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MODULAR MISSILE TECHNOLOGIES (MMT): A MODULAR OPEN ARCHITECTURE APPROACH FOR GUIDED MISSILES

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The United States (U.S.) Army's Aviation and Missile Research, Development, and Engineering Center (AMRDEC) Modular Missile Technologies (MMT) 6.2 Science and Technology (S&T) program is developing guided missile technologies that address user-defined capability gaps, while providing an innovative means of reducing the cost basis of guided missiles in general. These objectives are addressed by the development of a modular open architecture construct for guided missiles and their subsystems. The primary obstacle to a modular open architecture lies not in the hardware (where industry has made some progress) but in the underlying algorithms used in the development of guidance and control and fire control software. The MMT program is developing new algorithm technology that supports modular open architectures for guided missiles. These new algorithms are highly adaptable to physical changes in the design of a guided missile and allow individual subsystems to be independently procured and rapidly integrated into the system. The technological advances made by the MMT program are intended to be applicable to guided missiles across the Military Services.

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EXECUTIVE SUMMARY

The United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) Modular Missile Technologies (MMT) 6.2 Science and Technology (S&T) program is developing guided missile technologies that address user-defined capability gaps, while providing an innovative means of reducing the cost basis of guided missiles in general. These objectives are addressed by the development of a modular open architecture construct for guided missiles and their subsystems. The primary obstacle to a modular open architecture lies not in the hardware (where industry has made some progress) but in the underlying algorithms used in the development of guidance and control and fire control software. The MMT program is developing new algorithm technology that supports modular open architectures for guided missiles. These new algorithms are highly adaptable to physical changes in the design of a guided missile and allow individual subsystems to be independently procured and rapidly integrated into the system. As proof of this concept, the MMT program is developing a system solution that combines the capabilities of three separate product lines into one product line that performs the missions of all three at a reduced life-cycle cost. The technological advances made by the MMT program are intended to be applicable to guided missiles across the Military Services.

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I. BACKGROUND

The United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) Modular Missile Technologies (MMT) Science and Technology (S&T) program was begun in response to emerging capability gaps in the area of Aviation missiles. Additionally, the user and acquisition communities recognized the value of having Aviation missiles that are compatible with both manned rotary wing and Unmanned Aerial Systems (UAS). The MMT program was also challenged to combine the capabilities of three separate systems (two forward firing systems and one drop/glide system) into a single product line in order to benefit the logistics chain. At the same time, the Army has become increasingly cost conscious in all of its acquisitions.

The combination of the disparate capabilities of three separate systems is complicated by several factors including the means of delivering the effect (rocket-propelled and drop/glide), guidance (or lack thereof), payload types ranging from nonlethal (smoke and flares) to lethal, and target types ranging from point targets to area targets. Furthermore, this new missile system would need to radically address cost throughout its life cycle. The approach chosen for solving this dilemma was to create a small modular missile system product line from which multiple variants can be assembled and modifications can be made at a low cost throughout the life cycle of the system.

II. OBSTACLE

The objective of the MMT S&T program is a guided missile design that readily allows changes to a guided missile's subsystems independently of each other so that they can be procured separately and then integrated into the system at minimal cost. The shorthand term for this objective architecture is a modular open architecture. Due to the historical path of their development and the nature of the industry's incentives, the dominant architecture for guided missiles is neither modular (in the fullest sense) nor open. To understand this, it is necessary to discuss these terms in their general sense and then as they apply to guided missiles.

Modular architectures, in the broadest sense, permit independent development of the subsystems in a given system. Modularity is possible where the interfaces of the subsystems and their interactions with one another are sufficiently specifiable, verifiable, and predictable. The discussion on modular and interdependent architectures is described more fully in Reference 1. Modular architectures are used in cases where the primary goal is time-to-market, convenience, or customization. Open architectures have their origins in the computer networking world and are intended to ease the addition, upgrade, and swapping of hardware and/or software. Therefore, open architectures are supportive of modular architectures. The combination of these two types of architectures is called a modular open architecture. Products with modular open architectures also have a cost advantage over those rivals that do not have modular open architectures.

By contrast, interdependent architectures are used where the dependencies between subsystems are not well-understood and performance is the primary objective for the system. Interdependent architectures are necessarily closed architectures and usually proprietary. They entail lengthy rework efforts when the system is modified or when a new version of the system is needed. They also support high profit margins and therefore, have a higher cost basis than their modular competitors. From a life-cycle cost perspective, interdependent architectures are more expensive than modular open architectures.

