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A NEW NON-NUCLEAR MKIV (MULTIPLE KINETIC-ENERGY IMPACTOR VEHICLE) MISSION CONCEPT FOR DISPERSIVELY PULVERIZING SMALL ASTEROIDS

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This paper presents the initial preliminary study results for a new non-nuclear MKIV (Multiple Kinetic-Energy Impactor Vehicle) system that can dispersively pulverize small asteroids ($<$ 150 m) detected with short mission lead times ($<$ 10 years). The proposed MKIV system with its total mass in the range of approximately 5,000 to 15,000 kg can be launched from a single large booster such as Delta IV Heavy, Falcon Heavy or the SLS. Its baseline architecture is comprised of a carrier vehicle (CV) and a number of attached kinetic-energy impactors (KEIs). Near to a target asteroid, the CV will dispense several KEIs and guide them to hit near-simultaneously different locations widely distributed across the target surface area and to cause shock waves to propagate more effectively through the target body. In this paper, a simplified 2D hydrocode simulation model is investigated using both an in-house GPU-accelerated hydrocode and ANSYS AUTODYN commercial software. A multi-target terminal guidance problem and a planetary defense mission design employing heavy-lift launch vehicles are also briefly discussed in support of the MKIV mission concept.

INTRODUCTION

Despite the lack of a known immediate impact threat from an asteroid or comet, historical scientific evidence suggests that the potential for a major catastrophe created by an asteroid or comet impacting Earth is very real. Humankind must be prepared to deal with such an event that could otherwise cause a regional or global catastrophe. There is now growing national and international interest in developing a global plan to protect the Earth from a catastrophic impact by a hazardous near-Earth object (NEO). This growing interest was recently spurred by the Chelyabinsk meteorite impact event that occurred in Russia on February 15, 2013 and a near miss by asteroid 367943 Duende (2012 DA14), approximately 40 m in size, on the same day.

A variety of NEO deflection/disruption technologies, including kinetic impactors, gravity tractors, and nuclear explosions, have been investigated by planetary defense researchers during the past two decades [1–6]. Kinetic impactors and nuclear explosions are the most practically viable technologies for asteroid deflection or disruption, as concluded in the 2010 NRC report [6].

The so-called "kinetic impactor" utilizes its linear momentum to cause an instantaneous ΔV of the center-of-mass of a target body as a result of its hypervelocity collision with the target body. In

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fact, such a kinetic impactor is a technically viable option for deflecting a small hazardous asteroid that can be detected with sufficient mission lead times (> 10 years). However, it is probable that the kinetic impactor will cause unintentional fragmentation of a target asteroid because its hypervelocity kinetic energy can be too excessive compared to the gravitational binding energy as well as the energy required for disruption of the target asteroid. The term “kinetic impactor” should be distinguished from the term “kinetic-energy impactor (KEI)” that utilizes its hypervelocity kinetic energy for intentionally disrupting a target body.

All of the non-nuclear techniques, which are intended mainly for deflection missions, will require mission lead times much longer than 10 years, even for a relatively small NEO. When the time-to-impact with the Earth exceeds a decade, the velocity perturbation needed to alter the orbit of a target asteroid sufficiently to deflect it away from Earth impact is relatively small (approximately 1 to 2 cm/s). Thus, most non-nuclear options as well as a nuclear standoff explosion can be employed for deflection missions when we have sufficiently long warning times. However, due to various uncertainties and constraints in asteroid detection and tracking, the warning time or mission lead time can be very short. An 18-m diameter meteor exploded with the energy of 30 Hiroshima nuclear bombs 30 km above the city of Chelyabinsk, Russia on February 15, 2013, with no warning at all. Asteroid 367943 Duende (2012 DA14), which had a near miss of the Earth on the same day as the Chelyabinsk event, was initially discovered on February 23, 2012. That is, we would have had only one year of warning time if the 40 m DA14 was going to collide with Earth. Another recent example is asteroid 2014 RC, which had a close encounter with Earth on September 7, 2014. This 20-m asteroid was initially discovered on August 31, 2014 by the Catalina Sky Survey near Tucson, Arizona, and independently detected the next night by the Pan-STARRS 1 telescope, located on the summit of Haleakala on Maui, Hawaii. We would have had only one week of warning time if 2014 RC was going to collide with Earth.

If a NEO on an Earth-impacting course is detected with a short warning time (< 10 years), the challenge becomes how to mitigate its threat in a timely and reliable manner. For a small asteroid impacting in a sufficiently unpopulated region, mitigation may simply involve evacuation [6]. However, for larger asteroids, or asteroids impacting sufficiently developed regions, the threat may be mitigated by either disrupting the asteroid (i.e., destroying or fragmenting with substantial orbital dispersion), or by altering its trajectory such that it will either avoid impacting the predicted impact location, or miss the Earth entirely. When the time to impact with Earth is short, the velocity change required to deflect a NEO becomes extremely large. Thus, for the most probable mission scenarios, in which the warning time is shorter than 10 years, the use of high-energy nuclear explosives in space may become inevitable [6]. To date, however, there is no consensus on how to reliably and safely mitigate the impact threat of hazardous NEOs with short warning time.

A scenario in which a small Earth-impacting NEO is discovered with short warning time is nowadays considered the most probable scenario because smaller NEOs greatly outnumber larger NEOs, and smaller NEOs are more difficult to detect. Most direct intercept missions with a short warning time will result in arrival closing velocities of 10 to 30 km/s with respect to a target asteroid. A rendezvous mission to a target asteroid that requires such an extremely large arrival ΔV of 10 to 30 km/s is not feasible. When the warning time is short, disruption (for dispersive pulverization or vaporization) is likely to become the only feasible strategy, as was concluded in the 2010 NRC report [6]. Despite the various uncertainties and concerns about the nuclear disruption approach, nuclear disruption can become an effective strategy if most fragments disperse at speeds in excess of the escape velocity of an asteroid so that a very small fraction of fragments impacts the Earth.

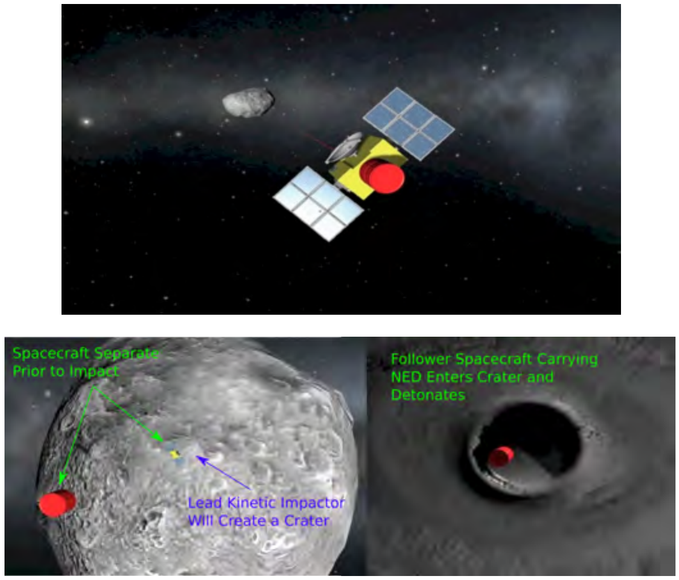


Figure 1. A notional depiction of the HAIV mission concept [14].

Because nuclear energy densities are nearly a million times higher than those possible with chemical bonds, a nuclear explosive device is the most mass-efficient means for storing energy with today's technology. However, in this paper, we propose a new non-nuclear approach as an option that can be employed to dispersively pulverize small asteroids ($<$ 150 m in diameter).

