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Genius Sand: Miniature Kill Vehicle Technology to Support Boost Phase Intercepts and Midcourse Engagements

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Genius Sand: Miniature Kill Vehicle Technology to Support Boost Phase Intercepts and Midcourse Engagements

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Abstract

This paper summarizes Lawrence Livermore National Laboratory's (LLNL) approach to a proposed Technology Demonstration program for the development a new class of miniature kill vehicles (MKVs), that we have termed Genius Sand (GS). These miniaturized kinetic kill vehicles offer new capabilities for boost phase intercept (BPI) missions, as well as midcourse intercepts and the defeat of advanced countermeasures The specific GS MKV properties will depend on the choice of mission application and system architecture, as well as the level of coordinated or autonomous operations in these missions. In general the GS MKVs will mass from between 1 to 5 kilograms and have several hundred meters per second of Δv and be capable of several g's of acceleration. Based on the results of our previous study effort [1], we believe that it is feasible to develop and integrate the required technologies into a fully functional GS MKV prototype within the scope of a three-year development effort.

We will discuss some of the system architecture trades and applicable technologies that can be applied in an operational MKV system, as a guide to focus any technology demonstration program. We will present the results of a preliminary 6DOF analysis to determine the minimum capabilities of an MKV system. We also will discuss a preliminary design configuration of a 2 kg GS MKV that has between 300-500 m/s of Δv and has at least 2-g's of acceleration capability. We believe a successful GS MKV development effort will require not only a comprehensive component miniaturization program, but a rapid hardware prototyping process, and the ability to utilize high fidelity ground testing methodologies.

Introduction

This paper summarizes LLNL's approach to a proposed Technology Demonstration program that will develop a new class of MKVs, that we have termed Genius Sand. These MKVs have masses between 1 to 5 kilograms each, depending on their desired capabilities. We will describe a preliminary design configuration at 2 kg that has 500 m/s of Δv, with at least 2-g's of acceleration capability. Based on our FY01 study effort, we believe that it is feasible to develop and integrate the required technologies to enable us to prototype a fully functional MKV within the scope of a three-year development effort.

The Advanced Interceptor Technology (AIT) Program at LLNL has been pursuing research and development of advanced lightweight, miniature kinetic kill vehicles for more than a decade. During the Brilliant Pebbles (BP) program LLNL developed a concept for a sub-kilogram class size MKV (0.1 to 1 kg). Genius Sand (GS) was coined to indicate the high levels of miniaturization that these vehicles required. This concept was proposed in order to extend the effectiveness of the Boost Phase Brilliant Pebble system in the decoy-rich, multi-warhead environment of the midcourse battle space. This concept called for the Brilliant Pebbles spaced based interceptor to carry approximately a dozen Genius Sand vehicles that could be deployed in midcourse engagements against RVs and other countermeasures. With advances in processor speeds, miniature sensors and avionics, lightweight propulsion, integrated optics, and composite materials, we believe GS MKV technology can also be applied to a BPI mission by achieving higher acceleration, greater Δv capability, and a longer detection range.

Proposed Operational Concepts

The GS concept has potential applications for (1) a Boost Phase Intercept mission, and (2) a Midcourse Intercept mission. We will briefly describe the operational concept of each of these missions.

Boost Phase Intercepts

For the BPI mission, we envision that a net of 10 or more GS MKVs weighing 3 to 5 kg each would be deployed, in a single launch to 10 or more predicted

Distribution Statement C: Distribution authorized to U.S. Government Agencies and their contractors. Critical Technology. June 25, 2002. Other request for this document shall be referred to LLNL, P.O. Box 808, Livermore, CA 94551-0808 intercept points (PIPs), as such they would cover the complete BPI engagement volume in space. Advantages of this approach are: (1) one or more GS may attack the target and thus increase the kill probability, (2) objects that are indistinguishable from the true target will also be attacked and thus increase the hit probability, and finally (3) the most likely BPI countermeasure consists of booster jinking or GEM maneuvers that would be rendered ineffective because a boosting target while maneuvering away from one GS may actually be maneuvering itself into a collision trajectory with another GS in the net.

Independent of any specific basing mode, a BPI mission would require a Carrier Vehicle (CV), carrying multiple GS MKVs, to deploy its payload to multiple Predicted Intercept Points (PIPs) as is shown in Fig. 1 (assuming a surface basing mode). Each GS would then home to its initial perspective PIP. These PIPs can be updated frequently as the estimate of the threat maneuvering envelope changes. For the BPI mission, it is generally agreed that each GS will need to have more than 500 m/s of Δv and greater than 5 g's of acceleration. Each GS will also have the capability to communicate with the CV and receive PIP updates. This is similar to a shotgun approach, but is more effective because of the "smart pellets" or Genius Sand MKVs can independently home to a target. Under this scenario, multiple GS MKVs can either attack the same target thus increasing the kill probability, or the pack of GS MKVs might attack a salvo launch of multiple boosting targets .

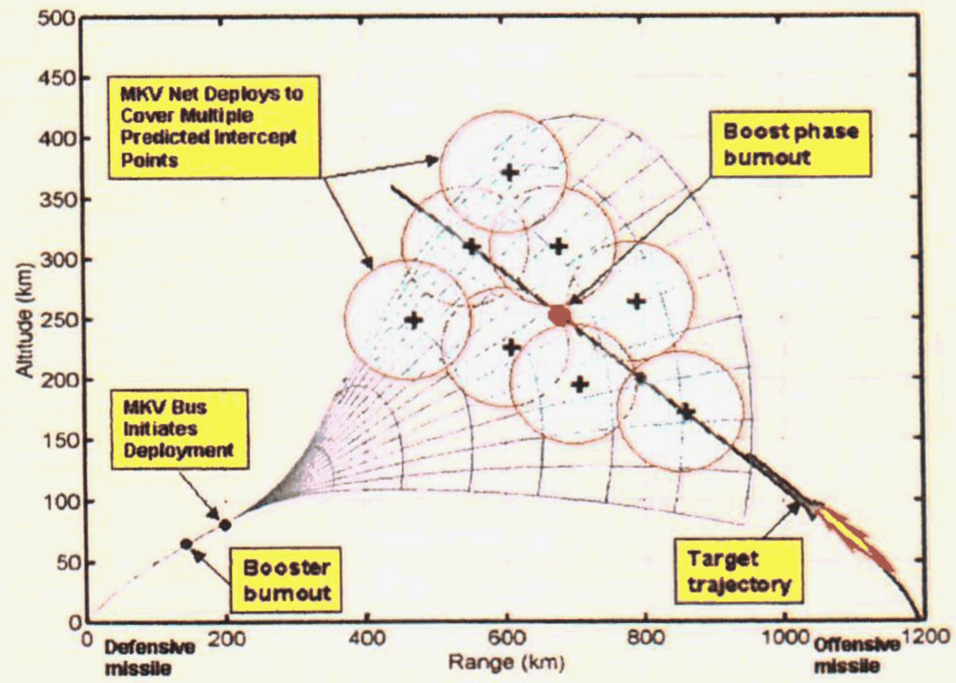


Fig. 1. Example of deploying a net of MKVs to cover all the boost phase predicted intercept points

Because the PIPs completely cover the maneuvering envelope of the target booster, it renders the jinking or GEM evasive maneuvers ineffective. For example, a booster maneuvering away from any one particular PIP will automatically fall inside the intercept volume of another PIP. This is why a shotgun is effective against a bird on an unpredictable flight path, and a shotgun with smart guided pellets will be even more effective. The MKV based BPI system contains a number of different variables to trade, in order to optimize the system performance. Parameters to investigate include the number, mass and capabilities of the GS MKVs as well as the size and capability of both the Carrier Vehicle and the booster stack that places the GS MKVs across the PIP of the target. The defense has a flexible range of reach and coverage options for the GS MKVs that will prove difficult for the offense to easily counter, making this an effective approach for BPI engagements.

