

RAPID AND SCALABLE ARCHITECTURE DESIGN FOR PLANETARY DEFENSE

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ABSTRACT

A modular/swarm spacecraft architecture, based upon existing spacecraft buses and launch vehicles, is proposed to mitigate near-Earth object (NEO) planetary threats. Each spacecraft that is part of this swarm would utilize mass driver technology to remove mass from the object to yield an Earth-avoiding trajectory. Such a design philosophy focuses on developing rapid and scalable NEO mitigation plans incorporating the world's current launch vehicle/spacecraft bus manufacturing capability. Specific planetary threats are examined, each with different impact times and masses, and based upon predetermined fictitious Defined Threat (DEFT) scenarios. Potential advantages envisioned in such an architecture design include: integrating the analysis of spacecraft development/deployment/launch, ability to complete the mission given the loss of part of the swarm, scalability of response for different size threats, and flexibility to initiate an immediate response leaving the option to develop more advanced systems.

NOMENCLATURE

ACS	Attitude Control System
AU	Astronomical Unit
CAPS	Comet Asteroid Protection System
ConOps	Concept of Operations
DDT&E	Design, Development, Testing, and Evaluation
DEFT	Defined Threat
ETO	Earth To Orbit

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K-T	Cretaceous-Tertiary
ISTS	In Space Transfer Stage
LD	Lunar Distance
LEO	Low Earth Orbit
LPC	Long Period Comet
MADMEN	Modular Asteroid Deflection Mission Ejector Node
NEO	Near-Earth Object
NIAC	NASA Institute for Advanced Concepts
RASC	Revolutionary Aerospace Systems Concepts
ROSETTA	Reduced Order Spreadsheet for Evaluation of Technologies and Transportation Architectures
SEI	SpaceWorks Engineering, Inc.
TFU	Theoretical First Unit

INTRODUCTION

Both recent observations of planetary bodies and geological records confirm the ever present threats from asteroids and comets all around the Earth that could be large enough to cause the widespread destruction of modern society. Specifically, in the last 100 years, a massive impact most likely took place in Siberia (Tunguska in 1908) from a 40-60 meter wide asteroid that devastated 2,000 square kilometers of area with a destructive force equivalent to 10-50 megatons of TNT (several hundred to several thousand times the energy at Hiroshima in 1945). Additionally, the Earth's surface still shows scars of previous larger-scale impacts. It is believed that the Meteor Crater in Arizona was caused by the impact of a 100-meter diameter meteor over 20,000 years ago. The more massive K-T (Cretaceous-Tertiary) impact (10 km diameter object), which took place approximately 65 million years ago, is believed to have led to the extinction of the dinosaurs. While K-T class impacts are very infrequent, objects with diameters of approximately 1 km can be expected to intercept the Earth every 100,000 years¹.

Clearly, some thought and planning must take place in order to provide a reasonable level of protection against such disastrous events. Identification and cataloging of Near-Earth Objects (NEOs) and celestial bodies is an

important first step. Observation and tracking of small (1 km or less) objects is a difficult task given the low albedos of the target bodies and their small size. However, accurate long-term orbital prediction models must be developed to allow for adequate response time. NASA and Cal Tech's Jet Propulsion Lab maintain an active list of NEO objects sorted by a weighted scale indicating their approach distance and destructive potential (the Palermo scale). In 2003, over 10 objects were identified that passed within 1.5 times the distance from the Earth to the Moon (1 lunar distance = 384,000 km). The smallest objects in the JPL database are 20 meters in diameter with typical NEOs in the 500 m - 1 km diameter range². Currently, the highest active object on the Palermo scale is asteroid 1997 XR2, a 230 m diameter asteroid having an impact probability of 9.7×10^{-5} in the year 2101. NASA has proposed new observatories that will be able to detect even smaller objects. For example, NASA's Revolutionary Aerospace Systems Concepts (RASC) program conducted a study called the Comet Asteroid Protection System (CAPS) that promoted a lunar telescope installation for conducting NEO detection research⁸. The question remains: "What should be done if a planetary impactor on a collision course with Earth is actually confirmed?"

Effective planetary defense architectures must overcome a variety of challenges. The large variance in size, shape, composition, and detection time of NEO impactors requires a robust system. Economics and launch vehicle capacity limit the size and scope of the vehicles. Designs must be able to easily incorporate technological advances to maximize efficiency. A modular architecture of smaller devices can help overcome many of these challenges by providing the means to build up defensive capability immediately while allowing for system improvements and modifications over time.

BACKGROUND

In 1998, Hollywood released two movies on the subject of planetary impactors, *Deep Impact* (Paramount Pictures) and *Armageddon* (Buena Vista). In both of these films, writers created situations in which large impactors are discovered on collision trajectories with Earth with short warning times. In both cases, nuclear devices are used to try to fracture the incoming asteroid or comet. In one case, the nuclear device is launched on a military missile. In the other case (*Armageddon*), the rather implausible approach of sending a crewed shuttle out of Earth orbit to intercept the comet and manually implant a nuclear device is adopted. These

fracture/fissure approaches are probably best left as Hollywood solutions. Given the large momentum of an incoming impactor on close approach (as much as 7 - 10 km/s of approach velocity), the direction of the center of mass of the resultant piece or pieces is unlikely to be seriously affected by a nuclear blast.

Given a reasonable lead-time, a sustained impulse or force applied to the impactor for an extended duration may be the best way to achieve the desired collision avoidance. Applied far from Earth, changes in the asteroid's velocity of less than 1 m/s are generally sufficient to change the minimum approach distance by several hundred thousand kilometers. Even with such a small ΔV requirement, propellant-oriented solutions are still impractical. To change the velocity of Asteroid 1997 XR2 by 1 m/s would, for example, require 175 MT of propellant even assuming a very high performance electric propulsion system. Either propellantless or in-situ propellant (i.e. reaction mass from the target body itself) solutions are more practical.