This paper will present a brief overview of a HAIV (Hypervelocity Asteroid Intercept Vehicle) mission concept of blending a kinetic-energy impactor and a nuclear subsurface explosion, followed by the description of a new non-nuclear MKIV (Multiple Kinetic-Energy Impactor Vehicle) mission concept for dispersively pulverizing small asteroids. A 2D hydrocode simulation model of the MKIV system concept will be examined using both an in-house GPU-accelerated hydrocode and ANSYS AUTODYN commercial software. The 2D hydrocode model is comprised of a reference 5,000-kg MKIV system simply consisting of a 1,000-kg carrier vehicle and four 1,000-kg KEIs and a 2D circular, 100-m solid object with a nominal density of 2,000 kg/m^3. A multi-target terminal guidance problem and a planetary defense mission design employing heavy-lift launch vehicles will also be briefly discussed. It is emphasized that the nuclear HAIV and non-nuclear MKIV systems complement to each other.

HAIV MISSION CONCEPT

NASA Innovative Advanced Concept (NIAC) Phase 1 & 2 studies, entitled "An Innovative Solution to NASA's Near-Earth Object (NEO) Impact Threat Mitigation Grand Challenge and Flight Validation Mission Architecture Development," have been conducted at the Asteroid Deflection Research Center (ADRC) of Iowa State University in 2011–2014. The study objective was to develop an innovative, yet practically implementable, mitigation strategy for the most probable impact threat of an asteroid or comet with short warning time ($<$ 10 years). The NIAC study has resulted in a HAIV (Hypervelocity Asteroid Intercept Vehicle) mission concept employing both a kinetic-energy impactor and nuclear explosive devices (NEDs), as illustrated in Figure 1.

The HAIV mission concept is intended to optimally reduce the severity and catastrophic damage of the NEO impact event, especially when we don't have sufficient warning times for non-destructive deflection of a hazardous NEO. Detailed technical descriptions of the HAIV concept can be found in [7–16]. The NIAC study results can also be found in the final technical report, which can be downloaded from the ADRC website (www.adrc.iastate.edu).

Most direct intercept missions with short warning time will result in arrival closing velocities of 10 to 30 km/s (relative to a target asteroid). A rendezvous mission to a target asteroid, requiring such an extremely large arrival ΔV of 10 to 30 km/s, is not practically feasible. A nuclear subsurface explosion, even with shallow burial to a depth of 3 to 5 m, can deliver a large amount of energy into the target asteroid, so that there is a likelihood of totally disrupting the target asteroid. Such subsurface nuclear explosions are known to be at least 20 times more effective than a nuclear contact burst [17]. However, state-of-the-art nuclear subsurface penetrator technology limits the impact velocity to less than about 300 m/s because higher impact velocities prematurely destroy the fusing mechanisms/electronics of nuclear explosive devices [17].

The HAIV system concept overcomes such practical constraints on the penetrated subsurface nuclear explosion. It will enable a nuclear disruption mission with intercept velocities as high as 30 km/s. The HAIV is a two-body space vehicle consisting of a fore body (leader) and an aft body (follower), as illustrated in Figure 1. The leader spacecraft creates a kinetic-impact crater in which the follower spacecraft carrying NEDs makes a robust and effective explosion below the surface of the target asteroid body. Surface contact burst or standoff explosion missions will not require such a two-body vehicle configuration. However, for a precision standoff explosion at an optimal height of burst, accurate timing of the nuclear explosive detonation will be required during the terminal guidance phase of hypervelocity intercept missions.

For a small target asteroid, the terminal guidance phase may begin 2 hrs prior to the final intercept collision. The nuclear fuzing system may be activated, arming the NED payload, much earlier in the terminal phase operations timeline. Instruments located on the leader spacecraft detect the target NEO, and a terminal guidance subsystem on-board the HAIV becomes active. Measurements continue through visual/IR cameras located on the leader spacecraft and an intercept impact location is identified on the target asteroid body. The high-resolution visual/IR cameras provide successive images of the NEO to the terminal guidance system for a few trajectory correction maneuvers. Separation must occur between the leader spacecraft and the follower spacecraft before the leading kinetic impactor collides with the target. A variety of existing launch vehicles, such as Delta II class, Atlas V, Delta IV, and Delta IV Heavy, can be used for the HAIV mission carrying a variety of NED payloads ranging from 300-kg (with approximately 300-kt yield) to 1,500-kg (with approximately 2-Mt yield).

Because the hypervelocity kinetic-energy impact and nuclear subsurface explosion simulations rely heavily on energy transmission through shocks, the simulation research work conducted for the HAIV mission concept study [10–12] used Adaptive Smoothed Particle Hydrodynamics (ASPH) to mitigate some of the computational and fidelity issues that arise in more complex, high-fidelity hydrocode simulations. The propagation of the nuclear explosive shock can be seen for an illustrative benchmark test case shown in Figure 2. The shock propagation process dissipates some energy due to interactions with the rebounding shock front. In the center area of deeper regolith, the seeding process naturally results in a much more porous material, absorbing energy from the shock. Upon reaching the second core at the far side, some large chunks escape the disruption process in some cases (even with lower material strengths). An improved ASPH code, implemented on a modern low-cost GPU (Graphics Processing Unit) desktop computer, has been developed for the HAIV

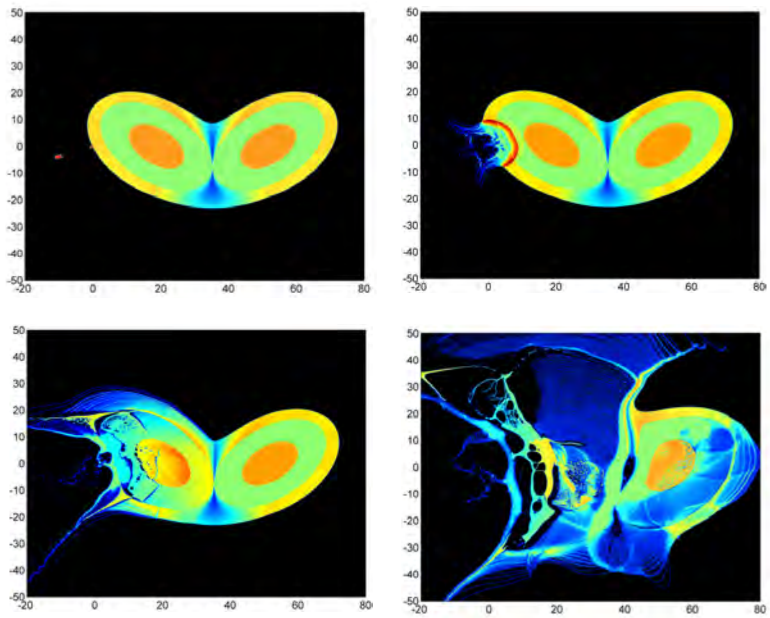


Figure 2. A 70-m asymmetric 2D model disrupted by a 10-km/s kinetic-energy impact and a subsequent 70-kt nuclear subsurface explosion of the HAIV system [10–12].

mission study [10–12].

NEW NON-NUCLEAR MKIV MISSION CONCEPT

As discussed in [18], a hypervelocity kinetic-energy impactor (KEI) with an impact speed larger than approximately 5 km/s has a “mass-multiplication efficiency” of approximately 10^5 to 10^7, i.e., a unit mass of optimally configured KEI can dispersively pulverize 10^5 to 10^7 times its own mass of a target asteroid. For example, a 1000-kg hypervelocity KEI may be able to pulverize and disperse an asteroid with a mass of 1E8 to 1E10 kg. In [18], the specific energy (per unit asteroid mass) required for dispersive pulverization of asteroids of 30 m to 10 km in diameters is stated as approximately 100 to 10,000 J/kg and the specific energy for vaporizing them is stated as approximately 1E6 to 3E6 J/kg.

A 1,000-kg KEI with an impact speed of 10 km/s has a kinetic energy of 5E10 J, and it can cause a center-of-mass ΔV of at least 1 cm/s for a 100-m (diameter) spherical asteroid with a uniform density of 2000 kg/m^3 via an ideal linear momentum transfer. Note that a 100-m (diameter) spherical asteroid with a uniform density of 2000 kg/m^3 has a mass of 1E9 kg and that its gravitational binding energy is approximately 8E5 J, which is relatively small compared to the kinetic energy (5E10 J) of a 1000-kg hypervelocity KEI with an impact speed of 10 km/s.