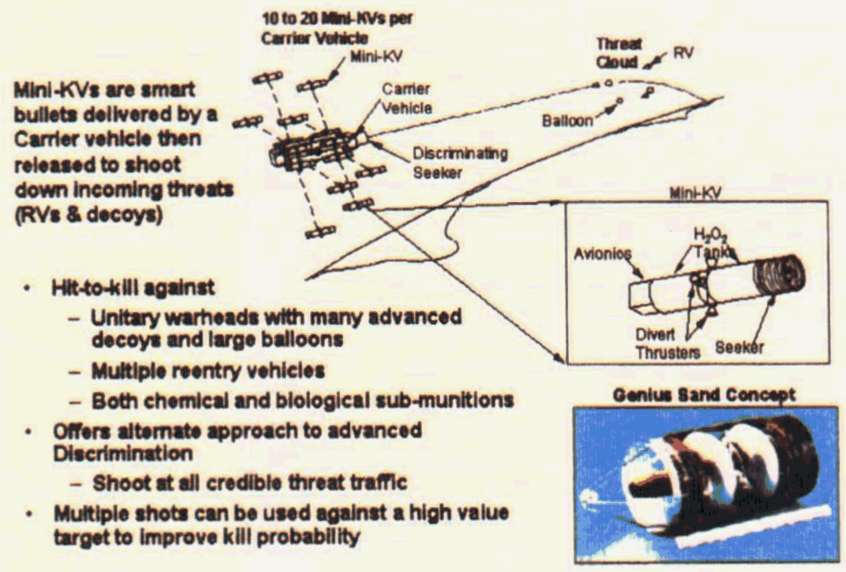
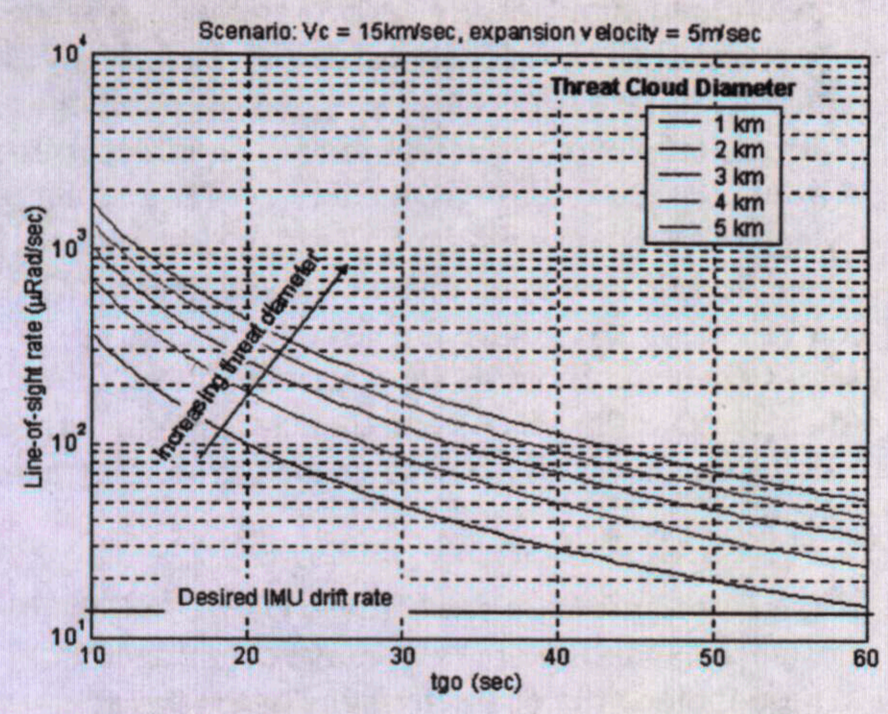


Fig. 2 Multiple Mini-KVs Concept of Operations

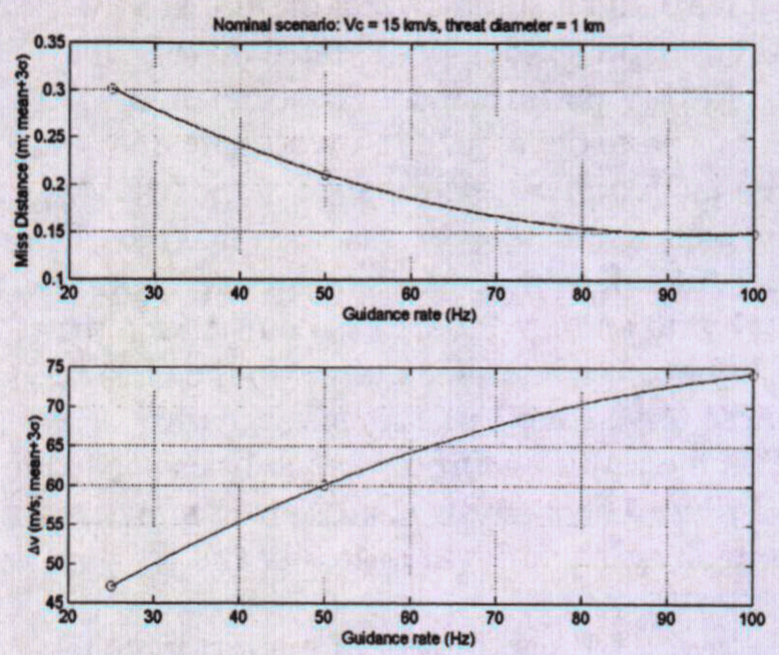
Midcourse Intercepts

For a target and decoy-rich midcourse environment or for a submunition payload of several dozen bomblets, a single kill vehicle per launch system would not be cost effective since we need more than one kill vehicle per target cluster in order to achieve an acceptable kill probability. Under the existing BMD paradigm, this would require multiple missile launches to effectively negate this threat. For an offensive missile carrying MIRVs or submunitions, and countermeasures, this could quickly deplete the inventory of interceptors. A GS MKV system would be attractive to address this problem. As shown in Fig. 2, a CV would deploy its payload of GS MKVs to multiple targets or to the most likely targets. Each MKV would be capable of performing endgame homing and is also capable of communicating with the CV or other MKVs. Again we have the similar situation that one or more MKVs may attack the same target, which increases the kill probability, or all likely targets (after discrimination processing) would be attacked, increases the hit probability. The system performance trades are also similar to the boost phase mission described earlier.

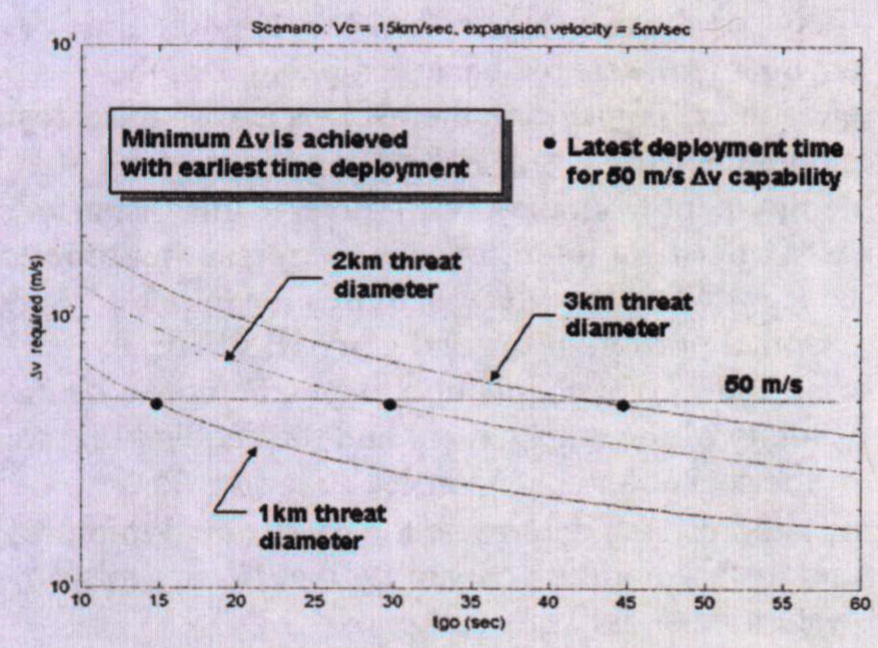
(3a)