In its infancy, guided missile performance was never satisfactory. There were many unknowns associated with missile guidance, especially the interactions of the subsystems. Under these circumstances, interdependent architectures were a necessity. However, decades of missile research have vastly improved the ability of designers to specify, verify, and (most importantly) predict the behavior of missile subsystems at the interfaces. Yet, the dominant system architecture for guided missiles is the interdependent architecture.

Hardware is not the limiting factor. Indeed, there are several missile systems that claim to be modular and many are at the hardware level. Many guided missiles have readily identifiable joints which allow them to be separated into segments. However, digging deeper into the details tends to reveal that the hardware interfaces contain proprietary elements. So, the hardware interface may be modular but not open.

The limitation in current technology's ability to support a modular open architecture for guided missiles is most apparent in the missile's guidance and control and fire control software. The interdependent nature of these software items is revealed most readily when a hardware change that affects the missile's mass properties or aerodynamics is proposed. Any physical change resulting in a change in the guided missile's mass properties or aerodynamics entails significant rework to the missile's guidance and control software. Similar impacts occur in the fire control software when changes affect the missile's employment, trajectory, or prelaunch parameters. Those software end items are the direct product of the underlying algorithms that were used to develop them. The algorithms were developed to support an interdependent architecture and oftentimes are specific to a single point solution. They were not intended to support a modular open architecture and are not intended to evolve rapidly. Thus, the final key to creating a guided missile system with a modular open architecture is the development of guidance and control and fire control algorithms that will support a modular open architecture.

In summary, one of the root causes of the high costs of guided missiles is their interdependent (proprietary) architectures, which are dictated by the inflexibility of their underlying algorithms. These proprietary missiles are expensive to develop and modify, and their interdependent architectures ensure that they stay that way. The goal of MMT is to change this paradigm by developing and demonstrating new algorithms that support a modular open architecture for guided missiles.

III. APPROACH

The first step in the concept development process was the selection of an airframe diameter. The 2.75-inch diameter format was chosen for several reasons. First and foremost is that there is already a large industrial base that manufactures 2.75-inch diameter missile components at a low cost. Second, warhead effectiveness studies indicated that the warhead needed to be approximately 5 pounds to address the target set. Finally, the 2.75-inch diameter format is suited to lightweight solutions and dense packaging for a high number of stowed kills.

The next step in the definition of the MMT architecture was to define a set of distinct subsystems (Figure 1) into which the missile can be easily disassembled and reassembled to form different airframe types suitable for the needs of the manned rotary wing platforms and UAS. Manned rotary wing missions dictate a rocket-propelled solution. UAS can utilize rocket-propelled missiles; however, the drop/glide configuration is also suitable for the UAS mission due to their operation at high altitude and long loiter times. Therefore, the first obvious module is the solid rocket motor to propel forward firing variants. A glide kit is used for drop/glide variants to increase the useable footprint of the round.