In [18], dispersive pulverization of an asteroid into meter-scale fragments by exploiting the hypervelocity kinetic energy was proposed as a practically viable option for mitigating the impact threat of small asteroids, especially with short warning times. However, fragmenting a solid object into pieces of pre-specified maximum scale (e.g., 1-m fragments) requires the imposition of a fracture-level stress field having the same periodicity. In order to maximize the fragmentation benefits of large-scale crack propagation, the simultaneous imposition of such stress field over as large fraction of the object as may be technically feasible was considered in [18]. As a result, various innova-

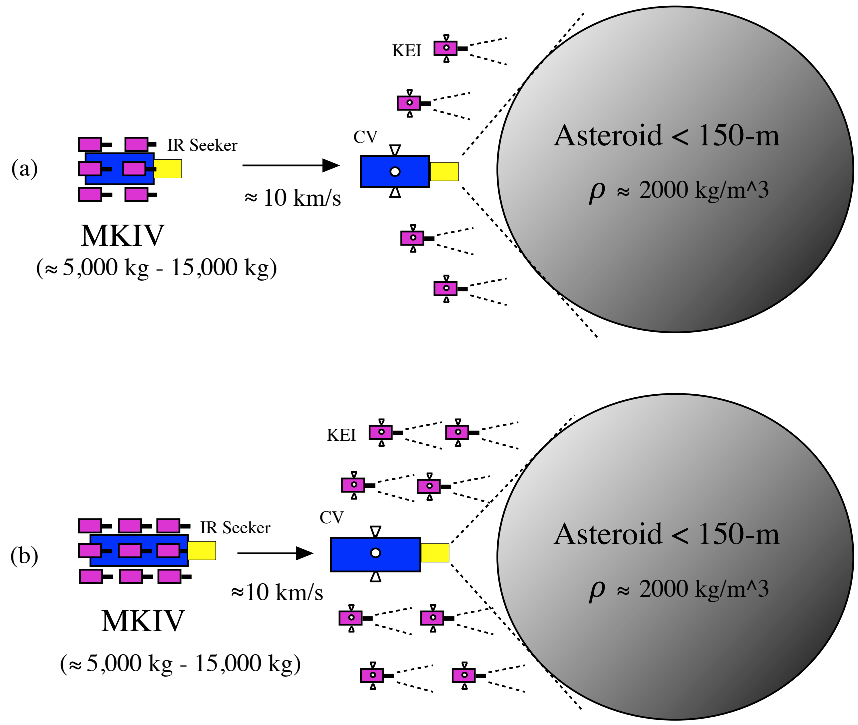


Figure 3. Conceptual 2D illustration of a non-nuclear MKIV mission concept for dispersive pulverization of a small asteroid.

tive ways (e.g., a massive 3D penetration projectile lattice, multiple large spinning nets, etc.) of effectively distributing the hypervelocity kinetic-impact energy to dispersively pulverize an asteroid have been proposed in [18]. However, a deployment of such large complex structures in space will require advanced space technologies that will not be readily available in the near future.

In this paper, expanding upon the fundamental "mass-multiplication efficiency" property of the hypervelocity KEI as described in [18], we propose a new non-nuclear MKIV (Multiple Kinetic-Energy Impactor Vehicle) mission concept for dispersively pulverizing small asteroids detected with short warning times ($<$ 10 years).

Similar to an MKV (Multiple Kill Vehicle) system architecture by Lockheed Martin [19], which was once envisioned in early 2000s (and to be re-developed probably in late 2010s) as part of the Ballistic Missile Defense System of the United States, our proposed MKIV system consists of a carrier vehicle (CV) with on-board visual/IR seekers and a number of KEIs attached to the carrier vehicle, each equipped with its own divert and attitude control thrusters. As illustrated in Figure 3, near to a target asteroid, the CV will dispense several KEIs and guide them to hit near-simultaneously different locations widely distributed across the target surface area and to cause shock waves to effectively propagate across the wider surface area. Figure 3(b) also illustrates a variant of our proposed MKIV concept that attempts to exploit a potential effectiveness of the 3D penetration projectile lattice concept as proposed in [18].

The proposed MKIV system with its total mass in the range of 5,000 to 15,000 kg can be launched from a single large booster such as Delta IV Heavy, Falcon Heavy or the SLS. The MKIV system will complement the HAIV system carrying NEDs, which was originally conceived for disrupting larger asteroids (> 150 m). The MKIV concept can also be extended to a nuclear multi-HAIV system for much larger asteroids (> 500 m). Note that it may be impractical to design a single massive (> 5,000 kg), yet highly agile, kinetic-energy impactor with its precision terminal intercept maneuvering capability. However, the proposed MKIV system will require a further system-level tradeoff study for its terminal intercept guidance [15, 16], similar to the case of two different deployment concepts of the MKV [19, 20]. The MKV-L by Lockheed Martin consists of a CV and attached KEIs, while the MKV-R by Raytheon consists of identical multiple KEIs without a CV. Animated conceptual mission operations (e.g., deployment of multiple KEIs, autonomous terminal intercept engagement scenarios, etc.) of both MKV-L and MKV-R concepts can be seen in [21].

GPU-BASED HYDROCODE MODELING AND SIMULATION OF MULTIPLE KINETIC-ENERGY IMPACTS

Simulation results of multiple kinetic-energy impacts obtained using an in-house GPU-accelerated hydrocode are discussed in this section. Modeling and simulation of hypervelocity kinetic impacts and nuclear explosions for deflecting or disrupting asteroids is a complex physical/computational problem, and it has been extensively investigated in [9–12, 22–28]. A simple 2D simulation model considered in [27, 28] is comprised of a reference 5,000-kg MKIV system simply consisting of a 1,000-kg CV and four 1000-kg KEIs and a 2D circular, 100-m object with a nominal density of 2,000 kg/m^3. The main objective of conducting a hydrocode simulation study in [27, 28] was to determine whether an asteroid can be dispersively pulverized by the proposed MKIV system more effectively than by a single massive KEI of the same total mass as the MKIV system.

Benchmark Simulation Cases

An ideal 2D hydrocode simulation model for a single KEI is illustrated in Figure 4. The target body is modeled as a 2D circular, 100-m diameter solid body with a nominal uniform density of 2,000 kg/m^3, while the KEI is modeled as a 1×1 meter box. No porosity effects are considered for the target asteroid. The asteroid body is modeled as granite, while the KEI is modeled as aluminum.

Two distinct mission scenarios for multiple kinetic-energy impactors are illustrated in Figure 5. For multiple KEIs in parallel, shown in Figure 5(a), all KEIs are assumed to hit simultaneously at time $t = 0$, and the kinetic energy transferred to the target body is monitored in simulations. The multiple KEIs arranged in series, as illustrated in Figure 5(b), is slightly more challenging for hydrocode simulations. Each KEI is spaced 10 meters apart, and at time $t = 0$, the lead KEI hits the target. It is assumed that each KEI is completely destroyed in these simulations before the following KEI hits the bottom of the crater. All KEIs again are assumed as 1×1 meter boxes.

Figure 6 illustrates another MKIV system option to be further considered in future work. This configuration attempts to exploit the advantages of both parallel and serial impacts. Also, it represents a multiple-HAIV system that may be required for disrupting much larger asteroids (> 500 m).