Some researchers have proposed solar or magnetic sails as mitigation concepts, but the resultant thrust available from these devices is too low to have a timely impact on the asteroid's course³. In the aforementioned CAPS study, the NASA RASC team briefly considered a GW-class laser-based approach that would ablate volatile surface material from the asteroid or comet⁴. The escaping gases would impart a small change in momentum to the target body. While this approach has the advantage of creating relatively benign ejecta from in-situ sources, the launch, deployment, and station-keeping requirements of such a large laser would seem impractical. The thrust of this system would also be small, requiring extended operations. In addition, limitations are placed on the type of impactor that can be affected in this way, given that the surface must be ablated.

Renowned physicist Gerard K. O'Neill, founder of the Space Studies Institute at Princeton University, was an advocate of mass-driver solutions for extraterrestrial purposes. These mass-driver devices use electromagnetic coils to accelerate resource material or in-situ debris to speeds of 100 m/s or more. A reactive force is applied to the target body in the process. For example, O'Neill advocated the use of solar-powered mass drivers on the moon to launch lunar resources into low lunar orbit. In addition, he advocated the use of mass-drivers to maneuver small asteroids into high Earth orbit-again for the purpose of mining their metallurgical resources.

Before his death in 1992, Prof. O'Neill suggested that a mass-driver might also be used in planetary defense applications. Asteroid material would be used as ejecta ("propellant"). In a paper entitled "A Robust, Non-nuclear Defense Against Asteroids" presented at an early Asteroid Mitigation Workshop, O'Neill encouraged further work on the concept⁵:

A concept that has received relatively little attention in the literature is the employment of a mass driver to apply a steady acceleration to the asteroid which, given sufficient time, will develop lateral movements that can convert a strike on Earth into a miss. The major advantage of this approach is that all the energy comes from the sun and all the reaction mass is obtained from the mass of the asteroid itself. The only mass that needs to be transported to the asteroid is that of the solar collectors, power supplies and acceleration coils which convert electrical energy to kinetic energy. It is recommended that this little-studied approach receive research funding. One key issue that deserves examination is the design of mass drivers which are optimized towards low velocity ejecta since these designs convert the highest percentage of the collected solar energy to momentum transfer to the asteroid.

His calculations indicate that given an operating time of 10 years, a 140 kW mass driver could move the closest approach distance of a large asteroid (1×10^{12} kg) by a few Earth diameters⁵. O'Neill considered a single, monolithic mass driver solution that would nominally be solar-powered.

Advancement in robotic technology has progressed substantially over the decades. Recent research has focused on the harnessing the potential capabilities of biologically-inspired design as seen in nature^{6,7,8}. This has also extended to the concept of using multiple robots in combination to perform tasks. Dr. Steven A. Curtis of NASA's Goddard Space Flight Center and his other NASA colleagues (including those at JPL) have proposed various exploration concepts that utilize swarm intelligence. They draw inspiration from biological analogues as stated⁷:

ANTS [The Autonomous Nano-Technology Swarm] is a mission architecture drawn in analogy to biological social insects...In nature, biological ants are one of the most successful species to appear. Elements of their success lie

in their division of labor, their collaboration, and their numbers. Their numbers provide reliability through redundancy for many functions of the swarm. However, individual ants are themselves highly autonomous and capable creatures, however they do depend on other members of their society to perform tasks necessary for their survival and procreation. Because individual ants are specialized to a given task, they are much more likely to succeed in that task than a non-social generalist. The ants and their swarm benefit from these successes, and the colony continues on with its competitive advantage. In some sense, we aspire to produce systems with the robustness and adaptability of ants. Biological ants are capable of relatively sophisticated behaviors with relatively simple neural structures and communication mechanisms, we seek to emulate both the individual and swarm capabilities in the ANTS mission architecture.

There have been many ideas weaved together to develop the asteroid concept presented herein. From mass driver technology to notions of swarm intelligence, various technologies and approaches have been combined to develop a potentially unique approach to planetary defense against asteroids and comets.

OBJECTIVE

A new approach to mitigate and protect against planetary impactor events is proposed. The primary objective of this systems concept is to apply small perturbations to Near-Earth Objects (NEOs) in an attempt to divert them from their path toward Earth impact. Unlike past proposals from other individuals or organizations, this project concept proposes a rapid and scalable solution consisting of hundreds or thousands of small, nearly identical spacecraft that will intercept the target body and conduct mass driver/ejector operations to perturb the target body's trajectory to the point where an impact with Earth can be avoided.

In the nominal configuration, each spacecraft will be independently controlled and powered, but will work in loose coordination with other members of the network. Such a spacecraft, referred to here as a Modular Asteroid Deflection Mission Ejector Node (MADMEN) spacecraft could conceivably be nuclear powered, pre-deployed outside of low earth orbit (likely at an Earth-Moon or Earth-Sun libration point), and be capable of

using chemical propulsive boost to rapidly intercept an incoming target. Upon arrival at the target, each MADMEN spacecraft will begin to eject small amounts of mass from the asteroid that will, over time, have the effect to slightly change the heliocentric orbit of the target so that Earth impact is avoided.

This modular approach can offer a number of unique mission advantages including: overall mission reliability through massive redundancy, faster production capability due to use of existing spacecraft bus production capability, efficiencies-of-scale of the MADMEN spacecraft during production, flexible and practical launch and transfer to an on-orbit pre-deployment location, a tailorable response depending on the size and nature of the incoming threat, and the production of only small particles of ejecta that will not independently survive Earth atmospheric entry.