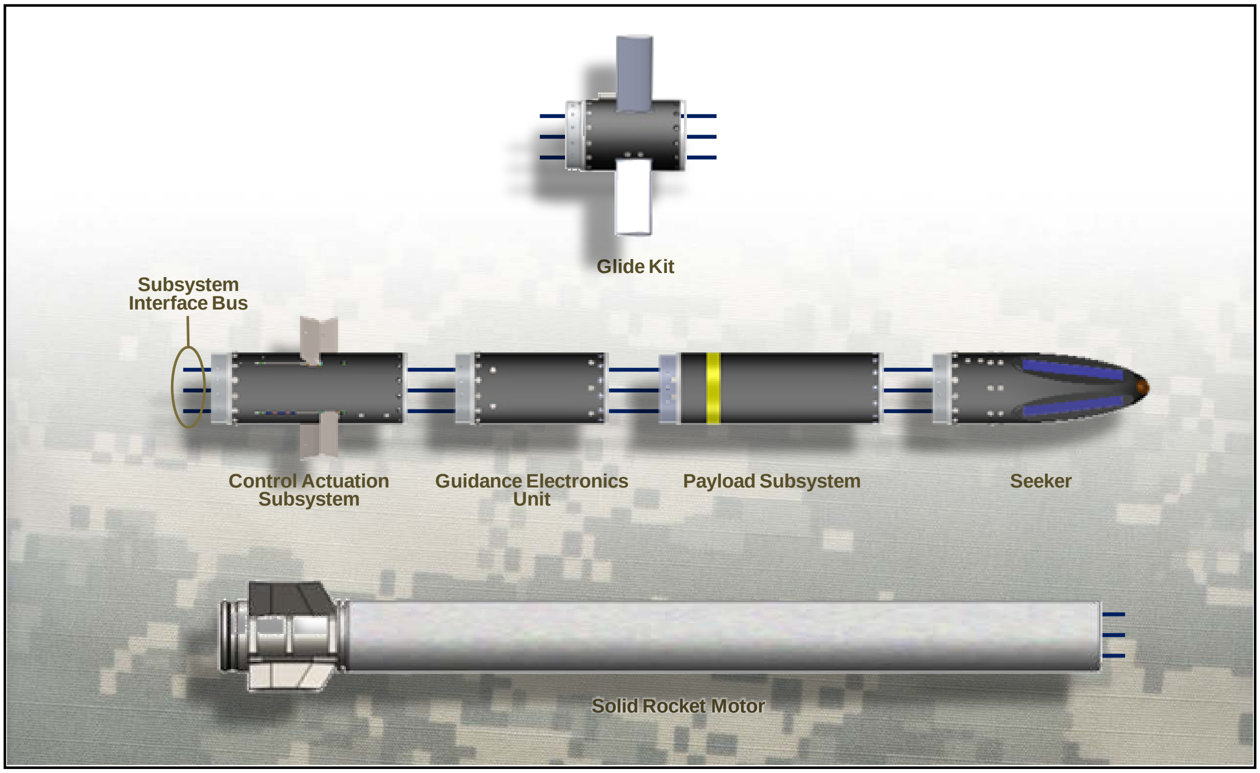

Figure 1. Phase One MMT Subsystems

To maximize reuse of modules, the Control Actuation Subsystem (CAS) was set up as a separate module as well. As such, the CAS provides tail control of drop/glide variants and canard control of forward firing variants. The high dynamic pressures and accelerations associated with rocket-propelled missiles drives the size, weight, and power requirements for the CAS. Even so, the same CAS is still suitable for the drop/glide variant envisioned for MMT.

Observation of existing missile systems shows that they have a history of modification to their payload sections over the course of their life cycle. Payloads can be either lethal (that is, warheads) or nonlethal (for example, flares). Given the variety of missions and payloads that a system based on MMT would have to perform, the payload section (including the fuze) was identified early as a separate module.

Over time guidance electronics and seekers also receive modifications to improve performance, add capability, or mitigate obsolescence. Studies of mass properties and aerodynamic stability using very detailed Computer-Aided Design (CAD) models for the MMT variants indicated that these should be separate modules. To enable rapid integration of different seeker types, it was determined that all processing for the seeker should be performed in the seeker module. The MMT guidance electronics unit provides guidance, navigation, control, power regulation, and communications (external and internal) functions.

The Phase One common subsystems are a guidance electronics unit, a CAS payload subsystem, and seeker. The add-ons are a glide kit for a drop/glide variant and a solid rocket motor for a forward firing variant. With the exception of the seekers, all of the subsystems previously described are being developed under the MMT S&T program[1]. Also included, but not shown, is a launch tube container for the forward firing variants.

The MMT concept includes a common subsystem interface that incorporates the mechanical interconnect between each subsystem and an electrical bus that runs through each subsystem from one end of the missile to the other. This subsystem interface is a government-developed and nonproprietary interface in order to ensure that the interface is indeed open. The electrical bus includes 28 volts of direct current power, a set of serial digital lines, and a third set of lines related to safety. Each subsystem taps the lines that it needs for proper function (with some restrictions imposed for performance, safety, or reliability reasons).

This approach to modularity allows the formation of two basic but aerodynamically different configurations from a common set of subsystems and a second set of add-ons. This architecture allows the creation of a drop/glide variant and a forward firing variant having a majority of common parts between them, as shown in Figure 2. Thus, MMT is in position to demonstrate the feasibility of using a single product line to form multiple missile variants.