Several simulation test cases are considered in [27, 28]. For Case 1, the size of the single KEI is not varied, while its mass is varied from 162-kg, 600-kg, and up to 1000-kg. The depth of the generated crater is monitored at several elapsed times. For Case 2, the KEI mass is held at 1,000-kg, but the shape is varied from a box to a rectangular body. Again, the crater depth is monitored at several times. Case 3 explores a single massive 5,000-kg KEI, while Cases 4 and 5 consider the multiple impact scenarios in parallel and series, respectfully. In this section, we briefly discuss only

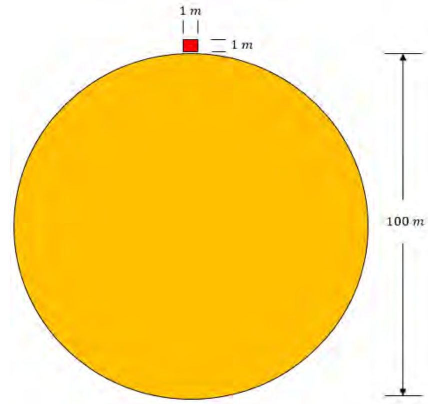
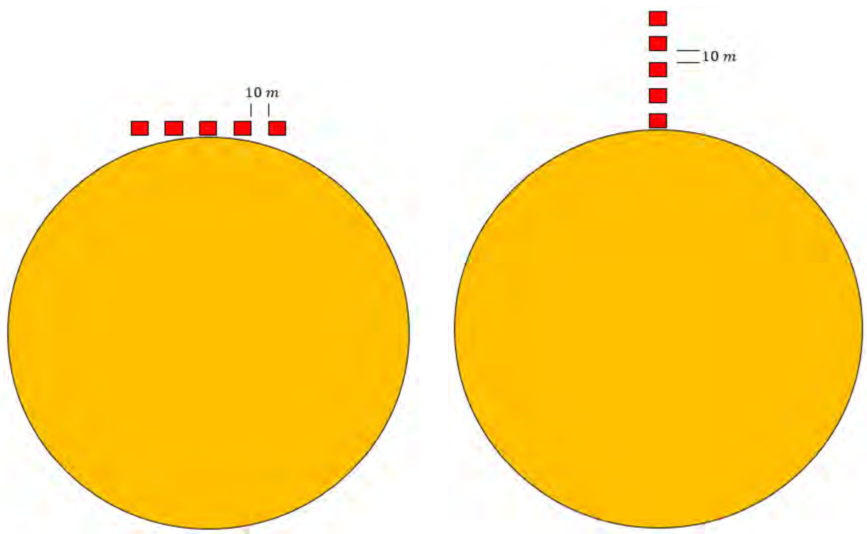


Figure 4. An ideal 2D hydrocode simulation model with a single kinetic-energy impactor [27, 28].



(a) Multiple KEIs in parallel (b) Multiple KEIs in series

Figure 5. 2D Illustration of two distinct mission engagement scenarios of multiple KEIs [27, 28].

Cases 3, 4 and 5 as follows.

Case 3

This case considers a single massive KEI with a mass of 5,000-kg traveling at 10 km/s. The simulation results showing the density contours are shown at three different elapsed times in Figure 7. The single massive KEI generates a substantially deep crater, roughly 5-m in depth at 3 milliseconds of simulation time. The shock wave produced in the asteroid body is significantly stronger than Case 1 with a 1000-kg KEI.

Case 4

In this test case, a parallel deployment of multiple KEIs with the CV impactor is considered. At $t = 0$, it is assumed that all impactors strike the target. All impactors have the same initial

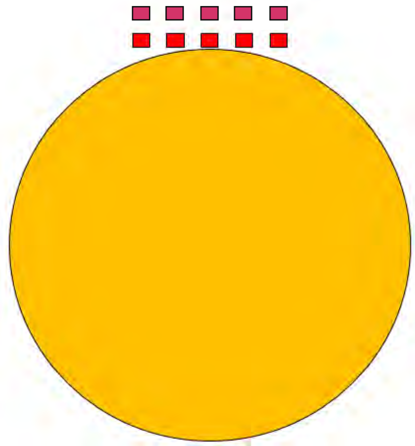
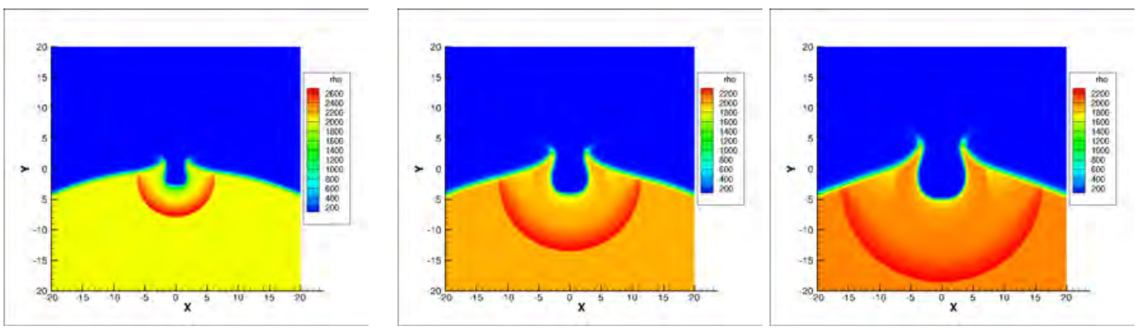


Figure 6. A 2D hydrocode simulation model representing either multiple KEIs in parallel/series shown in Figure 3(b) or a multiple-HAIV system.



(a) elapsed time = 1.0 ms (b) elapsed time = 2.0 ms (c) elapsed time = 3.0 ms

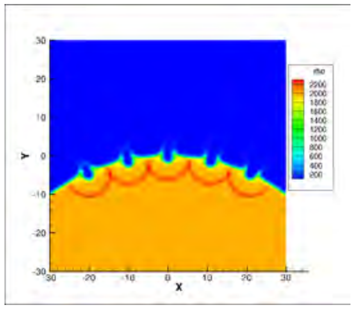
Figure 7. Case 3 results for a single massive 5,000-kg KEI [27, 28].

kinetic energy, traveling downward at 10 km/s. It is important to note that the CV impactor in the middle hits perpendicular to the target body, while the remaining four KEIs are slightly off from perpendicular.

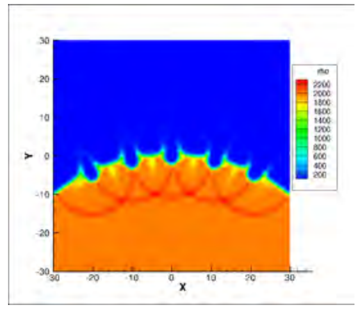
Simulation results for Case 4A (with a nominal asteroid density of 2,000 kg/m^3) is shown in Figure 8 at four elapsed times. A nearly symmetric set of shock waves is present in the simulation (nearly symmetric because in the initial condition, exactly 10 meters separation between the impactors could not be set). It can be seen that this MKIV case with parallel KEIs causes severe damage distributed across the target surface, which may be ideal for less dense or porous target bodies. To examine this, the density of the target was reduced to 1000 kg/m^3, and the same initial conditions for the impactors were imposed. Figure 9 shows the simulation results at four elapsed times. Once the elapsed time is close to 60 milliseconds, the incoming shock wave comes in contact with the other side of the target, which starts to experience spallation.

Case 5

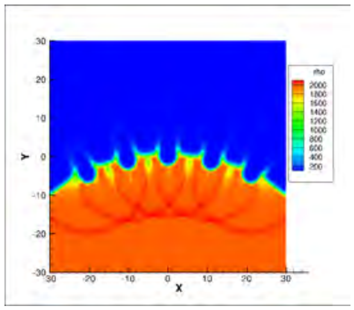
Rather than placing multiple KEIs in parallel, an array of multiple KEIs in series is considered for Case 5. At $t = 0$, the lead CV impactor makes contact with the target. Each impactor is traveling



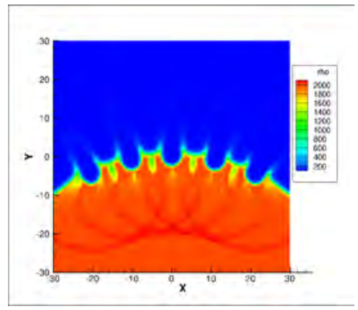
(a) elapsed time = 1.0 ms



(b) elapsed time = 2.0 ms

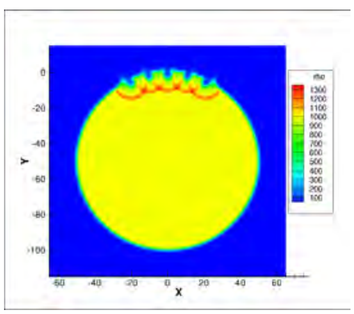


(c) Time 4.0 ms

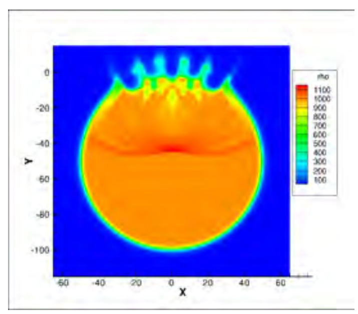


(d) elapsed time = 8.0 ms

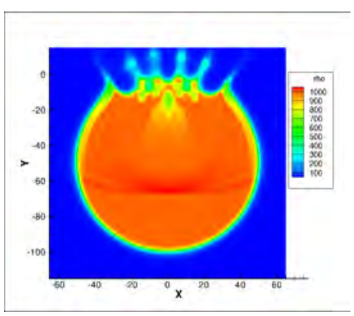
Figure 8. Case 4A (with an asteroid density of 2,000 kg/m^3) results for parallel KEIs [27, 28].