(4a)



(3b)



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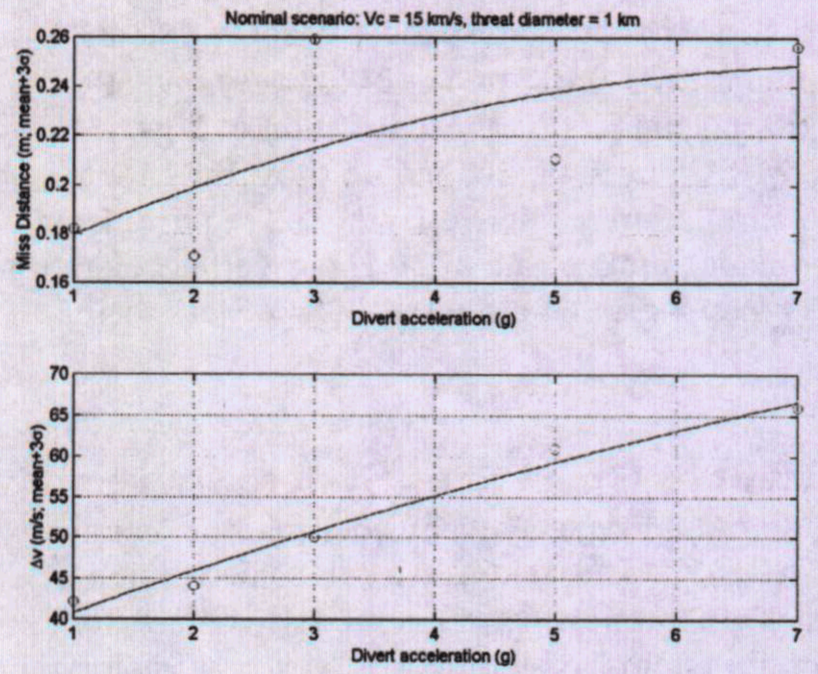

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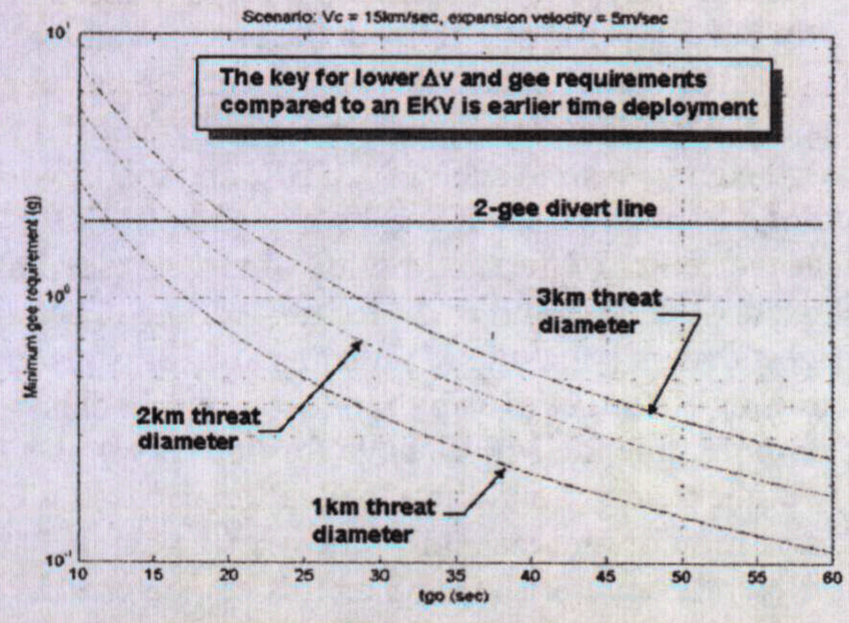

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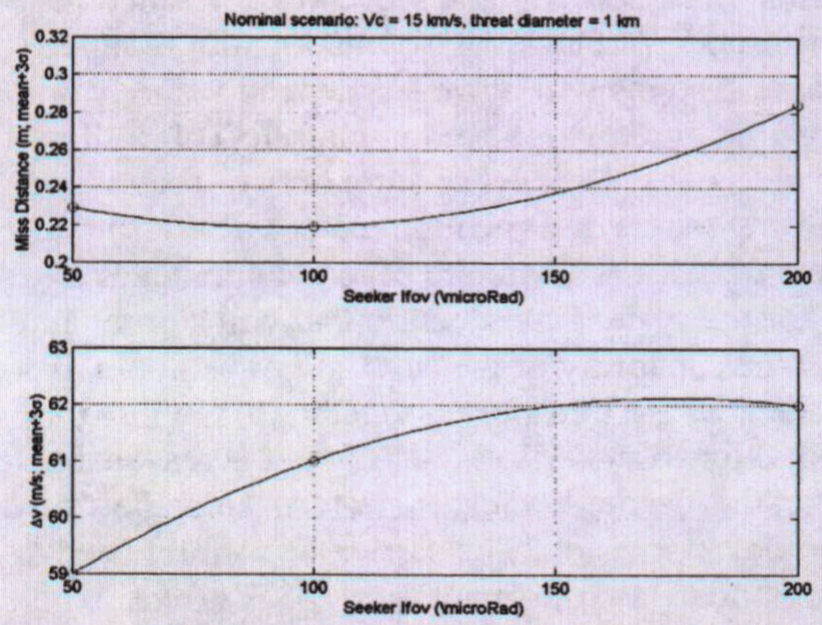


Figure 3a Showing line-of-sight (LOS) rate as a function of time to go or tgo. A 2°/hr drift rate IMU would be adequate to measure LOS rate. Fig. 3b shows a Δv of 50 m/s is adequate for a 45 second divert maneuver. Finally, Fig. 3c shows that a MKV with a 2 g acceleration is adequate for a homing intercept.

Figure 4a shows a six DOF Monte-Carlo simulation indicating a 3σ miss of less than 30cm can be achieved with a guidance rate of greater than 25 Hz. Fig. 4b shows a divert acceleration of less than 3 g to support a Δv budget of 50 m/s. Finally Fig. 7c shows a seeker IFOV of less than 50 μrad is needed to support a Δv budget of 50 m/s.

System Performance Analysis

Figures 3 and 4 summarize a preliminary analysis based on six-degree-of-freedom (6DOF) models of MKV performance. These detailed calculations were developed to investigate a lower bound on the required performance of the MKV in midcourse engagements. We assumed that the carrier vehicle would place the MKVs on an intercept trajectory with an individual target cluster and the MKV only need to interdict a target in the cluster. Since these targets are ballistic this scenario represents the lower end of the capabilities needed in the GS MKVs The analysis results are summarized in Figures 3a, 3b, 3c and Figures 4a, 4b, and 4c.

The key MKV parameters of interest include: vehicle divert acceleration, Δv, seeker IFOV and FOV, guidance update rate, inertial measure unit (IMU) drift rate, and total MKV mass budget. Figures 3a, 3b, and 3c respectively show that an acceptable IMU drift rate is ~2°/hr, a Δv budget of only 50 m/s, and a divert acceleration of 2 gs. Similarly, Figures 4a, 4b, and 4c show the Monte Carlo simulation results verifying the requirements for guidance update rate of 30 Hz, divert acceleration of less than 3 gs, and a seeker IFOV of less than 50 μrad.