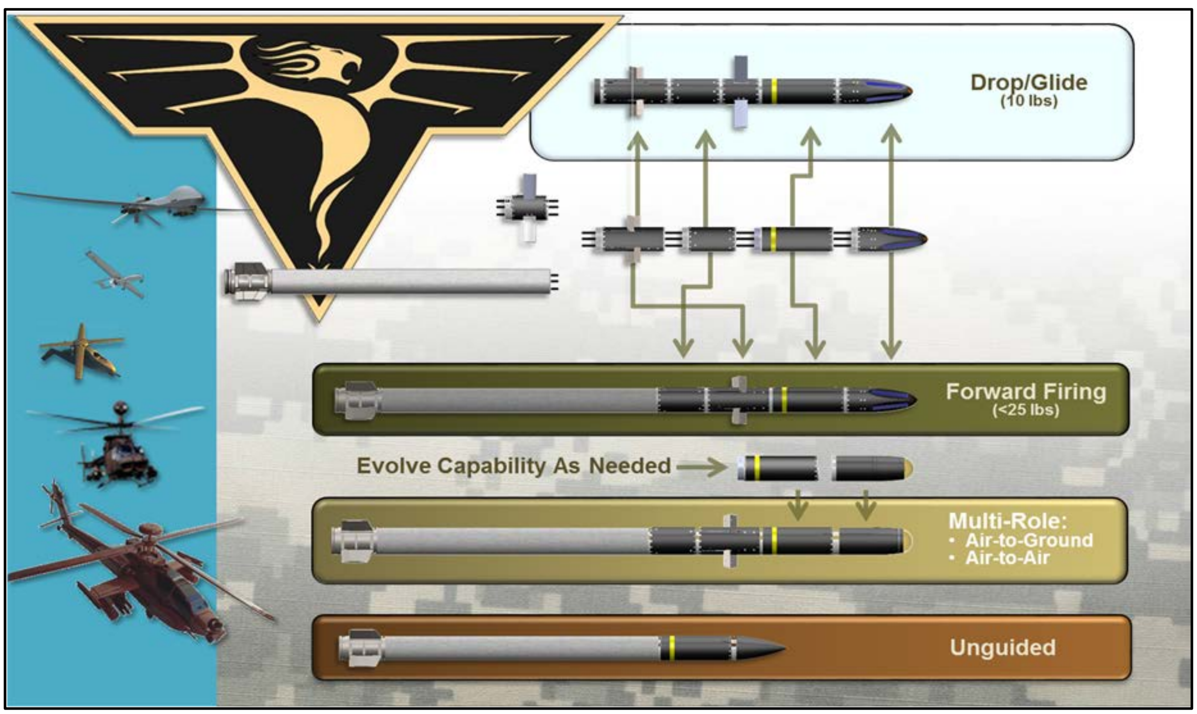

Figure 2. MMT Variants

[1] Seeker development for MMT is coordinated with other existing S&T programs.

The initial variants assume a precision air-to-ground mission. However, in order to prevent boxing the design into that mission set, the MMT program assumes a block development strategy that includes variations such as a multi-role capability (air-to-air and air-to-ground) and even unguided rounds for suppression of area targets.

Note that in Figure 2, the CAS and the guidance electronics unit trade places in the stack when forming up the drop/glide and forward firing variants. The subsystem interface is identical at each segment and permits the various subsystems to be stacked in any order. Each subsystem is queried on start-up to determine the order of the subsystems in the stack. This feature also allows the maximum flexibility in design of future variants. For instance, if a penetrator warhead is desired, then the subsystem interface allows the new payload to be placed up front with a new seeker behind it.

In parallel with the hardware, MMT is developing the algorithms necessary to support the modular open architecture. The key algorithms are those that affect the operations of multiple subsystems. For a guided missile, those algorithms are the autopilot, guidance, navigation, and fire control. MMT's objective is a set of algorithms that are as insensitive as possible to changes in the missile's airframe, warhead, seeker, and so forth. This is not to say that pieces of data cannot be changed. Classes of data such as look-up tables and constants are fair game for change, but the algorithms that operate on the data should not have to change to adapt to the new data. The algorithms should not have to be rewritten if the missile is propelled by a rocket motor or uses a glide kit. No changes to the algorithms should be needed in order to upgrade the missile from a Semi-Active Laser (SAL) seeker to a millimeterwave seeker (or dual-mode or tri-mode). No changes to the algorithms should be needed to change the warhead from a blast/fragmentation type to a flechette type or to a shaped-charge type. No changes to the algorithms should be necessary in order to launch from different Aviation platform types. No changes to the algorithms should be needed to address targets that are on the surface or in the air.

The MMT S&T program also keeps in mind that a modular open architecture should be expansible even beyond what has been described thus far. For instance, the same algorithms should also be suitable for a guided missile that requires tail control of a rocket-propelled variant. This can be accommodated with either of two approaches (whichever is more cost effective). The CAS and rocket motor could remain as two separate subsystems, or they could be combined into a single subsystem. The algorithms should be insensitive to either option.

Further illustration of the need to remain flexible is that guided missiles have a variety of propulsion systems. Propulsion systems can be multistage. For example, a soft launch section may be integrated into or attached to a boost and sustain motor for flight. For other applications, the propulsion system may even be an electrically driven propeller or an air-breathing turbofan. Airframe diameter should not matter either and neither should the fact that the missile is ground launched from either a slewing launcher or a vertical launcher.