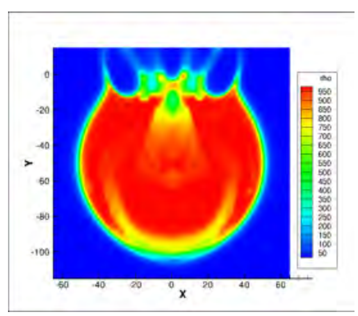
(a) elapsed time = 3.0 ms



(b) elapsed time = 18.0 ms

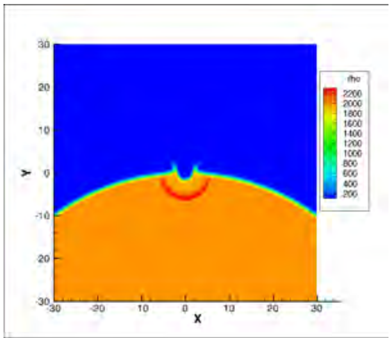


(c) elapsed time = 38.0 ms

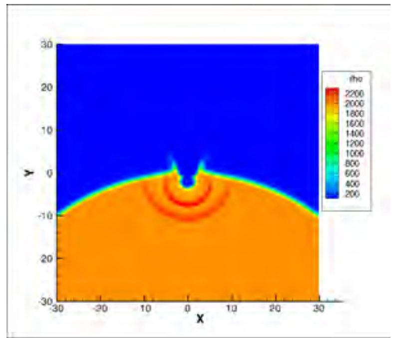


(d) elapsed time = 58.0 ms

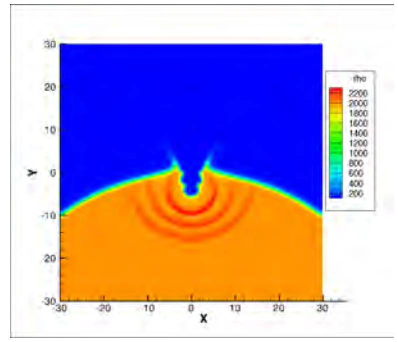
Figure 9. Case 4B (with an asteroid density of 1,000 kg/m^3) results for parallel KEIs [27, 28].



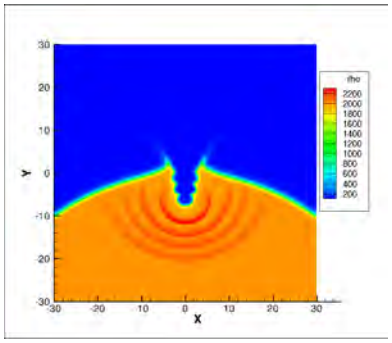
(a) elapsed time = 1.0 ms



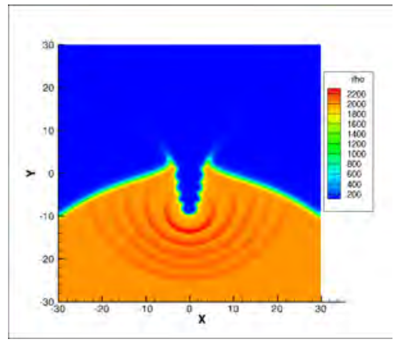
(b) elapsed time = 2.0 ms



(c) elapsed time = 3.0 ms



(d) elapsed time = 4.0 ms



(e) elapsed time = 5.0 ms

Figure 10. Case 5 results for serial KEIs [27, 28].

downward at 10 km/s, meaning that after an impactor hits, a follower impactor will make contact roughly 0.1 milliseconds after. Results for five different elapsed times are shown in Figure 10. Each subfigure illustrates the density contours 1 millisecond after the impact. For example, Figure 10 (c) is 1 millisecond after the third impactor has struck the target, or total time of 3 milliseconds. A benefit of this approach is the increased depth of the crater, which at 5 milliseconds is roughly 10 meters. Hence, one possible solution to effect a deeper subsurface explosion is to employ multiple KEIs in series, as was also previously suggested in [18].

Summary

The effectiveness of multiple kinetic-energy impact approaches is briefly discussed herein using the simulation results presented in this section.

Lightweight impactors, with density much less than the target body, produce relatively small craters (approximately 1 - 2 meters in depth) in a short elapsed time. The multiple impactors in parallel does have the capability to inflict high damage in a wider area, which may cause a more effective disruption for soft or porous targets. A serial array of multiple impactors is shown to be very effective for deep penetration (Figure 10). The depth of the crater is significantly increased, allowing more energy to be coupled from a nuclear subsurface detonation for the HAIV mission. In [27,28], only a 2D circular target with constant density was considered. Future work must include more realistic asteroid bodies. Additionally, the density of the targets should be varied, including porosity, to further investigate the effectiveness of a non-nuclear MKIV system as well as the HAIV concept. A new equation of state (EOS) is desired, as the current one used in [27, 28] does not hold for the high temperatures and pressures associated with the problem.

ANSYS AUTODYN Hydrocode Simulation Results

The ANSYS AUTODYN commercial software was used for a hydrocode simulation study of the various concepts proposed in [18]. A hypervelocity collision problem of a 2D 100 $\times$ 100 m asteroid model impacting a thin rectangular body was examined. The study goal was to determine the minimum thickness of the rectangular body that is necessary to fragment the asteroid. Both bodies were constructed of Al2024-T3 which utilizes the Tillotson EOS (equation of state). No strength model or failure model was considered in this preliminary study.

The asteroid body is represented by 10,000 particles. Upon impacting the other thin body, a shockwave propagates through the asteroid body. In the absence of intermolecular bonds, the shock-wave energy is not spent on breaking bonds. Therefore, some particles in the aft of the asteroid experience a reduction in the velocity. This velocity difference between the front and back particles leads to a fragmenting behavior. If the simulation is run for a long time, every scenario will result in fragmentation. For the purpose of the simulation, the fragmentation/deformation was observed right after asteroid particles emerge from the other side of the structure. The distance between the particles and the overall deformation can be considered as a qualitative fragmentation measure. In a real collision situation, energy in the shock wave is dissipated to break the molecular bonds. The fragmentation of the asteroid is governed by a strength model. Therefore, for very thin structure, the asteroid will emerge through the fragmented structure with less damage/deformation.

Several test cases with varying thicknesses were simulated. These test cases were run until the fragmented asteroid particles emerged right out of the collision. As the thickness of the structure increases, the fragmentation of the asteroid increases. At higher thicknesses, the asteroid gets buried in the structure, while it penetrates the structure at lower thicknesses. The minimum thickness where the fragmentation/deformation occurs lies between 4 m and 5 m. The thickness of 6 m can be taken as the minimum thickness for a safer assumption. The front layer of the particles is displaced as they are affected by the collision first.

In this section, some initial preliminary simulation results of multiple kinetic-energy impacts obtained using the ANSYS AUTODYN hydrocode are also presented. The purpose of simulating the same test cases (described in the preceding section) using a commercial hydrocode is to validate the results obtained using a new GPU-based hydrocode being developed at the ADRC of Iowa State University and also to get a different perspective on the complexity of hydrocode simulations of hypervelocity kinetic impacts as well as nuclear subsurface explosions.

