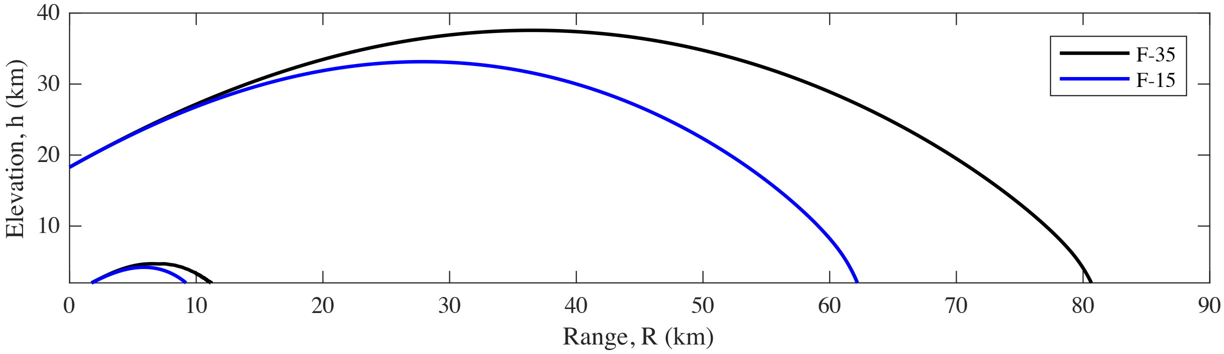

Figure 2: Indirect Fire Range Capability for F-35 and F-15 Platforms

The rounds used in this study implement the MASS system, a patent pending technology that allows for significant drag reduction in aerial hard-launch systems (Ref. [13]). Accounting for the MASS geometric alteration, the same mass of high explosive was used in the range studies above to maintain equivalent terminal effects and lethality of the projectile family.

The range of these systems may be further extended until comparable to most medium range AAM (such as variants of the AIM-120 AMRAAM) by significantly increasing the caliber. To demonstrate this potential, an AC-130U gunship was equipped with the MASS technology, and a simulation of a fin stabilized round fired from the M2 105mm cannon at the service ceiling of the aircraft was performed in Figure 3. Ranges on the order of 150 km were demonstrated while maintaining high levels of kinetic potential on target by nature of the semi-ballistic trajectory. In this circumstance, the AC-130 would roll to the right rather than the traditional air support mission where the gunship engages in direct fire by rolling left. This capability would allow the AC-130 to provide air support from extended ranges and over obstacles such as mountain ranges for time critical targets.

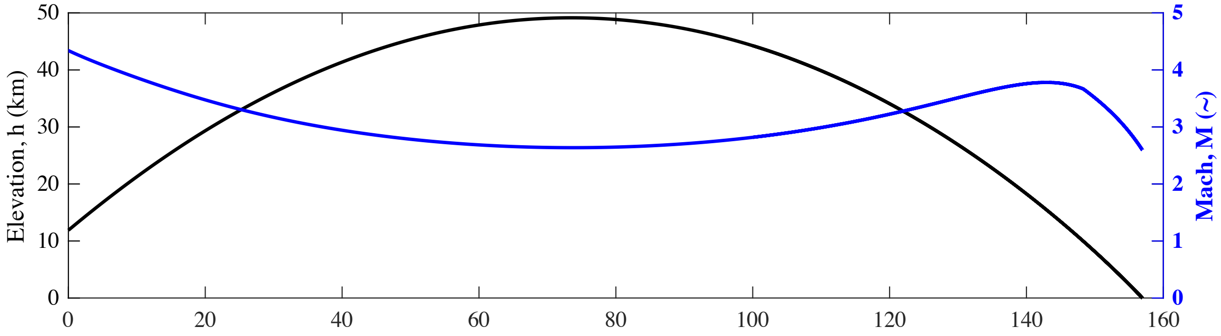

Figure 3: MASS Equipped AC-130 Indirect Fire

B. Terminal Engagement

A sample terminal engagement scenario is shown in Figure 4 where an aircraft fires the projectile to interdict a hostile AAM in a defensive overmatch maneuver. The methods for interception and modeling are described in detail in both Section III and Ref. [14].