That is just a short list of the flexibility that MMT seeks for its algorithms and resulting software. Though initially intended for the Aviation domain, the algorithms being developed under the MMT S&T program should also apply to guided missiles intended for the Ground domain as well. Obviously, there will be limits to the changes in a missile's subsystems, launch conditions, flight environments, and missions that the algorithms can endure, but part of MMT's task is to find, define, and where possible, push through those boundaries. Progress toward this end is already being made.

The autopilot and guidance algorithms have thus far been demonstrated in simulation to be insensitive to changes in seeker type, CAS design and location, airframe type (drop/glide or forward firing), and launch platform type (manned rotary wing, UAS, and ground-based launchers).[2] The algorithms do not change, only the data on which the algorithms operate changes.

To further refine this missile concept, demonstrate the technology, and reveal the potential flexibility of the acquisition strategy, MMT has proposed a series of flight tests and follow-on development work. The initial demonstration system is the 25-pound class forward firing variant followed by the 10-pound class drop/glide weapon, each of which will be built up from prototypes of the subsystems previously described. Subsequent development will evolve the core to incorporate a dual-mode seeker and a multi-mode warhead and will demonstrate a multi-role (air-to-ground and air-to-air) capability. Planned spinoffs include the unguided variant as well. Cost data for each variant are being gathered to inform the development and acquisition decision processes. These demonstrations will show that the MMT modular open architecture is inherently low cost, flexible, and rapidly evolvable.

IV. ACQUISITION SYSTEM PAYOFF

The overarching objectives of MMT where acquisition is concerned are to reduce the cost of a guided missile system and the time required to implement a change. These savings in time and money are being addressed in all phases of the life cycle.

A. Development Phase

The hardware-insensitive nature of the MMT autopilot and guidance is a major accomplishment. Under the old paradigm, even minor airframe changes require a 3- to 6-month effort to rework the autopilot. Most missile designs have a single solution in mind for the end item. MMT has multiple variants in mind from the start. Using traditional missile design techniques would have resulted in untenable costs and schedule delays for each of the various solutions envisioned by MMT.

Additionally, the MMT Six Degrees-of-Freedom (6-DOF) simulation was architected to purposefully reduce development time. The 6-DOF simulation is written in C++ and has been architected to reflect the modularity of the subsystems. The code can be copied directly from the 6-DOF simulation to the compiler for the corresponding real-time processor. This feature of the 6-DOF simulation allows rapid implementation of software changes during early development. A process that ordinarily takes months on the first pass only took a week for MMT. It has been exercised for both the mission computer in the guidance electronics unit and the processor for the CAS resulting in a tremendous savings in development time for the MMT S&T program.

The MMT 6-DOF simulation architecture has an additional benefit. Since the MMT 6-DOF simulation was designed to be as modular as the hardware it represents, versions of the

[2] Representative trajectories of the various configurations and launch scenarios are included in the appendix.

simulation can be produced that would enable a vendor or another research laboratory to experiment with new subsystem concepts. For instance, small businesses with novel seeker ideas could be given a version of the MMT 6-DOF simulation with the existing seeker model removed. The vendors' seeker models could then be plugged into the MMT simulation to allow those vendors to develop models of their seeker concepts in a closed-loop fashion without having to reinvent the entire missile simulation or its guidance and control loops. This would enable the seeker developers to refine their designs at the earliest stages and further reduce time to market. This same process could be used for multiple vendors across each subsystem. The MMT 6-DOF simulation is, in effect, a developmental force multiplier.

B. Production, Sustainment, and Demilitarization Phases

As has been previously stated, modular open architectures have a lower cost basis than their interdependent (proprietary) counterparts. Modularity keeps production time down by simplifying the integration, assembly, and test operations in the factory. Being both modular and open simplifies the process of cutting in a modified or new subsystem. The Government can then recompete the subsystems as often as necessary for whatever reason, including cost reduction, obsolescence mitigation, capability improvement, or any combination of those same reasons. Subsystems in a modular open architecture that reach the end of their shelf life can be quickly and easily removed, demilitarized, and replaced.

C. The Broader Picture

1. Missile Portfolio

The MMT concept is not limited to the one Aviation-focused product line previously described. The principals are equally applicable to other sizes of guided missiles with other missions. The algorithms and design techniques being developed under the MMT S&T program are equally applicable to those guided missile programs that are more cost conscious than performance-driven. Although the physical size or aerodynamic configuration may change from one missile system to the next, the MMT S&T program is taking care to ensure that the algorithm technology being developed under this program is robust enough to be transportable to other guided missile airframes.