The material properties are governed by the stiffened EOS, which is an extension to the ideal gas equation. Our in-house hydrocode algorithm developed in [27, 28] uses a grid-based Eulerian method. The kinetic energy from the impactors were deposited on the asteroid nodes directly below the impactor. The empty space between the asteroid material and the edges of the domain was modeled with a low density air-like gas. The asteroid, surrounding air was kept at 1 atm (= 101,325 Pa) for the initial condition as the EOS requires an initial pressure [27, 28].

An AUTODYN 2D model can use both SPH and the Euler solvers. However, the SPH solver was used for stable and accurate solutions in our simulations of multiple KEIs. The Euler solver resulted in occasional unphysical pressure/density distributions. Various simulation cases were considered as

1. Tillotson EOS for a single KEI

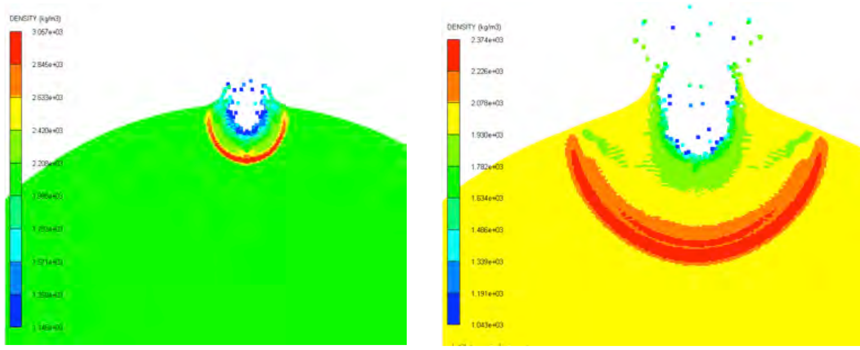


Figure 11. Case 3 results for an ANSYS AUTODYN 2D model with Tillotson EOS.

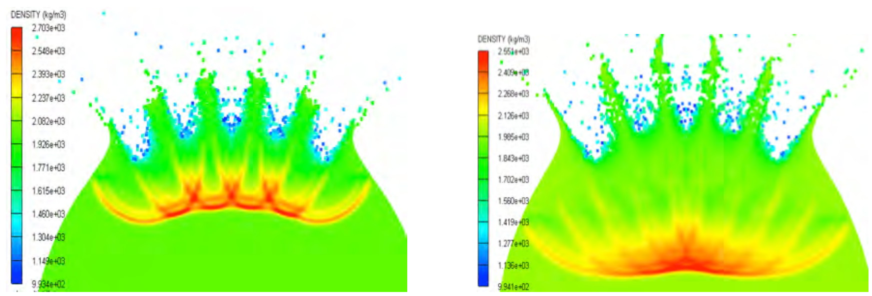


Figure 12. Case 4 results for an ANSYS AUTODYN 2D model with Tillotson EOS.

2. Tillotson EOS for parallel KEIs with kinetic-energy deposition on each asteroid node

3. Stiffened EOS with a single KEI

4. Stiffened EOS for parallel KEIs with kinetic-energy deposition on each asteroid node

Material parameters for aluminum and granite were obtained from AUTODYN material library and sources of literature. The density of aluminum was changed according to the simulation scenario and the density of granite was kept at 2,000 kg/m^3.

Figure 11 shows simulation results for Case 3. Figures 12 and 13 illustrate simulation results for Case 4. For both simulations, the shock fronts seem to travel faster than the in-house hydrocode simulations. The shock waves from different impact locations merge as the time progresses. The shock dissipation in the stiffened EOS is higher than the simulations governed by Tillotson EOS. Crater depths are significantly over-predicted by ANSYS/AUTODYN compared to the in-house hydrocode simulations.

Some observations of the AUTODYN simulation results are:

1. The AUTODYN solutions in general under-predicts the density peaks predicted by our in-house GPU-based hydrocode.

2. The locations of the shocks suggest that AUTODYN result has a higher shock propagation velocity.

3. Simulations using Tillotson EOS had the highest density peak magnitudes, while the stiffened EOS simulations resulted in the smallest density peak magnitudes at given time steps.

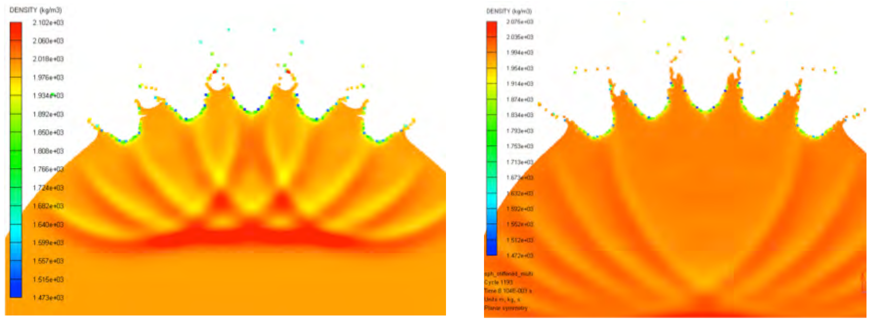


Figure 13. Case 4 results for an ANSYS AUTODYN 2D model with stiffened EOS.

4. Simulations with stiffened EOS had the highest shock propagation velocities.
5. Stiffened EOS simulations resulted in unphysical shock propagations as the simulations progress.

MULTI-TARGET TERMINAL GUIDANCE

As illustrated in Figures 14 and 15, a multi-target terminal guidance algorithm has been examined in support of the MKIV mission concept.

A multi-target terminal guidance algorithm for guiding several KEIs to hit near-simultaneously different locations widely distributed across the target surface area was simulated by acquiring the target asteroid at two hours before intercept. Once the target is detected by the CV's on-board visual or infrared cameras, an image-array algorithm determines impact locations for the remaining KEIs. A depiction of image separation and impact location determination can be seen in Figure 14. The terminal guidance algorithm determines the amount of vertical channels that are needed, which is based on the maximum vertical and horizontal pixel illumination of the asteroid on the image plane array. Then, area allocation is divided amongst the impacting KEIs. When an allocated array area is met, the centroid of the area is determined. This centroid is the location of impact on the target body. Similarly, the other remaining KEIs undergo the centroid process (chunk centroiding). However, these impact locations are calculated for both, the upper and lower image or the left and right image. The selection of the image plane processing is determined by the asteroid orientation on the image array. Once each impact location is determined for the KEIs and CV, this information is communicated to KEIs and appropriate control accelerations are commanded.

Each KEI and CV use the same hybrid guidance scheme described in [15, 16]. This scheme uses a combination of Kinematic Impulse (KI) and Pulse Proportional Navigation (PPN) to ensure intercept success. However, the closed-loop PPN guidance is very sensitive to line-of-sight (LOS) rate of the target. There are instances where the impact locations on the image plane array change due to shadowing, asteroid orientation change, or other factors. These factors may cause an event called "pixel jump." When the pixel jump is large, the first-order rate estimation causes a drastic jump in the estimated LOS rate. To remedy this situation, a sliding-window-averaging filter may be applied to the LOS data, which reduces the sharp changes in the LOS rate. At 60 seconds before the final impact, the commanded control acceleration is reduced to near zero to avoid large LOS rates caused by the asteroid illuminating more pixels on the image-plane array.