The preliminary results described herein have been performed under a Phase I contract sponsored by the NASA Institute for Advanced Concepts (NIAC). The study is entitled “The League of Extraordinary Machines: A Rapid and Scalable Approach to Planetary Defense Against Asteroid Impactors” and was awarded in October of 2003 under NIAC Call for Proposals CP-02-02. This report summarizes some of the activities and accomplishments during the first three months of the study (see Figure 1).

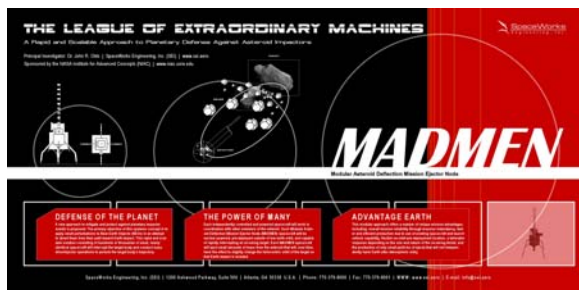


Figure 1. Project Poster Presented at NIAC Fifth Annual Meeting, Atlanta, GA, November 5-6, 2003

NIAC's charter is focused on grand, revolutionary concepts for architectures and systems. As such the institute provides an independent, open forum for the external analysis and definition of space and aeronautics advanced concepts that complement the advanced concepts activities conducted within the NASA Enterprise. NIAC is a part of the Universities Space Research Association (USRA).

This six month Phase I study effort is proposed to establish key quantitative data for the masses, dimensions, costs, schedules, and technology requirements to assess concept viability. Comparisons will be made with alternate approaches to verify the stated advantages. This Phase I investigation will attempt to specifically examine the following:

- Develop trend line curves for power requirements vs. mass throughput and ejection velocity.
- Develop a preliminary design for the mass-driver component of the MADMEN spacecraft and conceptual configuration based on these results.
- Develop a preliminary design and configuration for the MADMEN lander spacecraft.
- Perform basic in-space trajectory simulations to rendezvous with representative NEOs to determine ΔV and mission time requirements.
- Architecture optimization to determine the launch dimensions and mass constraints appropriate in order to provide access to a large number of launch vehicles.
- Conduct trade studies on the utility of pre-deploying large numbers of MADMEN spacecraft in the Earth-Moon or Earth-Sun libration points (vs. simple rapid response from ground launchers).
- Conduct a trade study to determine the most favorable in-space transfer approach to maneuvering the MADMEN spacecraft to the staging point or toward the target body (chemical vs. low thrust, for example).
- Conduct other trade studies on various design aspects of the lander spacecraft, including but not limited to: solar vs. nuclear power sources, impact-landing configurations vs. soft-land configurations, mass driver velocity, mining technology, mass driver power level, and Earth To Orbit (ETO) launch vehicles.
- Architecture cost analysis to achieve a preliminary estimate of the architecture cost (non-recurring: DDT&E and production, and deployment) as a function of technologies and scale of deployment (i.e. number of spacecraft sent per target).

- Use the cost and architecture design results to determine an appropriate size for the individual spacecraft (i.e. fewer and larger vs. more and smaller, sized by power as an independent variable).

The results of the work plan listed above will include an improved understanding of the design space, a more detailed baseline or reference concept design, preliminary weight statements, cost estimates, and schedules. Concept illustrations and renderings of the proposed concept will also be presented.

ANALYSIS OVERVIEW

This paper summarizes some of the results from the initial part of the project. A general description of the concept is presented along with a subsequent list of preliminary parametric studies. These were performed to provide some guidance as to the development of the baseline system concept. This includes development of the in-space transportation portion to reach a sample NEO. Descriptions of future work to be performed under this study are also provided.

At completion of Phase I, this project will have utilized a conceptual modeling process to examine both spacecraft development and launch vehicle manifesting for various NEO threats. This process will generate several candidate designs based upon current spacecraft buses (commercial, civil, military) incorporating mass driver technology used to eject material from the NEO target. The modeling will determine the optimum use of existing and future launch vehicles given constraints on availability. The process will also examine the range of capability of such architectures; for various out times (time before impact) and program start years, in order to maximize NEO size that can be affected by the design. Specific planetary threats (one comet, three asteroid-based) are examined each with different impact times and masses based upon predetermined fictitious Defined Threat (DEFT) scenarios. Limited trade studies conducted will include alternate spacecraft propulsion (solar, nuclear), mass ejection, and drilling schemes. The architecture's mission effectiveness will be examined probabilistically to determine the number of spacecraft in the swarm needed for various certainty levels that the NEO's path will be deflected. This will help develop a realistic assessment of the state of the possible for NEO threat mitigation given technology and production limitations.

CONCEPT OVERVIEW

A modular/swarm architecture, based upon existing spacecraft buses and launch vehicles, is proposed to mitigate near-Earth object (NEO) planetary threats. Each spacecraft is part of a large swarm or collection of similar spacecraft that would utilize mass driver technology to remove mass from the object to yield an Earth-avoiding trajectory. Each MADMEN spacecraft would be a self-contained mass driver. The concept envisions a fleet of hundreds or thousands of small mass-driver landers that would loosely coordinate with each other to "attack" a target body much as a swarm of killer bees might attack a large target (see Figure 2). Each spacecraft would be separately powered, maneuvered and controlled.

Such a design philosophy focuses on developing rapid and scalable NEO mitigation plans incorporating the world's current launch vehicle/spacecraft bus manufacturing capability. Potential advantages envisioned in such an architecture design include: integrating the analysis of spacecraft development/deployment/launch, ability to complete the mission given the loss of part of the swarm, scalability of response for different size threats, and flexibility to initiate an immediate response leaving the option to develop more advanced systems.