2. Missile Industrial Base

The Missile Industrial Base is organized along lines that reflect their proprietary architectures. Each prime contractor has a set of subcontractors, many of which are strategic partners with that particular Prime. What results at the end of the competitive process to develop a guided missile system is the best solution that a particular prime and its strategic partners can produce. A modular open architecture permits the Government to compete the development at the subsystem level, thus allowing the Government to develop the best solution that the entire Missile Industrial Base can produce.

In theory, competition drives costs down. In practice, however, guided missile systems tend to defy that maxim. Competition for most missile systems occurs only during the early stages of development, before a prime contractor has been chosen to produce the system. Once a prime contractor is chosen, the tendency in the acquisition of guided missiles is to stay with that prime contractor for the life of the system. This is a condition known as vendor lock and is driven primarily by two factors, proprietary (interdependent) architectures and the cost of qualifying those systems that use those architectures. The proprietary (interdependent) architectures and technologies typically used in the development of a guided missile system virtually eliminate any hope of future competition for that particular missile system. The results have been not only high costs in the initial production phases but also high costs for upgrades and mitigation of obsolescence.

For the foreseeable future, the Army's budget is expected to shrink. Cuts to the Army's budget reduce procurement outlays, thereby further heightening cost sensitivity within the Government. Reduced procurement budgets have other second-order effects as well. Corporate Research and Development (R&D) expenditures are expressed as a percentage of corporate revenue. Cuts in Department of Defense (DoD) procurement budgets will result in declining revenues, and the underlying corporate R&D will decline with it.

When procurement outlays were slashed in the 1990s, DoD contractors who did not exit the Missile Industrial Base altogether survived by dismissing a large part of their pool of creative technologists, shedding parts of their capital infrastructure devoted to missile development, and/or merging with former competitors. The expected reduction in military spending in this decade will have the same effects on what remains of the Missile Industrial Base (prime contractors and subcontractors). Product lines that DoD requires will become more expensive or even unavailable as vendors begin dropping out of the market. The established Missile Industrial Base is shrinking once again, and what little competition exists in the arena of guided missiles is dwindling with it.

Much has been said in recent months about the concept of reversibility. The desire behind reversibility seems to be that the impacts of decisions made today that eliminate a capability can be undone easily and quickly later. However, as was demonstrated in the aftermath of the restructuring of the defense industry in the 1990s, a reduction in the number of competitors in the Missile Industrial Base is neither easily nor quickly reversed. Traditional design techniques and processes for the development of guided missile systems require a breadth of knowledge, experience, and infrastructure that are difficult, expensive, and time-consuming to acquire. This costly combination of resources represents a significant competitive economic moat for any newcomer to the missile industry to cross. Thus, the number of players in the Missile Industrial Base can shrink quickly, but it is very difficult and slow to regrow.

Modular open architectures support the concept of reversibility by reducing barriers to entry. Smaller companies with new technologies have a much lower hurdle to overcome at the subsystem level. They do not require full knowledge of a modular open architecture system in order to develop a new subsystem for it. A modular open architecture for guided missiles will shrink the competitive economic moat so that the number of competitors in the Missile Industrial Base can be expanded at lower cost and in less time.

V. WARFIGHTER PAYOFF

The payoff of MMT to the Warfighter occurs in the near and far terms. Through this development effort, the U.S. Army's Aviation Branch will receive a new precision guided missile system that is lighter than existing Aviation missiles in the Army's inventory. Its small size will enable it to slip right into the existing logistics train. But the major feature of MMT-based guided missiles is the ability to be changed rapidly and at a low cost to keep ahead of evolving threats. This includes threats on the surface and in the air.

Early simulation results also indicate that the MMT airframe is also suitable for surface launch either from a slewing launcher or vertical launcher. While further study is necessary to determine if this capability in the 2.75-inch diameter airframe is operationally useful or not, the results obtained thus far suggest that the concept of a modular open architecture missile is more broadly applicable than just the Aviation mission. The lessons learned and, most importantly, the algorithms developed under MMT can be applied directly to other missions currently being served by guided missiles with proprietary architectures. Thus, the cost savings and rapid adaptability of a modular open architecture can be spread to the entire DoD portfolio of guided missiles.