Concept of Operations System Drivers

In our approach we consider that the Genius Sand Mini-KV is essentially a sub-scale version of a standard exo-atmospheric kinetic kill vehicle. Its essential systems, including, its Seeker, miniaturized IMU, processor module, power and propulsion systems, must perform many of the same functions as in a full-up KV. The level of functionality required by these systems will however, depend strongly on the overall system architecture chosen. This will in turn, determine the level of autonomy or redundant capability that is designed into each MKV or the system of MKVs. There are several approaches to take for the system architecture that will significantly effect the capability of the MKVs. For example, if we assume they are transported together to the threat cloud(s) by a Carrier Vehicle (CV), it is reasonable to rely on this carrier vehicle to perform some portion of the intercept mission. The carrier size would need to accommodate a large quantity of MKVs (tens to hundreds of vehicles), which may also offer the placement of a significantly larger Seeker telescope on the CV, as compared to that carried on each MKV. Also the total Δv and acceleration capability of the CV will affect these same parameters on the MKV. A large seeker telescope aperture on the carrier vehicle would be able to acquire and track the threat cloud significantly earlier, and with greater accuracy, than the seekers carried on each MKV. Further, if the systems are designed to enable the carrier vehicle to coach the mini-KVs, either from Ground Based Radar (GBR) derived Target Object Maps (TOMs) or with the CV's own on-board seeker, then the MKVs can be dispatched much earlier, well before they can acquire the target on their own. This ability can significantly increase the fly-out divert distance that the MKVs can then access, since the sooner the lateral fly-out starts the farther they can go.

The requirements on the MKV's DACS and its divert distance capability are driven by several factors. These include the characteristics of the threat and the approach taken to the engagement. The physical extent of the threat cloud and the closing velocity (between the targets and the MKVs) at the time of the engagement, sets the basic scale factor of the encounter. To position themselves across the threat cloud, the MKVs will need some fly-out time after deployment from the CV to traverse this distance. Also of critical importance is the remaining time-to-go (tgo) when the MKV acquires the target during the terminal portion of the end game. Both the fly-out time and Tgo at acquisition, depend on the closing velocity of the engagement and the acquisition range of the seeker against a particular target. These mission drivers determine the Δv (or total impulse) and the acceleration capability that the propulsion system must deliver.

If the MKVs are deployed early, e.g. many tens of seconds before intercept, then they have more time to fly out a given distance from the carrier vehicle. In the assumed architecture the carrier vehicle has been dispatched to this set of target clusters by an off-board cueing system such as a GBR, and that it will attempt to position itself and its payload of MKVs near the center of the distribution of targets (several clusters of decoys and RVs) for off-loading. Then the largest distance that the MKVs must travel is just the radius of the target distribution (set of target clusters). The more time the MKVs have for this fly out the lower the velocity and the acceleration necessary for this portion of the mission. If the carrier vehicle has a sufficiently accurate TOM then this can be used to provide predicted intercept points (PIPs) to each MKV "prior" to dispatch, which could obviate the need for "post deployment" communication between the MKVs and the CV.

The MKV must perform a maneuver to generate sufficient velocity to minimize the miss distance.

This initial zero-effort-miss (ZEM) velocity, will depend on the amount of fly-out time available to the MKV. As an example, with 100 seconds available, an MKV that has generated a 100-meter/second change in velocity will travel 10 km. The vehicle's acceleration capability will determine how much time is spent generating this velocity. A 1-g (~10 m/s^2) vehicle would take approximately 10 seconds to generate this velocity change, whereas a 10-g vehicle would take only 1 second. Clearly the desire is to maximize the acceleration capability of the MKV DACS. However, high acceleration equates to high thrust which in-turn requires high mass flow, which leads to a higher dry mass DACS. The smaller the total mass of the vehicle, the lower the thrust required for a given acceleration capability and the smaller will be the amount of propellant required for a given Δv (or total impulse). With known values for vehicle mass and the required levels of thrust, the required mass fraction can be trivially determined using the rocket equation (assuming a given propellant specific impulse, Isp). However, it is a more challenging task, to generate an a priori estimate of all the various subsystem component masses prior to a point design. This task requires specific design knowledge and assumptions for each of the vehicles primary systems and must address the various system trades for the vehicle's operation.

Because of the distribution of aspect angles in the intercept geometries of these midcourse engagements, there is a rather large range of possible closing velocities between the targets and the MKVs. These can range from between 5 to 15 km/s with 10 km/s taken as the nominal value. *(Note: Depending on the basing mode and location of the interceptor relative to the targets, a tail chase engagement could encounter even lower closing velocities. For purposes of this discussion we assume that an arbitrary cut-off at 5 km/s will be used. In the rest frame of the target this still endows a 1 kg mass MKV with greater than 10 Mega-joules of kinetic energy, which should provide sufficient lethality against most targets of interest.)* This large (10 km/s) variation in the closing velocity, will significantly impact the operational scenarios that occur from the resulting range of mission timelines. Higher closing velocities will demand earlier MKV off-loads in order to provide sufficient fly-out time for them to travel to the edge of the target distribution. Allowing for a "minimum" fly-out time for this initial ZEM guidance maneuver (driven by the high closing velocity case), will fix the Δv and acceleration capability of the MKV, for this portion of the engagement.

In the terminal phase of the endgame, the MKV must acquire the target and guide itself to intercept autonomously. The shorter the acquisition range of the MKV's seeker, the less time there will be for the final terminal homing maneuvers. With a10 km/s closing velocity, an acquisition range of 10 km allows for only 1 second for an endgame maneuver. Even with a 10-g vehicle this allows for only a 50 m divert distance. With a 100 km acquisition range this would provide 10 seconds of terminal guidance which would result in up to 5 km of distance traveled (if the vehicle had an additional 1km/s of Δv). For a better comparison, if only 1 second of thrust was used, as in the first example, then this would lead to 950 m of divert distance traveled. Maximizing both the MKV's seeker acquisition range and its g-capability will maximize its intercept performance. However, both of these capabilities will drive up the mass and cost of the MKV. Larger seeker-telescope-apertures offer longer acquisition ranges but drive up both mass and production costs. Higher sensitivity IR FPAs required cryocooling, which also adds mass and cost to this system. These examples illustrate some of the complex competing trades that are found in this problem.

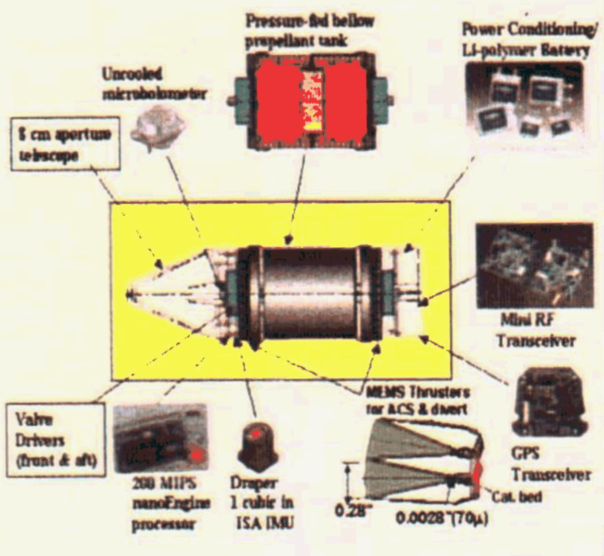
A weapon system that relies on some coordinated functionality (post-deployment), between the CV and MKV, will require some additional sub-systems, including, a communications link and GPS receiver. As mentioned above, the comm-link enables in-flight-target-updates (IFTUs) from the CV to the MKV, which will provide additional mission flexibility. This approach also mitigates a key limitation of a miniaturized KV, alluded to above, which is the size of its seeker telescope aperture. Allowing the MKV to benefit from an initial off-board target acquisition and tracking period, may allow the MKV's seeker system to be optimized only for the terminal end-game portion of its mission. Several concepts are being considered including both passive imaging (both IR and visible) as well as active bi-static illumination for the MKV. The carrier vehicle can provide target illumination (or designation) for the MKVs with a laser illumination system that could result in a very simple low cost visible CMOS imager on each MKV. Alternately (or in addition to) the MKVs could be fitted with new uncooled LWIR imagers (imaging microbolometer arrays) that would enable them to track even thermally cold targets during the final end-game homing portion of the fly-out. To support any coordinated operation between the carrier and MKV will require use of a miniaturized GPS system that can support operations at orbital velocities. Absolute position knowledge of the carrier and each Mini-KV platform will ease any on-board battle management that the carrier vehicle must perform in coordinating the dispatch of the swarm of MKVs. The MKVs can also use a GPS receiver to maneuver themselves to a PIP location, provided either before or after their off-load from the carrier vehicle.