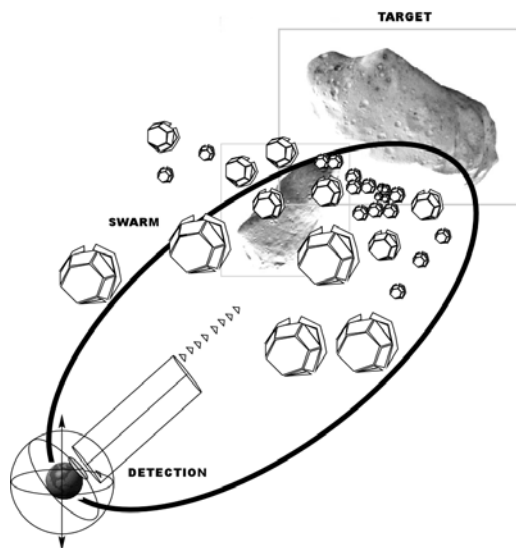


Figure 2. Illustration of MADMEN Swarm Concept

The revolutionary nature of this particular architecture is the use of several types of existing technologies (in combination) to develop a robust and scalable solution to the planetary protection problem. Many previous

attempts at these types of solutions have relied upon unproven technologies that can require long development times/testing, large deployments, and massive expenditures of resources. If a NEO threat is less than a few years away from impact, many of the previously discussed concepts will be worthless given the immaturity of their technical development. A more rational strategy would be to have a plan wherein the Earth can develop a more rapid, proven, easy implementable and scalable response to such a NEO threat. The existence of such a plan still leaves the option open of simultaneously pursuing more exotic mitigation strategies that will take longer to develop.

The approach relies on the use of mankind's current experience and infrastructure obtained over the many decades of space exploration. Thus mitigation options can be based upon the entire planet's combined space resources (specifically manufacturing and launch capability). This approach is coupled with one other capability achieved when examining the solution from such a global perspective. One of the key strengths of the global space community is not the sheer mass that can be constructed and launched at any one time, but the capacity to build and launch multiple spacecraft; the power of Earth's response to a NEO threat lies in the quantity of production possible. Such a capability would indicate an approach based upon quantity of spacecraft. This philosophy is one of the hallmarks of the concept described herein.

MADMEN Spacecraft

Each Modular Asteroid Deflection Mission Ejector Node (MADMEN) spacecraft will be equipped with a power source, a drilling/pulverizing mechanism, landing anchors, a mass driver accelerator, and associated subsystems (see Table 1). The completed Phase I study will subsequently determine exact masses and dimensions for the final baseline spacecraft and any associated trade studies.

Preliminary estimates (based upon parametric studies described further herein) indicate that each MADMEN spacecraft will be approximately 500-1,000 kg in mass and approximately 5-20 meters in length once fully deployed on the target body. Such estimates also suggest that each MADMEN spacecraft will be able to grind and eject approximately 100 kg of asteroid material per hour and eject that debris at a velocity of 100 m/s. Preliminary estimates assume a power requirement of less than 300 W per spacecraft. Depending on warning time, mass of the target asteroid, its rotation rate/orientation, and the desired ΔV to be

imparted, multiple MADMEN spacecraft will be dispatched to address the threat. Hundreds or thousands of such spacecraft may be required for a given threat. A notional MADMEN spacecraft is shown in Figure 3.

Table 1. Key MADMEN Lander Spacecraft Characteristics

Concept Characteristic	Benefit
Mass-Driver	Propellant-less operation uses asteroid's material as ejecta to deliver sustained impulse to the target without the requirement to provide and manufacture additional propellant.
On-board Power	Baseline power source is nuclear power for long life and deep space compatibility. Consider solar power as a trade study.
System Modularity	Allows massive system redundancy and increases overall mission reliability. Individual spacecraft can fail and still have mission success.
MADMEN Design Commonality	Ensures high production rates and economies of scale during production. Opens competition to a vast array of spacecraft bus manufactures.
Small Spacecraft Design	Allows launch and deployment on a variety of domestic and international launch vehicles. Launch of multiple MADMEN on small or large launchers can be accommodated. Lower launch costs and faster response time.
Small Ejecta Mass (per piece)	Creates smaller objects in ejecta debris field that are unlikely to survive entry into Earth's atmosphere



Figure 3. Illustration of MADMEN Lander Spacecraft

MADMEN Production and Deployment

The proposed end-to-end solution used here examines the entire architecture associated with NEO mitigation, integrating spacecraft response, as well as launch. The relatively manageable size and simplicity (excluding the power source) of the MADMEN spacecraft will enable its developers to make use of worldwide spacecraft production capabilities that will both ensure competition and achieve a high rate of annual spacecraft manufacture. Since a large number of spacecraft will be required, each manufacturer will be able to reach a certain economy of scale during production through process automation, robotics, labor learning effects, commonality, and standardization of parts and supply lines, etc. An initial assumption is to manufacture the MADMEN spacecraft using relatively "low-tech" materials and components. This is not to suggest a dismissal of new technologies; certain spacecraft technologies may be unique for this architecture, namely the mass-driver components. However, compared to other solutions, the inclusion of such technology is expressed in only the most critical areas where current capabilities are lacking. The result will be an extremely affordable spacecraft relative to the massive and expensive one-of-a-kind lasers or mass drivers previously discussed.

An additional benefit of the small mass and stowed size of the MADMEN spacecraft is the availability of the world's current fleet of existing launch vehicles to be used as launchers. No custom heavy-lift launcher is required. Multiple manifesting options exist with larger launchers (e.g. Proton, Atlas V, Delta IV, Ariane V), while smaller launchers could be used to deploy fewer MADMEN to the assembly point in a single launch. New reusable launchers could be employed as they are developed, but the ability to launch on current expendable launch vehicles is a key characteristic of our concept. Not only does this enable the concept to be responsive to near-term threats (next 10 or 15 years), it ensures that the launch will be as economical as possible due to competition.