VI. CONCLUSION

The MMT S&T program is already paying off in terms of the reduction in cost and time needed to develop a new guided missile system for the U.S. Army's Aviation Branch. This cost reduction also carries forward into the rest of a guided missile's life cycle. Though initially focused on the Army's Aviation missile capability area, MMT's payoff is potentially much larger and more far reaching. The algorithm technology developed by the MMT S&T program can be readily applied to other guided missile programs within DoD, especially those in which cost containment is the overriding objective. Where the Missile Industrial Base is concerned, the MMT concept also provides a means of reducing barriers to entry for new, nontraditional, and small businesses desiring to compete in the guided missile market.

REFERENCE

1. Christensen, C. M. and Raynor, M. E., The Innovator's Solution: Creating and Sustaining Successful Growth, Harvard Business School Publishing, 2003.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

<	less than
6-DOF	Six Degrees-of-Freedom
AMRDEC	Aviation and Missile Research, Development, and Engineering Center
CAD	Computer-Aided Design
CAS	Control Actuation Subsystem
DoD	Department of Defense
lbs	pounds
MMT	Modular Missile Technologies
R&D	Research and Development
S&T	Science and Technology
SAL	Semi-Active Laser
U.S.	United States
UAS	Unmanned Aerial Systems
Vdc	Volts Direct Current

APPENDIX
REPRESENTATIVE MODULAR MISSILE TECHNOLOGIES TRAJECTORIES

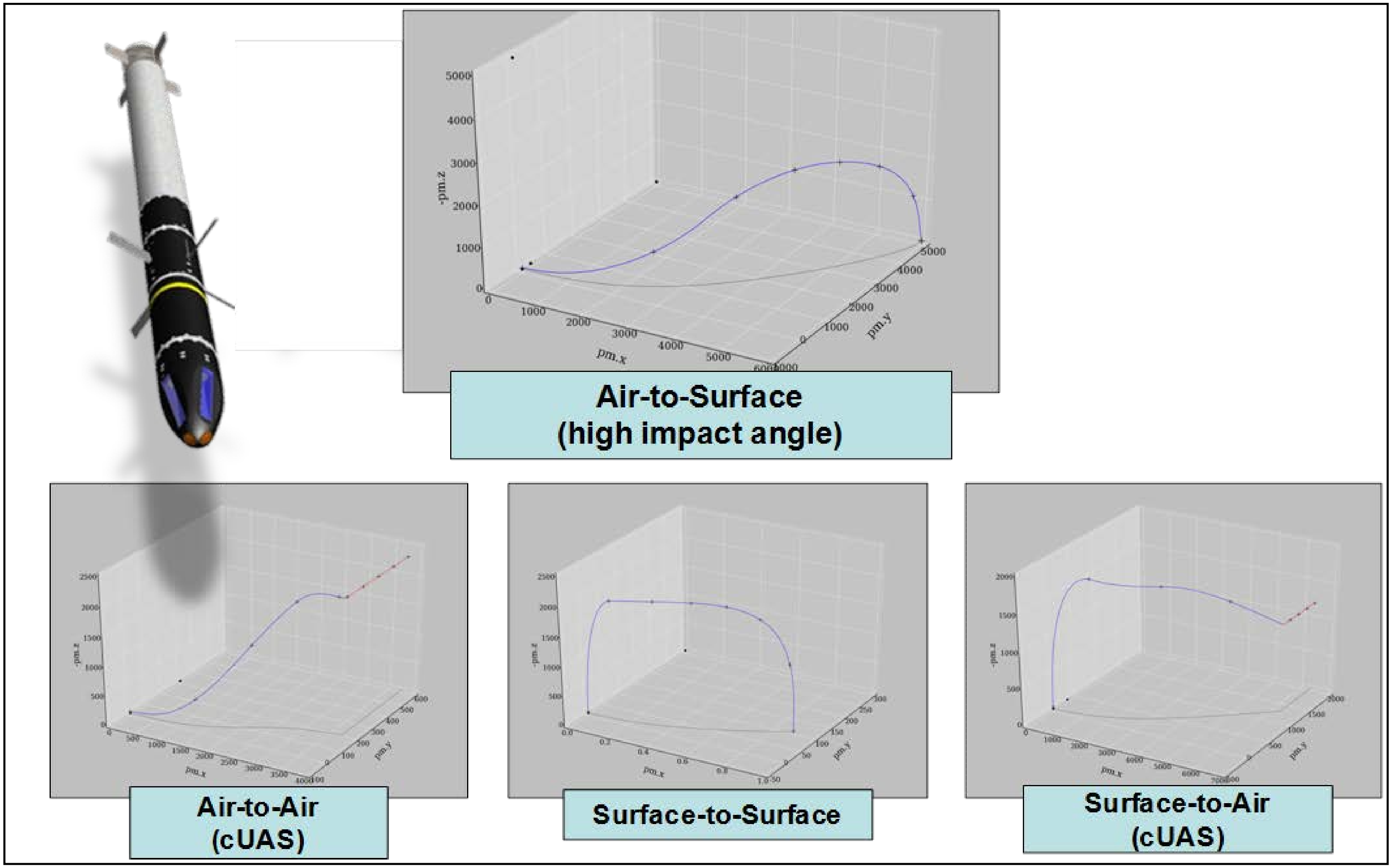

Figure A-1. MMT Rocket-Propelled Variant (Air-to-Surface and Air-to-Air Capable)