Another possible mode of operation is to have the carrier vehicle perform a significant breaking maneuver after it has deployed its payload of MKVs. This would enable the carrier to fall behind the swarm of MKVs and observe the engagement to monitor the success of the mini-KV's intercept performance. The carrier can perform a local kill assessment function, which observes the size of the flashes and resulting debris cloud. The high resolution, short-range imaging afforded by the CV offers a unique observation platform from which to assess the phenomenology of the intercepts, and can provide a high confidence indication of how many "real" targets were interdicted. Further, if a two-way communications capability is chosen for the MKV, then a compressed sequence of end-game imagery can be obtained from each vehicle, providing a terminal view of the target and an independent measurement of kill assessment from each MKV interceptor.

Subsystem Technologies

The mini-KV consists of a sub-scale version of kinetic kill vehicle. Its essential systems include a seeker, miniaturized IMU, processor, power system and DACS propulsion system. There is a variety of available technologies found in the consumer electronics area that offer high performance yet meet the strict volume, mass and power requirements needed for a few kilogram mass MKV. The proliferation of new CMOS imagers in the digital imaging market, advanced processors for handheld PDAs and notebook computers, and lightweight Li-ion battery packs in cell phones and other portable electronic products, provide a rich technology base on which to draw. In addition, the continued development of MEMS technologies will enable the further miniaturization of inertial measurement units (IMUs) to a level that will make their incorporation into an MKV both practical and affordable [2].

Cost is also a significant driver for the MKVs, and we are investigating a range of subsystem solutions that leverage the commercial sector's production base for this hardware. Since large numbers (tens to hundreds) of MKVs will be needed per engagement against a single threat cloud, of up to hundreds of objects, finding usable technologies that offer low costs and quantity production is essential. Through selection of the correct partition between carrier vehicle and MKV functionality and the correct selection of subsystem technologies, we expect that it will be feasible to get the recurring cost of the MKVs down to a few tens of thousands of dollars each, for an operational system with a high volume buy.



Prototype #2 H2O2 Liquid DACS	ISP=130s	
Mass Budget (kg)	Min	Max
IR Seeker (Microbolometer)	0.200	0.200
IMU(MEMS)	0.050	0.100
Processor & I/O	0.080	0.100
Power Conditioning/ Batteries/Harness	0.180	0.210
Comm/GPS	0.060	0.070
Payload Structure	0.100	0.100
DACS Dry Mass	0.450	0.550
ACS and DACS pressurant	0.150	0.150
Contingency	0.080	0.100
KV Dry Mass	1.350	1.580
Propellant Mass	0.65	0.420
Computed Δv (m/s)	501	300
KV mass fraction	0.325	0.210
Total KV Mass	2.000	2.000

MOOG **Caution: LLNL/Moog Proprietary Information**

Fig. 5 LLNL proposed second generation midcourse GS MKV prototype vehicle using a MEMS DACS, MEMS IMU, and lightweight avionics.

GS Vehicle Configuration

Figure 5 shows a preliminary representative design of a 2 kg mass prototype MKV for midcourse applications. This vehicle is capable of 500 m/s of Δv and 2 g's of acceleration. For BPI application, we would need 5 g's of acceleration and preferably more Δv in addition to a more capable set of sensors. This would require higher thrust, more propellant and likely result in a slightly heavier mass vehicle. As shown in the figure, the key technologies of LLNL's GS vehicle are: (1) lightweight self-pressurizing propellant tank, (2) micro-electro-mechanical system (MEMS) based thrusters for ACS and divert, (3) nanoEngine processor, (4) high energy density battery, (5) miniature avionics and a MEMS based IMU and (6) lightweight replicated compact composite optics.

Propulsion

In the propulsion area, we are investigating a liquid propellant based concept developed by LLNL and Moog Inc., for a MEMS Divert and Attitude Control System (DACS). We also plan to evaluate the feasibility of further miniaturizing LLNL's pumped propulsion system, currently under development for a larger high performance interceptor application the Advanced Technology Kill Vehicle (ATKV). A miniaturized pump-fed propulsion system offers Δv's in excess of 2 km/s, enabling these MKVs to be utilized against maneuvering targets in Boost Phase missions with little needed help from a carrier vehicle. A further capability that may be needed by the GS MKVs is an ability to generate both axial and divert thrust that can provide a flexible combination of Δv in the fly-out. This approach offers additional mission flexibility that can support boost phase and midcourse engagements. We would plan to utilize non-toxic propellants to reduce cost, development time and improve safety. Either a pressure-fed, self-pressurizing or pump-fed approach could be considered for this application. Mono-propellant hydrogen peroxide H_2O_2 appears as a viable candidate for this system since it is relatively straight forward to scale down to small thrusters and valves. Other propellants are also under consideration including both hydrazine and HAN (a non-toxic propellant under development by the Air Force). The use of high concentration peroxide (85-95%) offers a relatively high performance system, yet it can stand in for these other higher Isp propellants during development.

In the MEMS DACS the central propellant tank, is used as the main structural element of the vehicle. At this mass scale one cannot afford to have separate structural and propulsion elements, so the main propellant tank must act as the core of the Genius Sand MKV structure. The H_2O_2 propellant slosh can be controlled using either, a pair of bellows, a flexible plastic bladder or a pair of small pistons. Such positive ullage control enables the vehicle to maintain a fixed c.g. throughout its propellant expulsion. We are still considering a number of design options for this DACS, but todate Moog Inc., has already demonstrated a highly producible batch-fabricated miniaturized valve assembly that we expect will have low-production-costs, and can be utilized in this application. A MEMS based thruster assembly is under design to reduce both mass and volume, in an assembly that can take advantage of the IC industries' high-volume and low-cost fabrication techniques. We believe that with this design concept, we can scale the thruster components to the size needed for an MKV application. We expect that the MEMS DACS will support a 300-500 m/s Δv with a 2-g acceleration capability for a 2 kg mass GS MKV.

Seeker

The optimum choice of the Seeker design will first depend on whether we are designing for either a boost phase or midcourse capability or both. This will of course impact the choice of focal plane array(s). For boosting targets the signals are orders of magnitude larger and peak in the shortwave infrared (SWIR) whereas late nighttime midcourse engagements would likely only see signals in the longwave infrared (LWIR). The choice of seeker technology will also depend on the system architecture and the CONOPS selected for the engagement, e.g., whether highly cooperative or fully autonomous capabilities are desired. To better span this range of options for these applications, we are investigating both visible and LWIR imaging sensor technologies for the MKV. A visible channel would require adequate off-board illumination, either natural or artificial. Natural illumination can not be counted on to provide a robust system so we expect that this would function in the context of an active visible illumination scenario, where the CV provides laser illumination of the chosen target. This bi-static illumination approach requires the CV to detect and to choose the target that the MKV will see. The CV must itself be able to passively detect and track the threat cloud and determine which candidate targets are sufficiently compelling to provide the illumination for a designated MK. Preliminary link margin analysis indicates that significant laser power will be required along with the ability to cue each MKV to which target it should home towards. From the MKV perspective this is the simplest approach since a very simple Seeker can provide the necessary line-of-sight (LOS) measurements.

For the interdiction of targets in deep midcourse, it is clear that most of the targets will have reached thermal equilibrium with the space environment. Since one cannot always count on solar illumination to provide photons for the MKV's seeker system, a reasonable choice for an autonomous passive imaging system is to utilize a long-wave infrared (LWIR) sensor (8 to 12 micron waveband). This waveband is where most of the self-emission from the targets of interest will be found spectrally. Additional contributions can occur from the upwelling earthshine, that spans the mid- to long-wave portion of the electromagnetic spectrum. For boost phase missions an LWIR imager will still encounter sufficient self-emission to support terminal homing towards the target hardbody. However, the challenge will then be the plume-to-hardbody handover problem.

Even with the cost and mass of LWIR seeker systems continuing to fall, as their performance continues to improve, typical high end photo-voltaic FPAs require cryocooling and will be a challenge to meet the small mass and volumes at an affordable cost for the MKV application. However, due to the large interest and utility of LWIR imaging, in a variety of everyday situations, (e.g. night vision and fire-fighting applications) there is significant commercial and aerospace effort ongoing to develop this technology, and it is being pursued along a broad front of focal plane array (FPA) detector materials and device configurations.