System Reliability and Robustness

With the survival of thousands or millions of humans at stake, the reliability of proposed asteroid deflection system cannot be compromised. A partial victory as depicted in the previously discussed Deep Impact movie is unacceptable. This concept achieves reliability through massive redundancy of the lander spacecraft. Since each MADMEN is essentially independent, the loss of one or more of the spacecraft will not

compromise the overall mission success. Mission planners will simply dispatch more spacecraft than is necessary to achieve the required orbital adjustment. The use of multiple, identical spacecraft in such a configuration against a target is notionally referred to here as a "swarm". Similar to the Borg collective on the Star Trek series, parts of the swarm can be destroyed yet the remaining assets in the swarm fleet can still accomplish the mission. These swarms are robust enough (through design and embedded intelligence) to complete the objective. Even excluding failures on the outbound journey, the harsh circumstances of the environment near potential NEO threats themselves dictate multiple backups. A swarm concept has the backup design feature inherent in the architecture.

Scalability

In addition, a swarm approach of multiple MADMEN spacecraft allows the scalability of any response. Scalability refers to the addition of more members of the swarm, keeping the basic design of existing swarm members the same. Given the varied nature of any future threat (size, shape, composition, etc.), many possibilities are inherent in the design of a proper response. Swarm-type architectures allow the same process to be scalable to different threats. Given the nature of the swarm, in which each portion of the swarm is similar (but perhaps not necessarily identical) to other members of the swarm, this allows a solution which can be scalable (adding more members) without the typical effort of designing vastly new systems.

Concept of Operations (ConOps)

This particular concept would operate according to the following concept of operations.

- Manufacture an adequate number of MADMEN spacecraft. Likely done before the identification of a specific threat.
- Deploy the MADMEN to an orbital assembly point. Tradable location but likely somewhere above LEO. Perhaps an Earth-Moon or an Earth-Sun libration point.
- Identify a target planetary impactor on a collision course with Earth.
- Dispatch an adequate number of MADMEN toward the target (a response swarm with redundancy). Chemical boost stages can be used to decrease trip time (trade study).

- Arrive at the target body and impact or “soft” land MADMEN on surface (trade study).
- Each MADMEN spacecraft begins to pulverize and eject asteroid material at a given mass per hour (trade variable power vs. ejection velocity and mass)
- MADMEN work as a team to affect the orbit of the asteroid so that its new trajectory does not intercept Earth.

PRELIMINARY PARAMETRIC ANALYSES

The initial part of the research was involved in development of a baseline architecture consisting of the characteristics described above. Several parametric analyses were performed to help scope out the potential design space. Specifically these included trades of ΔV requirements, ejection power/energy/lander force, source power and launch power, and the number of MADMEN-type spacecraft required for a particular object. The potential NEO threats examined for these trades were not based on any one specifically defined object. The outputs of these parametric analyses, the reference configuration specifications, were used as guidelines for the design of the baseline MADMEN spacecraft. Some initial specifications generated for the reference configuration were modified given more detailed information about specific NEO threats (such as those in the defined threat scenarios) that were subsequently examined.

ΔV Requirement

This concept entails the use of impulse provided by numerous mass driver/landers to adjust the heliocentric orbit of a potential impactor. An assumption is that the most likely NEO threats or impactors will come from the population of Apollos and Atens asteroids that orbit near the vicinity of Earth’s orbit. In addition, it is assumed that the potential impactor is detected with enough lead-time to allow the swarm of spacecraft to reach it while it is near its apohelion.

Figure 4 highlights a trade study used to establish the baseline ΔV requirements for the mass drivers. For this case the impactor orbit has a perihelion distance of 1 AU and that potential impact therefore occurs at perihelion. For simplicity, it is assumed that the impulse applied by the swarm of landers is delivered impulsively, rather than over a significant time. A parametric study was performed to determine the ΔV required to change the impactor’s perihelion distance

by a small amount, measured in units of Lunar Distance (LD) or the distance from the Earth to the moon (1 LD = 384,000 km). For this class of NEO, apohelion distances are likely to be near 1.0-1.5 Astronomical Unit (AU), but apohelion distances up to 3 AU were considered.

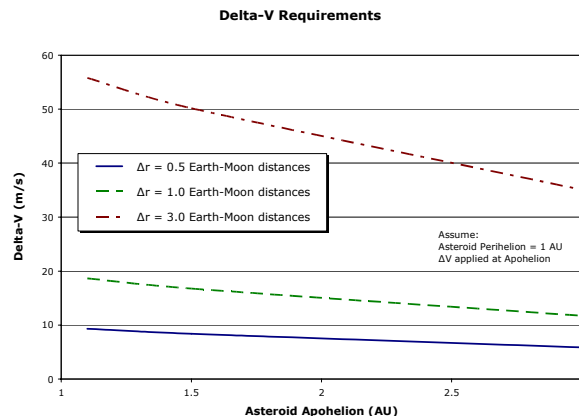


Figure 4. ΔV Requirements to Change Impactor Heliocentric Orbit

For small changes in perihelion radius (Δr), and the most likely apohelion radii, the required ΔV is under 10 m/s. While this seems like a small ΔV requirement, recall that the enormous mass of the asteroid makes even a small ΔV difficult to accomplish. A ΔV of 9.5 m/s was chosen as the nominal swarm requirement based on these preliminary results and assumptions.