Simulations are ran, using a scaled 216 Kleopatra asteroid model. This asteroid is scaled down to a 100-m diameter and is chosen due to its dog-bone like shape. A shape such as this will require

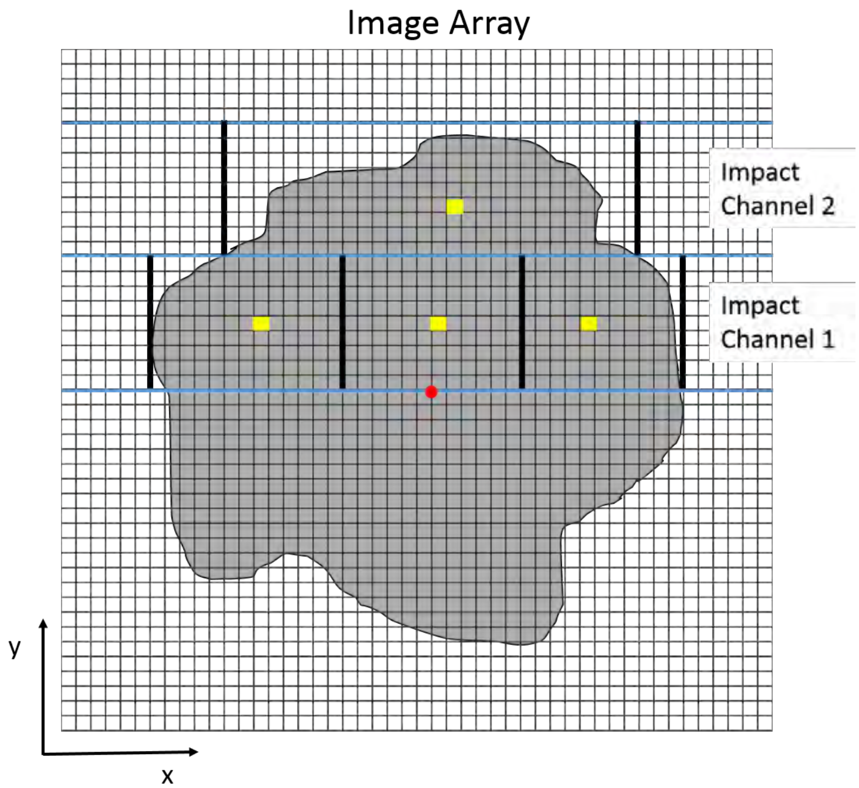


Figure 14. Graphical illustration of a multi-target terminal guidance algorithm for a reference MKIV system consisting of a CV and four KEIs.

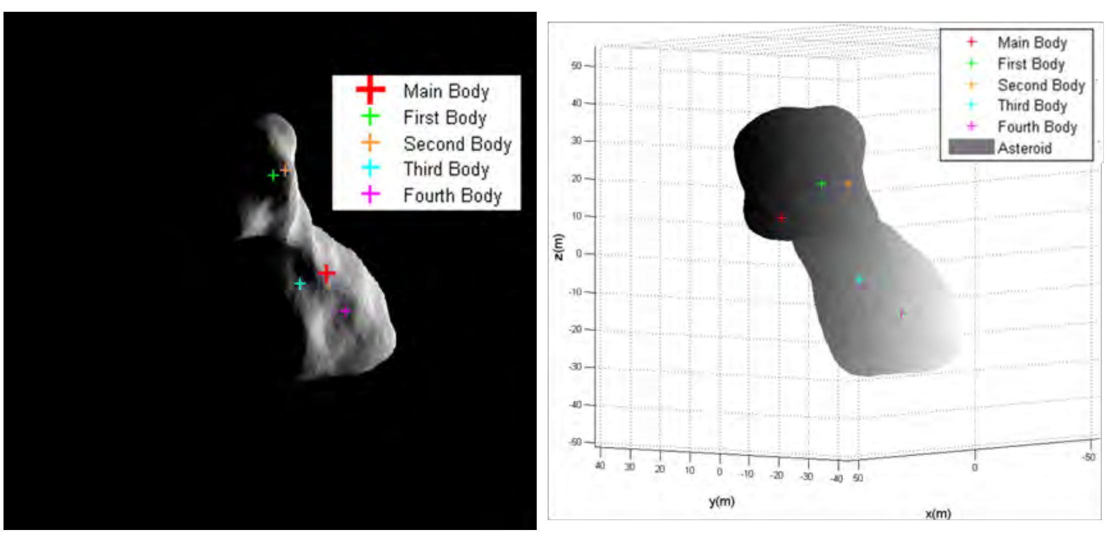


Figure 15. Simulated asteroid image with predicted impact locations (left image) and the actual impact locations on the asteroid (right image).

the multi-target terminal guidance algorithm to select impact locations on each lobe. Figure 15 depicts the preliminary results for the estimated impact locations selected by the algorithm and actual impact locations on the asteroid. As can be seen in this figure, the image used is of a visual camera and not an infrared camera. A visual camera is simulated to show difficulties in selecting an appropriate impact location. The right image shows that all impacts, by CV and KEIs, intercept the asteroid. However, all did not hit their intended location although all did hit the target asteroid. A further detailed study for the multi-target terminal guidance is needed.

HEAVY-LIFT LAUNCH VEHICLE (HLLV)

A large launch vehicle capable of lifting between 20,000 to 50,000 kg to low-Earth orbit is referred to as a Heavy-Lift Launch Vehicle (HLLV). The Delta IV Heavy, Ariane V, and Proton-M rockets are such HLLVs that are currently in service. This section provides a brief, system-level overview of the HLLVs of the United States, including Falcon Heavy and the SLS.

In Figure 16, the interplanetary mission capabilities of Delta IV Heavy, Falcon Heavy, and three variations of the SLS are shown in comparison with Atlas V 551 [29]. As can be seen in this figure, if all these launch vehicles were available for planetary defense missions employing a 10,000 kg MKIV system, the Delta IV Heavy would be capable of lifting the MKIV system to orbits that would have a C3 of up to only about 2 km^2/s^2. Based on the curves, the Falcon Heavy could outperform the Delta IV Heavy, lifting a 10,000 kg to C3 orbits up to about 18 km^2/s^2. The launch vehicles with the most versatility are the SLS Block 1, Block 1B, and Block 2B configurations capable of lifting a 10,000 kg spacecraft to C3 orbits of about 40 km^2/s^2, 75 km^2/s^2, and 90 km^2/s^2, respectively.

Falcon Heavy

The Falcon Heavy is scheduled for its first test flight soon, and is said to be the most powerful rocket in the world at the time of its operation. The Falcon Heavy is capable to lift over 53 metric tons into low-Earth orbit, more than twice the payload of the Delta IV Heavy, at one-third the cost. Missions using the Falcon Heavy will deliver large payloads to orbit inside a composite fairing, but will be capable of carrying the Dragon spacecraft. Drawing up the proven heritage and reliability of the Falcon 9, the second-stage Merlin engine (identical to its counterpart on the Falcon 9) delivers the payload to orbit after main engine cut off and first-stage cores separate. The second stage engine is capable of restarted multiple times in order to place payloads into a variety of orbits, including low-Earth orbit (LEO), geosynchronous transfer orbit (GTO), and geosynchronous orbit (GEO). Made up of a single engine, the Falcon Heavy second stage is capable of producing 801 kilo-newtons of thrust in a vacuum, and has a burn time of 375 seconds. The Falcon Heavy's first stage is made up of three cores. The side cores (boosters) are connected at the top and base of the center core's liquid oxygen tank. Each of the Falcon Heavy's side cores (boosters) is equivalent to the first stage of a Falcon 9 rocket with 9 Merlin engines. With a total of 27 Merlin engines, the first stage is capable of generating 17,615 kilo-newtons of thrust at liftoff. Not long after liftoff, the center core engines of the first stage are throttled down, until after the side cores separate, at which time they are throttled back up to full thrust. For missions that have exceptionally heavy payloads ($>$ 45,000 kg), the Falcon Heavy offers a unique cross-feed propellant system that feeds propellant from the side cores to the center core. This enables the center core to retain a significant amount of fuel after the boosters separate [30, 31]. Originally designed to carry humans into space and to fly missions with crew to the Moon or Mars, this launch vehicle could also be used to carry a large spacecraft into orbit to meet a potentially hazardous NEO.