If it is determined that the seeker must only provide the final endgame imaging, then recent developments in MEMS based microbolometer arrays could provide the most practical and affordable solution. Recent microbolometer imaging cameras offer high sensitivities (< 80 mK ΔT @ f/1 optical systems) and significant pixel counts (320 x 240) with uncooled device operation. Uncooled microbolometer devices are fairly recent developments, but they have been in research and development for over a decade. Several different material choices and device architectures have been demonstrated on these FPAs. These modern devices leverage CMOS and MEMS fabrication processes, and have eliminated the need for mechanical beam choppers which plagued earlier devices. Both amorphous silicon and Vanadium Oxide (VOx) microbolometer imaging arrays have been developed that respond electrically to thermally induced changes in their thermally isolated pixel elements. The amorphous silicon devices have time-constants that are an order of magnitude shorter (few milliseconds) than the VOx devices (10 to 30 ms). However, the VOx devices are more sensitive and the needed frame rates for this system can be supported by either technology. A fast (high light collecting, f/1) optical system will be needed to provide efficient photon collection over a broad LWIR spectral band. The diameter and focal length of the MKV seeker aperture and the choice of FPA, will determine the acquisition and tracking range against a given target signal.

It is noteworthy to mention, that under ambient solar illumination a small 1-meter diameter target is visible at several thousand kilometers, using only a small 5 cm aperture visible sensor. If a visible imager is desired, a broad range of devices can be used in an MKV seeker. Due to consumer demand, a large number of high performance visible imagers are candidates for this application. Imagers based on either CMOS active pixel FPAs or conventional CCDs can be considered for this application. CMOS arrays offer extremely low power and highly integrated functions including camera-on-a-chip systems. However, in order to guarantee target illumination in all instances, these imagers would require some form of active illumination. It is unlikely that the MKV's mass budget can tolerate carrying a laser illumination system. However, the carrier vehicle could carry a laser transmitter that could provide this illumination in a bi-static measurement mode, where the MKV images the targets using the reflected light provided by the carrier vehicle. Due to the high closing velocities of these engagements, the terminal imaging sequence occurs during a point of rapid changes in both the target cluster range and its resulting angular extent, as seen in both the MKVs and CV. This rapid variation adds significantly to the challenge of providing sufficient illumination across the entire target cluster for the large swarm of MKVs. Additional system analysis will be needed to determine whether a practical solution exists for this case. It is likely that flood illumination of the target clusters will not provide sufficient illumination, and that rapid beam-steering may be needed, further increasing the difficulty of implementing this scheme.

Figure 6 shows two state-of-the art CMOS visible imaging arrays. The one on top is a complete Camera-on-a-chip from Photobit, a color VGA sensor with 640 x 480 pixels. This CMOS Camera-on-a-chip combines low-power active-pixel technology in a standard format. The on-chip architecture encompasses the capture of photons, pixel readout, gain, analog-to-digital conversion, and an industry-standard digital interface. In addition, on-chip control registers can be programmed for a variety of applications. The lower image is a 500 Hz frame-rate black & white mega-pixel array (1024 x 1024 pixels). This array requires <0.5 watt at its very high 500

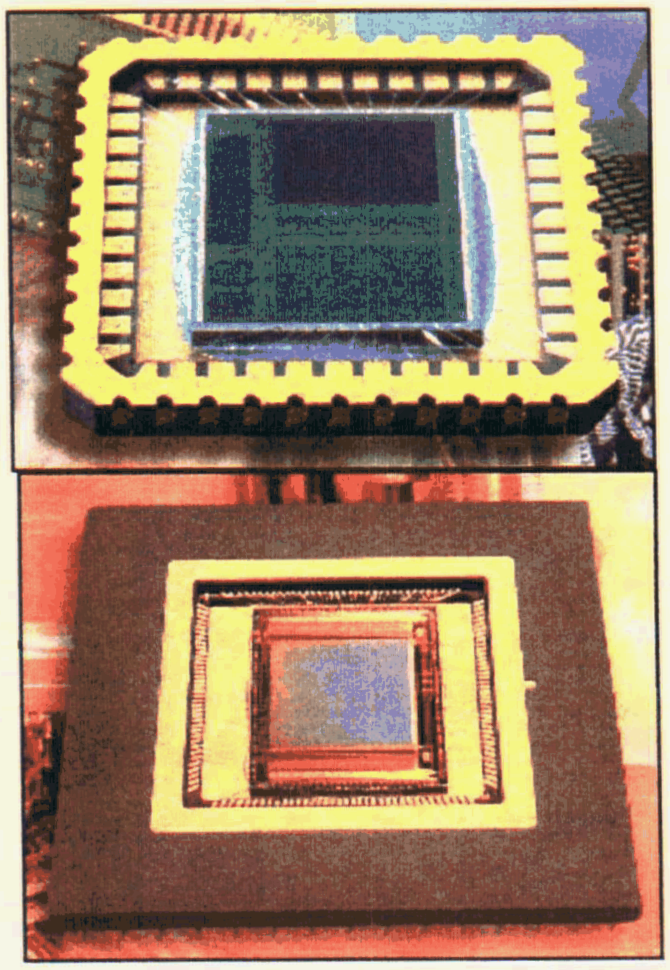


Fig. 6 Two state-of-the art CMOS visible imaging arrays. (Images courtesy of Photobit)

MHz pixel clock speed. This is a revolutionary performance advance over existing CCD imaging camera systems. LLNL has developed imaging sensors based on both of these candidate CMOS arrays and have utilized them in an Integrated Proximity Operations Sensor (IPOS) Suite. The IPOS has been integrated onto a small <20 kg test vehicle, which has demonstrated the ability to perform an autonomous docking on our 5DOF air table. These are just two examples of the many potential candidate FPA solutions for a visible imager on an MKV.

Processor/Avionics

The control processor and support avionics for the Genius Sand MKV must operate its imaging sensor(s), IMU and propulsion valves and potentially other payload system elements such as a GPS receiver and communications transceiver module. To meet the stringent mass and volume goals for the MKV we would need to apply state-of-the-art practices in the design and fabrication of this control electronics. The System-on-Chip (SOC) architecture offers a very highly integrated solution that leverages mainstream advancements in semiconductor circuitry and the design-reuse strategies that have brought intellectual property (IP) cores to market. For the final MKV design we would plan to use the SOC approach in the implementation of the avionics system. This would be accomplished in a stepwise fashion incorporating selected I/O cores that would support a COTS processor board in an early testbed vehicle. Following the successful implementation of this portion of the system, we will procure selected IP cores for the processor and remaining interface functions, thereby developing a full custom implementation that will support all of the MKV subsystems. This approach will maximize the use of existing commercial developments so that the MKV will be producible and supported by a number of commercial sources and can be easily transferred to an industrial prime or primes, following this technology demonstration. This system will be implemented with the latest Field Programable Gate Arrays (FPGAs), Application Specific Integrated Circuitry (ASICs) and Digital Signal Processors (DSPs), in order to minimize the mass and volume of these avionics modules while maximizing the performance of the system.

Power System

The state-of-the-art in power conditioning electronics has greatly benefited from the demand in portable consumer electronics systems. There are multiple sources for highly efficient miniaturized DC-to-DC converters and several primary (as well as secondary) batteries available for the power conditioning and supply electronics to be incorporated into the MKV. We have recent experience in developing a ruggedized and miniaturized power conditioning system for use in a DOE exo-atmospheric experiment and also in our ground test vehicles. There are several primary battery technologies that would be suitable for this system. The leading candidates for primary batteries are Lithium/Sulfuryl Chloride and Lithium/Thionyl Chloride, which have specific energies in the 450-500 Wh/kg at moderate to high discharge currents (0.25 to 0.5 Amps). Primary batteries will have at least a 2X mass advantage over rechargeable (secondary) batteries, but these are convenient for ground testing and applications such as microSats where a vehicle is used multiple times. Li-ion rechargeables are the leading choice for this application. The final mass allocation for an operational capability will depend on the nominal mission timelines and expected level and variability of the voltages and current levels needed. Our goal would be to incorporate the best solution to maximize the power provided and the total energy capacity.