Ejection Power, Energy, and Lander Force

A series of parametric trades were performed to help determine the appropriate ejecta mass per shot, its launch velocity, and the mass ejected per shot. It is recognized that the momentum imparted to the asteroid in the opposite direction is proportional to the momentum of the departing ejecta (mass per shot times launch velocity). Mass per shot is likely limited by the size and efficiency of the mining/extractor to less than 1 kg per shot for the small spacecraft considered. The temptation therefore is to increase the launch velocity as much as possible. However, there are competing considerations. For the trades conducted, it is assumed that the launch rail should be as long as reasonable but launch packaging and stiffness considerations can limit the launch rail to no more than 10 m.

As the launch velocity increases for a given shot mass, the mass driver power increases in a cubic fashion, thus driving up the size and mass of the mass driver capacitor units, as seen in Figure 5. The energy (or

work) used to accelerate the ejecta increases proportional to the square of the launch velocity thus requiring a larger spacecraft power supply (or alternately a longer cycle time between shots) in order to recharge the capacitor units.

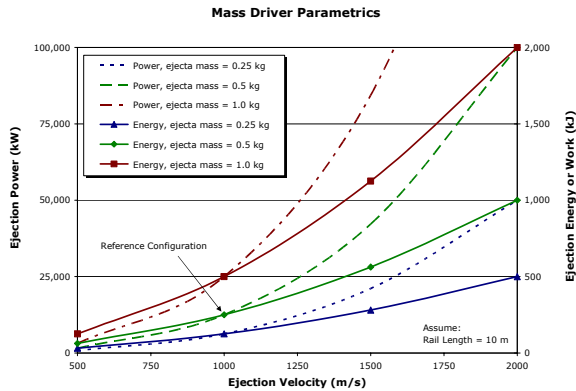


Figure 5. Ejecta Launch Power and Energy Trades

As shown in Figure 6, the compressive force on the lander and rail increases relative to the square of launch velocity. The downward force will benefit the mining process to some degree, but an excessive compressive load would require a massive lander structure and thus exacerbate the launch and deployment problem for the spacecraft.

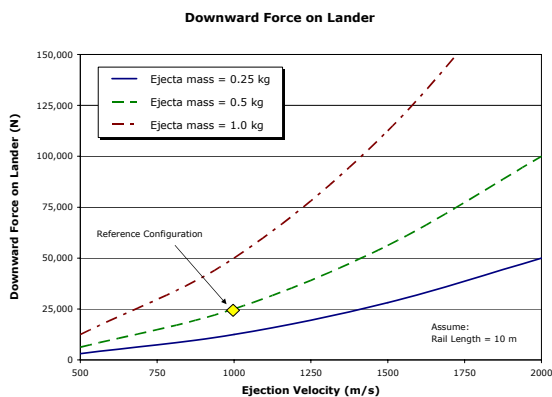


Figure 6. Effect of Launch Velocity on Lander Downward Force

From these preliminary results, a working baseline of a 10 m launch rail, 0.5 kg ejecta mass per shot, and a launch velocity of 1,000 m/s (well within the capability of today's rail launchers) was utilized. For this configuration, the ejecta will undergo an acceleration of almost 5,100 Earth g's for a period of 0.02 seconds. The mass driver power is therefore 12.5 MW per shot. The energy consumed per shot is 250 kJ.

Source Power Trade Study

While both ejecta launch conditions and rail length determine the mass driver power required per shot, the source power required to recharge the mass driver capacitor units is largely a function of shot frequency, which is how much time is allowed to recharge the capacitors between charges. A fast cycle time will benefit the overall architecture by requiring fewer landers to accomplish the mission in a given time period. However, faster cycle times require larger power sources onboard the landers, thereby raising unit cost and weight.

The relationship between source power and launch power is shown on a log-log scale in Figure 7 for three candidate launch rates. A preliminary launch rate of 1.0 shot per minute can be selected. For the reference configuration (launch power = 12.5 MW) and an assumed power conversion efficiency of 50%, the source power requirement for the mass driver was determined to be 8.33 kW. Assuming a similar power requirement for mining operations and a 25% margin for spacecraft telemetry and housekeeping power, the lander power requirement is less than 25 kW per lander. Additional trade studies will be performed once the spacecraft propulsion system is also evaluated. For example, if the spacecraft is to be powered by nuclear electric propulsion, excess power might be available in lander/mass driver mode.

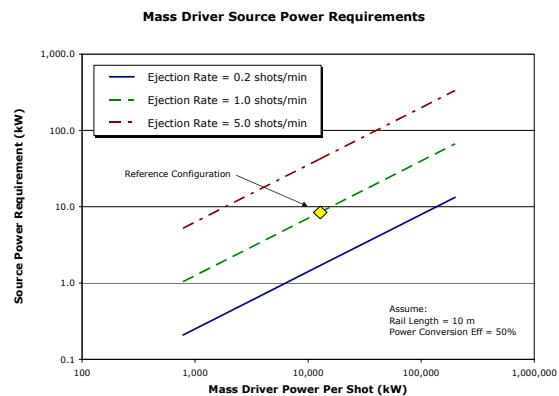


Figure 7. Mass Driver Source Power vs. Shot Power

Number of Lander Spacecraft Required

It is assumed that there should be a reasonably short period of action between when the spacecraft swarm arrives at the target and when surface operations can be stated to be complete. While long periods of operation are more efficient, there will certainly be great

anticipation by the public that the mission be completed and that there be adequate time to determine post-mission orbit of the asteroid to verify success. With this in mind, we have established a nominal period of action of 60 days to apply the required ΔV to the target impactor.

As shown in semi-log plot of Figure 8, the number of landers increases dramatically with the mass of the asteroid to be maneuvered. The nominal ejection rate chosen was 1.0 shot per minute based on previous considerations. For a “small” object, approximately the mass of the Tunguska impactor, the number of required lander spacecraft (with specifications based upon the previous parametric analyses) is approximately 20-25 depending on the system-level redundancy desired. For asteroids in the 10^{10} kg class (roughly 300 m in diameter) approximately 2,200-2,300 lander spacecraft would be required. For even larger asteroids such as those in the 10^{12} kg class, using the current concept would require over 200,000 landers to accomplish the mission in 60 days.