Space Launch System (SLS)

The design of the SLS serves to accommodate greater mass/volume to orbit, shorter transit times to destination, larger interplanetary science payloads, and enhanced reliability and safety for a variety of different missions. It is projected that the SLS Block 1 design will have the capability to carry up to five times greater mass to orbit than the Delta, Atlas, and Falcon launch vehicles. With the ability to launch such large payload masses, the SLS increases payload mass margins and offers greater propellant loads. It can also accommodate a range of fairing sizes including the existing five meter diameter size, as well as new 8.4 - 10 meter diameter fairings, and will have the capability to support up to six times greater payload volume over current launch vehicles. Based on the currently accepted launch capabilities of the SLS, shorter mission durations are also possible to various mission destinations. Taking the Europa Clipper mission for example, the flight time could be reduced by 70% through the use of the SLS rather than the Atlas V 551. Launching into a C3 orbit of 15 km^2/s^2 and requiring three planetary flybys (Venus-Earth-Earth) before arriving at Jupiter 6.4 years later, the same mission launched with the SLS would launch directly into a C3 orbit of 82 km^2/s^2, would not require any planetary flybys, and would arrive at Jupiter in 1.9 years. The capabilities of the SLS would allow for longer launch windows and provide more mission margin, in addition to significantly reduced cost for each year of transit reduced. Larger interplanetary science payloads enable three to four times the mass to destination and single launch of larger payload reduces payload complexity. The SLS launch vehicle range allows for missions previously deemed very difficult or infeasible to be reconsidered, such as the Asteroid Redirect Mission, Mars Sample Return, Saturn/Titan Sample Return, Ice Giant Exploration, Outer Planet Sample Return, large telescopes, and in-space infrastructure. Additional payload volume simplifies orbital operations, requiring less orbital assembly for large spacecraft. With the amount of energy able to be generated by the launch vehicle and imparted to the payload, significantly less time can be spent in Earth orbit - reducing the amount of propellant boil-off, and would eliminate the Earth flyby nuclear safety concern [33].

30-Day-Warning Mission Design

The shortest warning time mission design study conducted in [29, 34] was 30 days - up to 15 day mission duration and up to 15 day dispersion time. With such a short timespan for the spacecraft to get from the Earth to the asteroid, the mission trajectory should be fairly simple in terms of the ease of getting into the orbit and getting to the threatening asteroid. However, as can be noticed in Table 1, a mission at this late stage of the asteroid's approach is anything but easy. Needing over 4.5 km/s from low-Earth orbit to enter into the hyperbolic escape orbit of almost 28 km^2/s^2 to intercept a fictional asteroid 2015 PDC [29, 34], the difficulty of this interplanetary trajectory can be seen in Figure 17. It is assumed that the MKIV system was ready for an immediate launch after receiving such a short notice. The MKIV spacecraft needs to leave the ecliptic plane of the Earth to intercept the asteroid in 15 days. The combination of the launch energy given to the spacecraft to meet 2015 PDC and the position of the asteroid in its orbit (going away from periapsis) explains the large relative impact velocity and relative arrival angle between the spacecraft and 2015 PDC. The 30-day warning-time mission design can only be accomplished by the use of an SLS launch vehicle. Taking a closer look at the top 10 mission designs for this type of mission design conducted in [29, 34], only the top four missions would be able to be completed using the SLS Block 1 launch vehicle or larger - the rest of the top missions would require at least the SLS Block 1B configuration to be feasible.

Table 1. Design parameters for a 30-day-warning intercept mission to asteroid 2015 PDC.

Mission Parameter	Value
Asteroid	2015 PDC
Spacecraft Designation	MKIV
Spacecraft Mass (kg)	10,000
Departure ΔV (km/s)	4.425
C3 (km^2/s^2)	27.806
Departure Date	August 12, 2022
Mission Duration (days)	15
Dispersion Time (days)	7
Arrival Angle (deg)	25.411
Impact Velocity (km/s)	16.571
Arrival Date	August 27, 2022
Launch Vehicle	SLS

CONCLUSIONS

A new non-nuclear MKIV (Multiple Kinetic-Energy Impactor Vehicle) mission concept has been described for dispersive pulverization of small asteroids ($<$ 150 m) detected with short warning times ($<$ 10 years). A single large booster such as Delta IV Heavy, Falcon Heavy or the SLS can be employed to launch the proposed MKIV system with its total mass in the range of approximately 5,000 to 15,000 kg. Preliminary simulation results of a 2D hydrocode simulation model, comprising of a 1,000-kg carrier vehicle, four 1,000-kg kinetic-energy impactors, and a 2D circular, 100-m diameter solid object, have been discussed. However, a further study using a 3D hydrocode simulation model is necessary to validate the practical effectiveness of the proposed non-nuclear MKIV system for dispersively pulverizing small asteroids.

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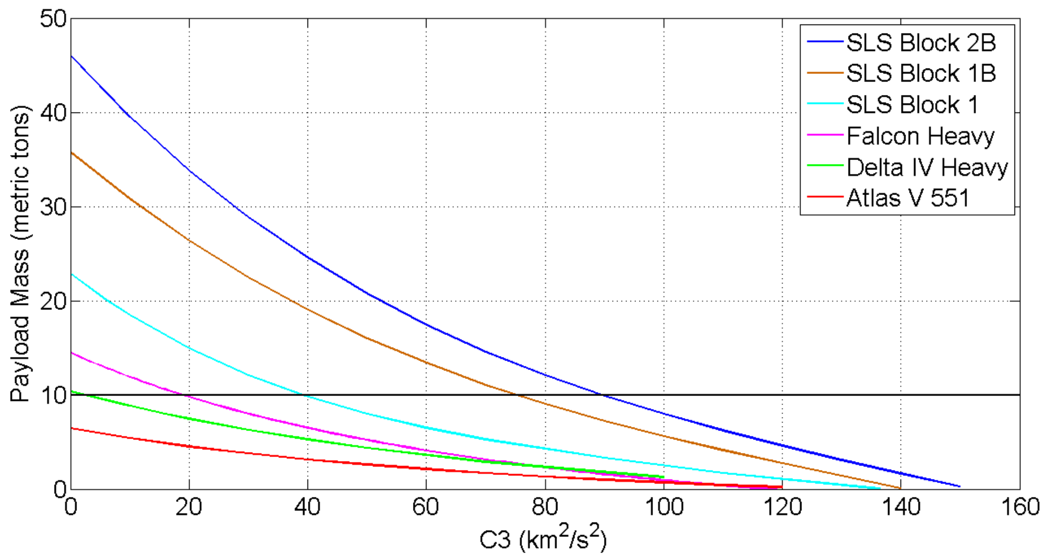

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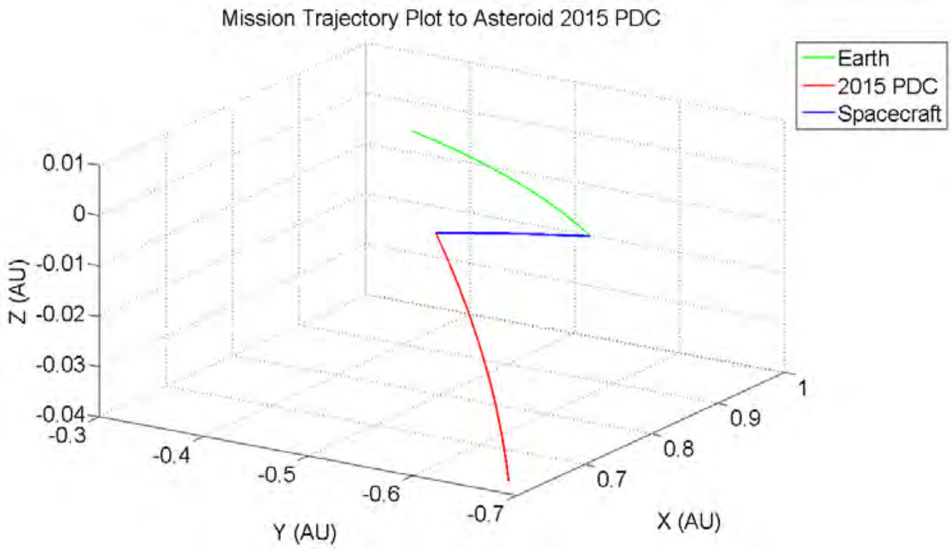

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