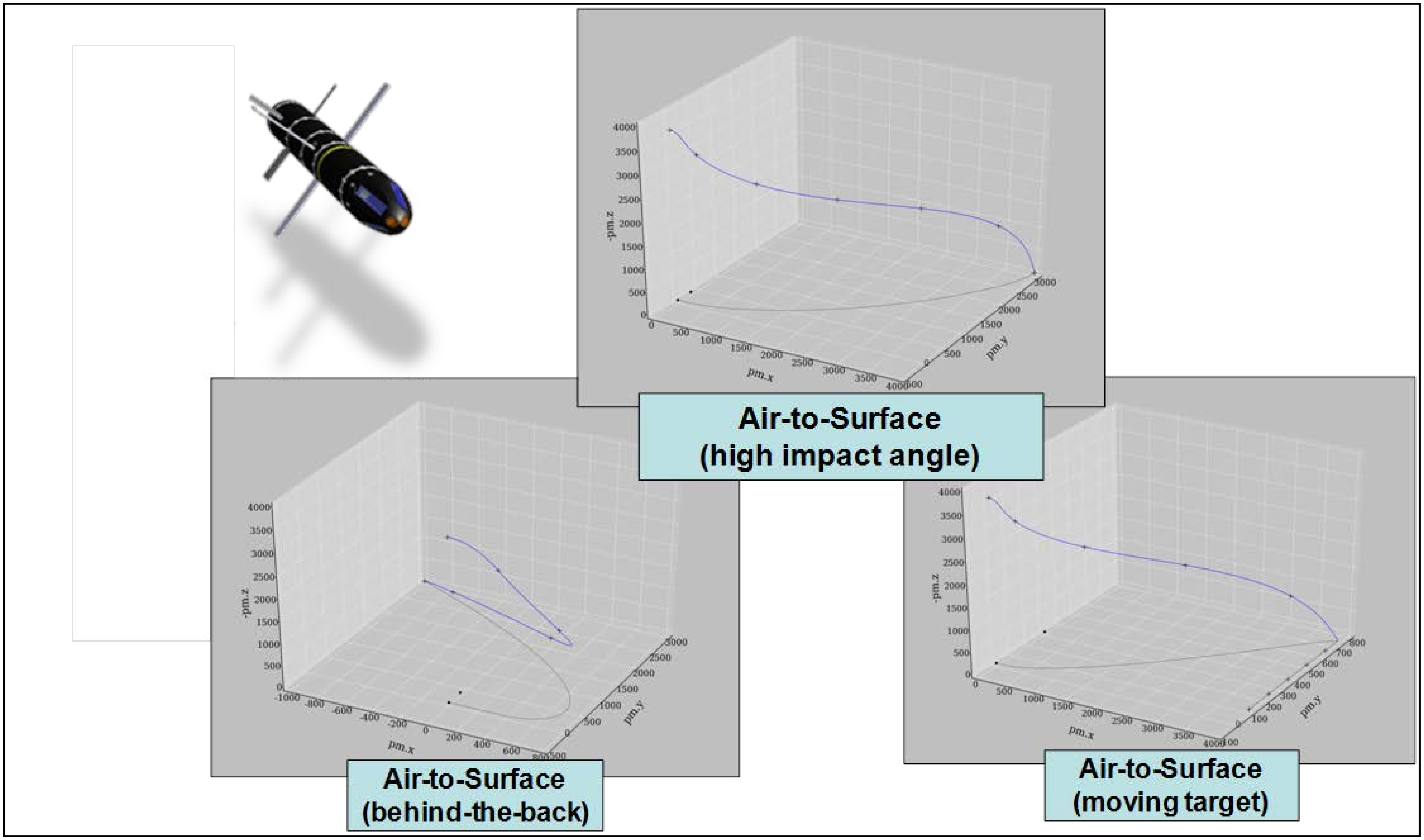

Figure A-2. MMT Drop/Glide Variant (Flexible Engagement Envelope)