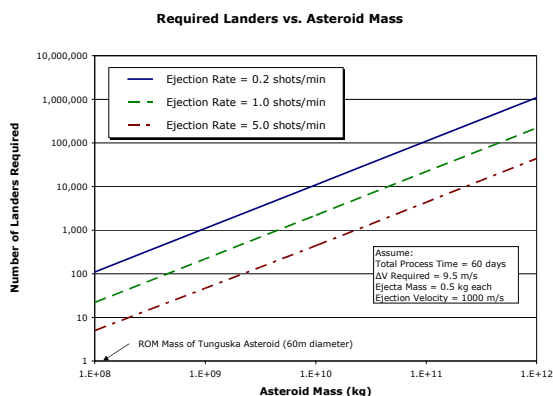


Figure 8. Number of Landers Required vs. Asteroid Mass

DEFT SCENARIOS

Based upon the most recent data, no current object is known to be in a threatening position with regards to the Earth. No object has been cataloged with a Torino Scale reading above a 2 (only one object has a reading of 1)¹. Thus fictional threats were obtained from scenarios developed for the AIAA sponsored 2004 Planetary Defense Conference: Protecting Earth from Asteroids (Orange County, California, February 23-26, 2004). Specific guidelines for the threats are stated as follows⁹:

For the 2004 Planetary Defense Conference, four fictitious Defined Threat (DEFT)

scenarios are posed where, without mitigation, solar system bodies (one comet, three asteroids) will strike Earth. These scenarios will encourage detailed designs of rendezvous, intercept and deflection missions and focused discussion of how the world community might prepare for mitigation efforts or possible disaster from policy, public education, and other perspectives...Three of the four scenarios are completely defined (asteroids D’Artagnon and Athos, comet Porthos)...The four scenarios are named for the approaching objects, D’Artagnon, Porthos, Athos, and Aramis¹. These threat concepts do not and cannot span the range of orbital characteristics, at this time, none of these names is assigned to an asteroid or comet warning times and object properties that could occur. They are, however, plausible possibilities and are intended to provide focus and direction in mission planning.

These scenarios call for smaller miss distances and provide increased detection times than the original design formulated by the just described parametric analyses. The baseline design presented here is rooted around one of these defined threats, D’Artagnon, an asteroid with a mass of 2.7×10^9 kg⁹. Table 2 lists the specific properties of the D’Artagnon asteroid used in this analysis. The DEFT scenario for this target states⁹:

D’Artagnan is an Aten-type asteroid that is discovered by Spaceguard on February 22, 2004. This solid asteroid spends most of its time closer to the Sun than the Earth and is difficult to observe. However, at the time of detection it is close to the apogee of its orbit and partially illuminated by the Sun against the dark sky. Prediction of the nominal orbit indicates that the next time the Earth and D’Artagnan come close, in September of 2009...this object is specifically designed to force consideration of what can be done with today’s technology in a “crash program” situation involving a modestly sized asteroid.

For scenarios involving smaller asteroids and long lead times, only a few landers may be required. However, larger threats such as Long Period Comets (LPCs) can require hundreds to thousands of landers, stretching the limits of manufacturing capability and launch capacity. Due to uncertainties in the size and orbit of each object, additional lander spacecraft can be sent to ensure adequate ΔV is applied.

Table 2. Defined Threat Specifications for D'Artagnon⁹

Item	Value
Time/Date of Detection	February 22, 2004 00:00:00: UT
Expected Date of Impact	September 14, 2009 11:04:26.117 UT
Approximate orbital elements at time of detection	q (perihelion distance) = 0.639030 AU
	e (eccentricity) = 0.288063
	i (inclination) = 4.788754 degrees
	Ω (right ascension of ascending node) = 350.540144 degrees
	ω (argument of perihelion) = 230.750220 degrees
	M (mean anomaly at time of detection) = 254.275083 degrees
	Period = 0.849613 years
Type	Type S Asteroid
Size	130 m x 120 m x 110 m
Mass	2.7×10^{12} g $\pm 40\%$
Density	3 ± 1 g / cm ³

BASELINE MADMEN LANDER DESIGN

Overview

A baseline configuration was established for the MADMEN spacecraft. Specific top-level assumptions were made about various subsystems in terms of enabling and enhancing technologies. For this preliminary baseline, architecture, it is assumed that a completely separate in-space transfer stage (ISTS) would be used to transport the MADMEN spacecraft to the target impactor.

The lander consists of several primary components. A nuclear reactor provides moderate power levels over long periods of time for the entire system. High energy density capacitors are charged for each individual shot, reducing the total load on the reactor. A mining system, similar to terrestrial coring drills, is used to extract material from the impactor. A swivel mounted drill bores into the NEO beneath the lander, extracting a moderate sized tube of material 0.16 m in diameter and 15m long. The material within the tube is removed, processed, and launched from the ejector. The drill is

then swiveled to a new position and the drilling process repeated, allowing each lander to access a reasonable volume of material while firmly anchored into place.

The ejector itself is a mass driver system consisting of a series of electromagnets arranged axially around a central barrel. A magnetized “bucket” containing ejecta is propelled along the barrel by the alternating attractive and repulsive forces of the mass driver. The ejecta are allowed to leave the barrel while the bucket is slowed down and some of its energy recovered via regenerative braking. The bucket can then be reused for additional firings. The high downforce from the mass driver is the primary driver for the structural weight and size. The reactor, mining system, and other subsystems must be supported, but a higher load is transferred along the mass driver’s structure, through the landing struts and anchors, and into the impactor.