The engagement environment describes the MASS equipped guided hard-launch munition intercept of a hostile AAM traveling at Mach 4 with a cross section of 0.2 m diameter. The munition is assumed to undergo indirect fire prior to this terminal engagement intercept and is assumed to have bled off kinetic energy: starting the intercept path at Mach 2.5 at distance of 3.2 km (2 mi) from the target. Atmospheric effects such as gusts are modeled for the flight of both the projectile and missile. The intercept path, directed along the flight path of the target, and the required control effector deflections for the canard configuration shown in Figure 5 are displayed for a single test case in Figure 4. Note, the buffet exhibited in the flightpath and effector deflections are the direct result of the non-Gaussian stochastic noise simulating the atmospheric gusts.

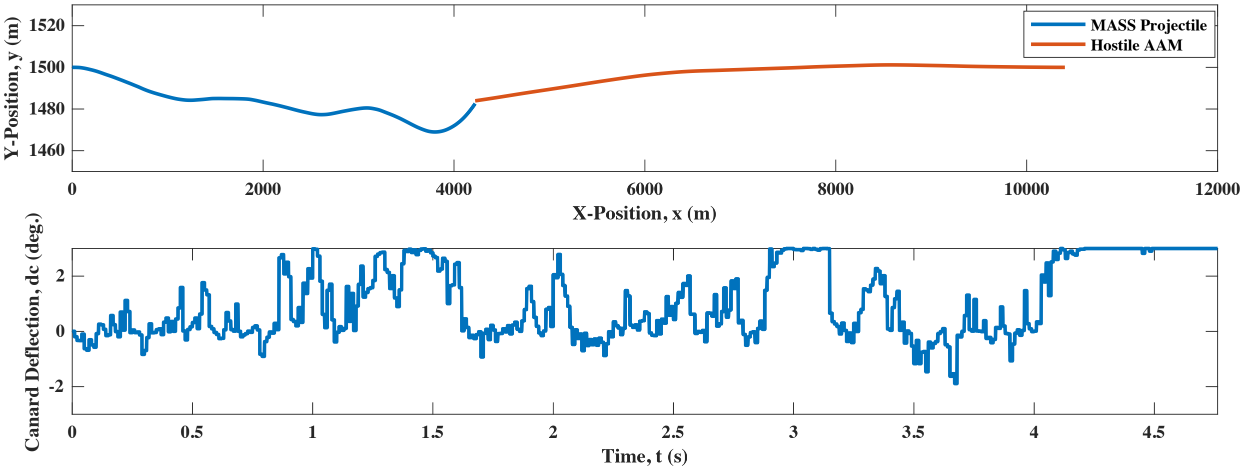

Figure 4: F-35 Sample Terminal Engagement Flight Path and Control Deflections

A Monte-Carlo type analysis of this engagement scenario was then performed for varying actuation bandwidth capability and varied target types. The limiting analysis case for the determination of actuation requirements is the missile intercept case as the highest response time and lowest CEP are allowable for successful target interdiction. Actuator bandwidths were varied from 10 Hz to 100 Hz against this missile type, and the resulting CEP for each series of simulations may be seen in Figure 5. The allowable miss radii using the relations found in Section III-C for this target type assuming a proximity detonation for this geometry was found to be approximately 0.3m.