IMU

Several candidate IMU technologies have been investigated and currently we expect that a MEMs IMU would be the best choice for this application. DRAPER labs development program appear as one of the most mature highest performance systems that could provide sufficient low drift rate operation to not require any updates during the MKV fly-out.

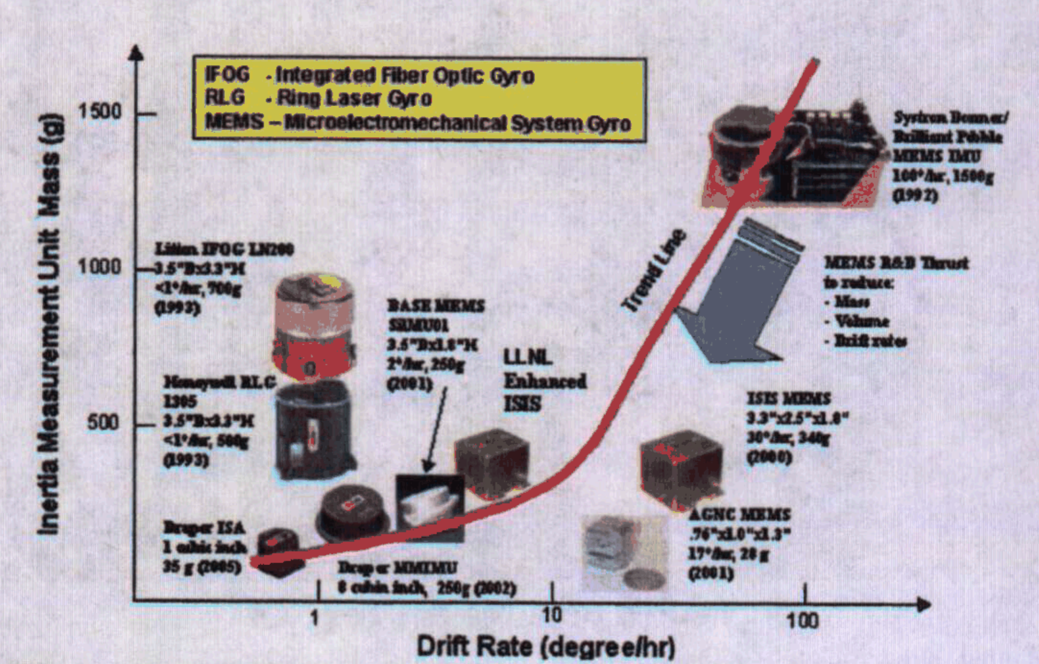
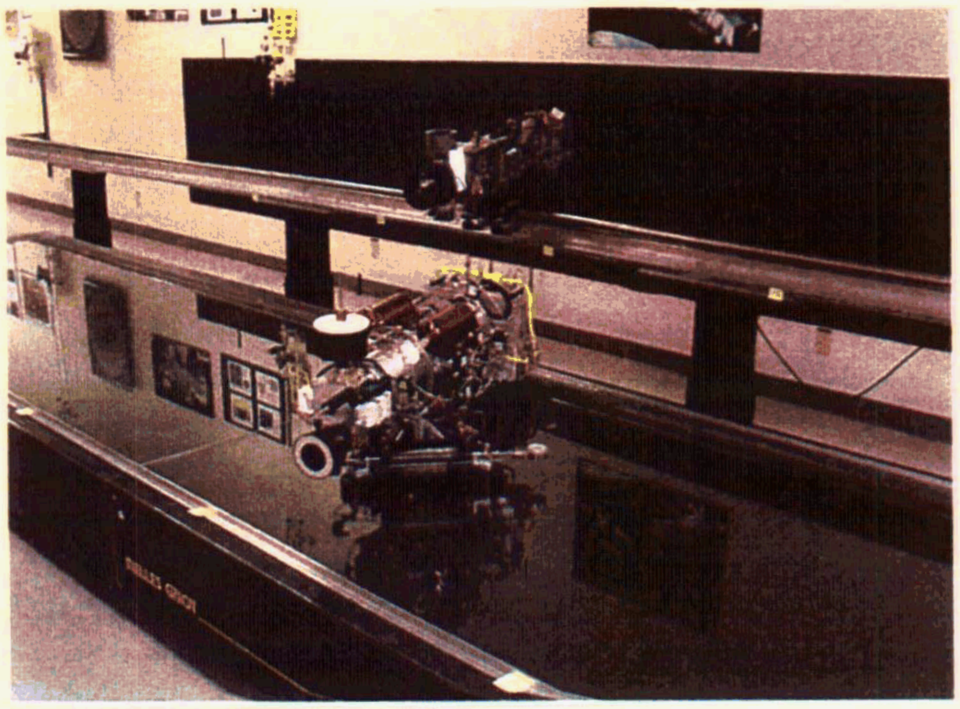
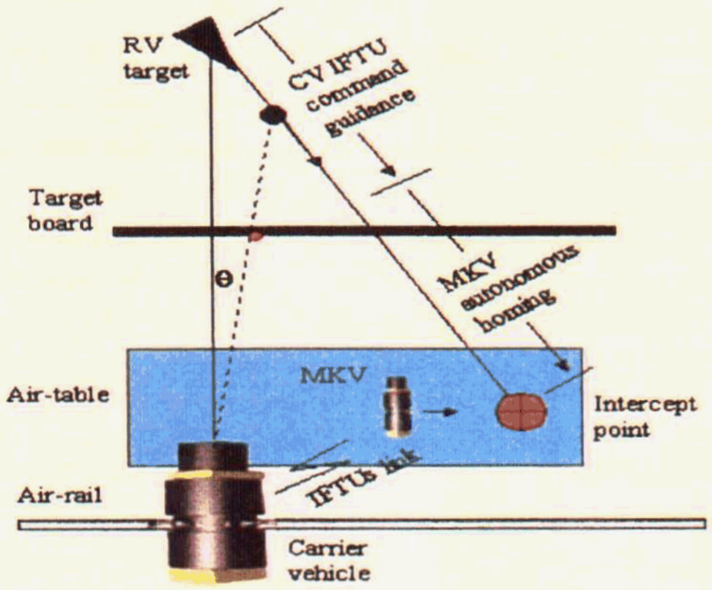


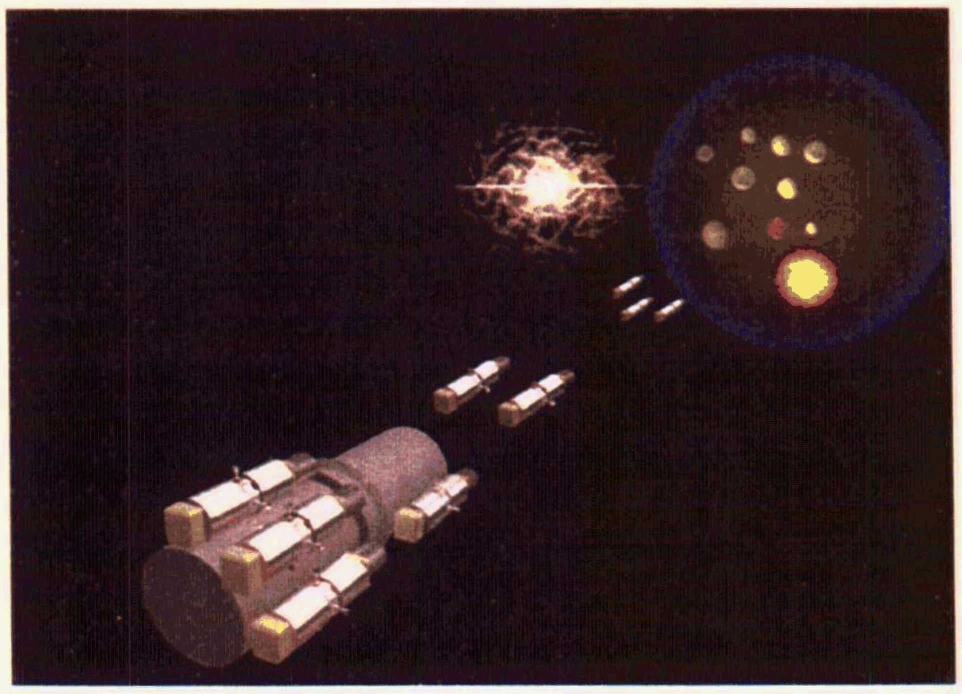
Fig. 7 Evolution in mass, volume and performance of selected inertial measurement units over the past decade.