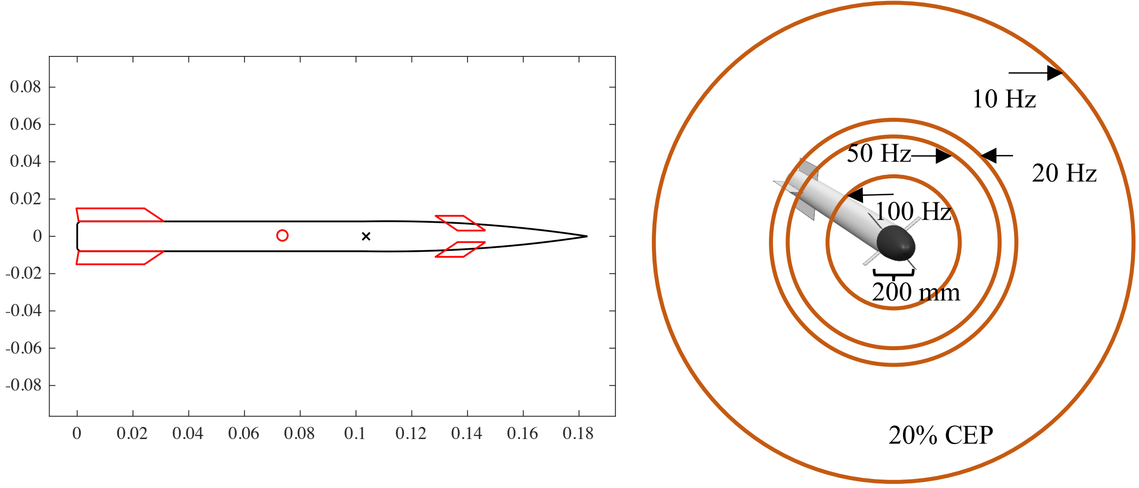

Figure 5: MASS Projectile Configuration and Scaled Bandwidth Circular Error Probable

C. Aircraft and System Performance Implications

With a retrofit of guided hard-launch munitions on aerial platforms, the ranges at which targets may be engaged and the total number of targets engaged by a given platform with gunnery may be increased substantially. Using the scaling laws discussed in Section III-C and the fin stabilized geometry specified above, the probability of a kill given a hit for these various platforms may be determined. From these data and the conventional air-to-air loadout of the F-

15 and F-35/A, the number of targets that may be engaged at a P_k of 95% is determined. The probability of a hit (P_h) is determined with the Monte-Carlo type simulation of the terminal engagement scenario discussed in the previous section for each geometry. For the target specified, a conservative P_h value of 90% from values found in Section IV-B for each caliber in the guided system, and approximately 5% in unguided systems was applied in the terminal engagement environment. A summary of the conventional gunnery capability and extended capability of each of the aircraft platforms when equipped with guided gunnery is given in Table 1. Payload weights to interdict ten targets assumes short range missile loadout (AIM-9) and gunnery kills (if possible for the platform), and includes gun weight excluding the feed system.

Table 1: Targets Engaged by System at 95% P_k

PLATFORM	STANDARD LOADOUT	CONVENTIONAL GUNNERY (ROUNDS REQUIRED)	GUIDED HARD-LAUNCH	W_{PL} 10 TARGETS	W_{PL} 10 TARGETS WITH GUIDED GUNNERY
F-15	940 rounds	1 (~600)	32	1,000 kg	170 kg
F-35	180 rounds	0 (>300)	10	960 kg	190 kg

With a retrofit of this technology onboard these airframes, increases in capability are noted. This has significant implications for new airframe design as the guided projectiles have an increased packing factor within the airframes as compared to standard missile systems. Unlike conventional missiles, guided hard-launch systems do not require large bomb bays with internal trapeze assemblies or external pylons that increment radar cross section. These volumetrically expensive components may be reduced or even removed in future fighter designs, allowing for smaller, less expensive and complex airframes to accomplish mission requirements afforded to advanced fighter aircraft currently fielded.

V. Conclusion

Guided hard-launch munitions provide significant benefits in air-to-air combat when retrofitted onto existing aircraft. Ranges on the order of short and medium range air-to-air missiles may be accomplished without reducing HE mass onboard the projectile or altering the existing gunnery systems. The guidance lent to these rounds opens up potential BVR engagement for both fighters and attack aircraft such as the AC-130. Projected payload weights needed to interdict 10 aerial targets was reduced by a factor of five, and significant cost savings associated with airframe operation may be possible in terms of reduced fuel burn required for a given mission. New airframe designs may take advantage of this technology to significantly reduce the overall weight and volume of a platform to achieve the same mission specifications by exchanging internal and external missile mounts with storage for guided gunnery shells.

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