(8a) Dynamic Air Table



(8b) Proposed CV & MKV experiment



(8c) Envisioned deployment concept

Fig. 8 Proposed joint CV and MKV hit-to-kill experiment to demonstrate MKV deployment concept

Integrated Testbed

An integrated testbed can be used as a means to provide a high fidelity evaluation of subsystem technologies and integrated performance of several component configurations. 4DOF and 5DOF tests are used to evaluate system performance. Figure 8 shows a functioning dynamic air bearing table and ground test vehicles that have been developed at LLNL and which could be used to support CV and MKV integrated testing. Our approach is to develop both a hardware testbed as well as a software testbed that accurately models the performance capabilities of an MKV and our laboratory set-up. Using our 6DOF model of the MKV hardware and algorithms, we will perform a set of Monte-Carlo simulations and validate the system performance measures with as many ground intercept flight experiments as needed (usually 10 or more would be sufficient). A good match between Monte-Carlo intercept flight experiments and Monte-Carlo simulation runs would give us the highest confidence that the final miss distance performance measurements are accurate. We have successfully conducted such an experiment and the results are published in the1999 AIAA Weapons Effectiveness Conference. (See Ref. [3,4])

Summary

We have generated a preliminary conceptual design of an MKV we have named Genius Sand as a tribute to the earlier generation of developments of LLNL's Brilliant Pebbles SBI system. We have evaluated a preliminary set of trades to determine how these flow-down into our MKV concept system. Further effort on this front is needed to evaluate further define the interactions between the MKVs and their CV.

We expect that a combined visible and LWIR capable Seeker will provide the most flexible system architecture. We currently are examining several ways to implement the miniaturized liquid DACS for the MKV. We believe a non-toxic propellant such as high concentration hydrogen peroxide (85-95% H2O2) offers a very effective propellant for this application. Several propellant pressurization approaches are under consideration and several appear quite feasible. Further development work on high flux density catalyst bed offer the hope of very small high thrust thrusters for these miniaturized DACS. A miniaturized reciprocating pumps also appear feasible at this scale. We believe that continued developments in commercial electronics will allow for the very small System on Chip (SOC) implementation of the full avionics set for this these MKVs as well as very light weight batteries and power conditioning circuitry. With a focused development program and LLNL's integrated ground testing approach we believe that a high performance MKV can quickly and affordably be developed for both midcourse and boost phase mission applications.

Acknowledgements

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References

[1] Ledebuhr, A.G., "Genius Sand: A Miniature Kinetic Kill Vehicle Technology Demonstration for Mid-Course Counter-Countermeasues and Submunition Kills," Prepared for the Missile Defense Agency and SMDC JCTI, November 15, 2001.

[2] Connelly, J., Kourepenis, A., and rt. Al., "Micromechanical Sensors in Tactical GN&C Applications," AIAA GN&C Conference and Exhibit, 6-9 August 2001, AIAA 2001-4407.

[3] Ledebuhr, A.G., Ng, L.C. and et. el.,"Micro-Satellite Ground Test Vehicle for Proximity and Docking Operations Development," 2001 IEEE Aerospace Conference, paper F270, March 10-17, 2001, also LLNL UCRL-JC-141110, dated October 26, 2000.

[4] Ng, L.C., Breitfeller, E., Ledebuhr, A.G., and Handler, F., "Air-Bearing Guided Intercept and Line-of-Sight Experiments (AGILE)," Presented at the First Biennial AIAA National Forum on Weapon System Effectiveness, April 6-8, 1999; also LLNL UCRL-JC-128922, dated April 1, 1999.

Biography

Dr. Arno G. Ledebuhr earned an undergraduate degree in Physics and Math in 1976 from the University of Wisconsin and masters and doctorate degrees in Physics from Michigan State University in 1982. Dr. Ledebuhr spent the following four years at the Hughes Aircraft Company and earned 15 patents in projection display technology. He has been at Lawrence Livermore National Laboratory since 1986 and led the development of advanced sensors for the Brilliant Pebbles interceptor program and the design of the Clementine sensor payload. In 1996 he was the Clementine II Program Leader and is currently the Program Leader for the Advanced Interceptor Technology Program. His interests include micro-spacecraft and kinetic kill vehicle technologies, including sensors and propulsion systems.

Dr. Lawrence C. Ng received his B.S. and M.S. degrees in Aeronautics and Astronautics from the Massachusetts Institute of Technology in 1973, and a PhD degree in Electrical Engineering and Computer Sciences from the University of Connecticut in 1983 under a Naval Undersea Warfare Center (NUWC) Fellowship. In addition, Dr. Ng received his commission as an Air Force officer in 1973 and served at the Hanscom Air Force Base in Bedford, MA. His work experience includes: four years with General Dynamics Electric Boat Division in Groton, CT, responsible for the development of the TRIDENT submarine digital control systems; seven years at the NUWC where he led the development of the advanced sonar signal processing for the Seawolf submarine. Since 1986, he joined the Lawrence Livermore National Laboratory where he was the group leader of the signal/image processing and control group and is currently the Chief Scientist for the Advanced Interceptor Technology Program. Dr. Ng is focusing his research in micro-spacecraft guidance and control, integrated ground testing, and ballistic missile defense systems analysis. In addition Dr. Ng is a member of several professional societies, including honorary memberships in Sigma Xi, Tau Beta Pi, and the National Research Council. He has published numerous papers in signal estimation and precision vehicle guidance and control.

Joe Kordas, Deputy Program Leader, received his B.S. degree in Physics from St. Procopius College in 1970 and M.S. degree in Biophysics from Michigan State University in 1974. He has worked at LLNL since 1974. His areas of interest are space-based optical sensors, instrumentation, and systems. He has worked with CCD detectors and cameras for the last ten years and was the lead electronics engineer for visible sensor development for Brilliant Pebbles, the lead electronics engineer for sensor development for the Clementine I Program and the Clementine II Deputy Program Leader. More recently, he has just completed a term as the LLNL Project Leader for the JTA-4, a high fidelity flight test vehicle for the W87. Currently, he is the ATKV Technologies Deputy Program Leader.

Dr. Donn McMahon, Mechanical Systems Engineer, leads the systems engineering development efforts for the Advanced Interceptor Technology Program at LLNL. He received his B.S. degree in Mechanical Engineering from MIT (1988) and the M.S. (1990) and Ph.D. (1994) degrees in control systems from UC Berkeley. He leverages off his cross-disciplinary background in mechanical and electrical systems and software development for the development of integrated intercept technologies, target discrimination algorithms, and multi-body interceptor system analysis. Dr McMahon is an expert in automotive vehicle dynamics and control systems, and has been the lead controls systems engineer for the National Ignition Facility (NIF) Transport & Handling Group. In this capacity he had primary responsibility for control system hardware and software development, system integration, and transition to operational status of five different automated optics handling systems. He has also provided engineering expertise to the SLAC accelerator project, a waste water treatment plant, and military tank model simulations. Dr. McMahon has published several papers on nonlinear control techniques for automotive and transportation systems and automated systems for optics handling.

Mark Jones, Electronics Lead, has worked in the field of electronics since 1977. He holds a B.S. degree in Computer Engineering from the University of the Pacific, Stockton, CA. Mark came to LLNL in 1984 where he has worked in electronics engineering, software development, and system integration on space-related projects including Brilliant Pebbles, MSTI, Clementine, and Clementine II. Currently, Mark leads the avionics effort for the ATKV Technologies Program.