Additional subsystems include thermal control, data processing, navigation and sensing, and communication systems. Small attitude control system (ACS) thrusters provide the ΔV to maneuver the lander from a transfer vehicle to the impactor, land on the impactor, and anchor into place.

A Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA) modeling process was employed to develop a parametric performance and sizing model. A ROSETTA model is a spreadsheet-based meta-model which is a representation of the design process for a specific architecture (e.g., ETO, in-space LEO-GEO, HEDS)¹⁰. ROSETTA models contain representations of a baseline design into which technologies can be infused. Using the baseline requirements, the mass ejector landers were designed and sized from both historical data and physical relationships^{11,12}. Simple trajectory and in-space transfer stage (ISTS) sizing disciplines were also added to the ROSETTA model.

The ROSETTA model was then optimized using a genetic algorithm from the OptWorks suite of Excel-based non-gradient based optimizers (available from Pi Blue Software, Inc.). Due to the complex nature of the design space, a simple gradient-based optimizer would stall on local minima. A genetic algorithm optimizer can handle such multiple local minima and better attempt to determine the global minimum within a design space. The genetic algorithm also provides the option of using discrete variables for discrete choices, such as material type, which will be used for later trade studies. For the optimization, the design variables, limits, and final values are given in Table 3. The

objective function was total mass of the landers required (mass per lander times the number of landers) for the sizing case based upon the D'Artagnon defined threat. For this case, the total number of MADMEN lander spacecraft was 329 with an individual spacecraft mass of 1,343 kg. This was for a baseline surface operation time from the mass driver system of 60 days.

Table 3. MADMEN Lander Spacecraft Optimization Parameters

Item	Minimum	Maximum	Final Value
Ejecta Mass per shot (kg)	0.1	1	0.1
Rail Length (m)	1	10	10
Shot Frequency (shots per minute)	1	10	10
Core diameter (m)	0.01	1	0.166

The optimization resulted in characteristics slightly different than those indicated by the parametric analyses that had generated the reference configuration. Table 4 displays the difference between the initial values as determined by the parametric analyses and those determined through a more thorough examination of the ROSETTA model. The final values used to generate the baseline single MADMEN spacecraft had a smaller downforce on the lander than initially indicated by the parametric analyses. The greater shot frequency increased the reactor power requirement, but only slightly.

Table 4. MADMEN Lander Spacecraft Characteristics

Concept Characteristic	Initial Value	Final Value
Required ΔV to Target Asteroid (m/s)	9.5	9.5
Mass-Driver Rail Length (m)	10	10
Ejecta Mass per shot (kg)	0.5	0.1
Ejection Velocity (m/s)	1,000	1,000
Ejection Power Required per shot (MW)	12.5	25
Ejection Energy (Work) per shot (kJ)	250	68
Shot Frequency (shots per minute)	1	10
Downward Load During Launch (kN)	25	5
Estimated Source Power (kW)	< 10	15

The mass breakdown for a single, baseline MADMEN lander spacecraft is given in Table 5. The mining system is the largest single element, requiring a large drill and tubing to core out a sufficient volume of the impactor. The rapid shot rate requires a heavy reactor and the large downforce necessitates increased structure, particularly along the ejector.

Table 5. Baseline MADMEN Lander Spacecraft Mass Breakdown Statement (MBS)

Item	Mass (kg)
1.0 Power System	278.8
Reactor	121.6
Energy conversion	60.8
Capacitors	34.0
Power conditioning	12.2
Shielding	50.2
2.0 Mining System	381.2
Drill	163.9
Main bit	16.4
Tubing	193.9
Ore Processing	7.0
3.0 Ejector	75.1
Mass Driver	75.0
Bucket	0.1
4.0 Propulsion	69.6
RCS Thrusters	60.0
Tanks	4.6
Lines	5.0
5.0 Thermal Control	40.5
Radiators	40.5
6.0 Main Structure	237.5
Anchors	5.0
Anchor Drive	20.0
Supports	12.5
Mining Frame	25.0
Vehicle Frame	50.0
Ejector Frame	125.0
7.0 Data Processing	8.0
Attitude/Orbit Determination	2.0
Attitude/Orbit Control	2.0
Device Pointing	2.0
Integrated Function	2.0
8.0 Navigation Sensing/Control	4.0
Celestial/IMU	4.0
9.0 Telecom and Data	4.0
TCM Module	2.0
Command and Data Handling	1.0
Communications Payload	1.0
10.0 Margin (+15%)	164.8
Total Dry Mass	1,263.5
11.0 RCS Propellants	80.0
Cruise stage egress	26.5
Main	23.0
Reserves and residuals	3.5
Impactor landing	53.5
Main	46.5
Reserves and residuals	7.0
Near Earth Departure Mass	1,343.5

Note: Any errors due to rounding

IN-SPACE TRANSFER STAGE (ISTS)

Overview

Given the modular nature of the MADMEN lander spacecraft, a similar philosophy was developed for the components needed to get these spacecraft to their target body. For this baseline architecture the MADMEN spacecraft are sent directly from Earth to the target body. The in-space transfer stage (ISTS) transports the MADMEN lander spacecraft to the target using conventional rocket engines performing a two burn sequence for earth escape and target capture. Once near the target body, the ISTS releases a MADMEN lander spacecraft and it performs the final maneuver towards the surface. For this initial assessment, a top level design decision was to place integer number of MADMEN lander spacecraft on each ISTS such that the entire stack would fit on currently available expendable launch vehicles. No in-space operations segment was assumed for this analysis.

Trajectory Modeling

Based upon the chosen asteroid threat, D'Artagnon, an initial analysis was performed of the required in-space trajectory to the target. A simplified patched conic approach was utilized from Earth escape to the target in order to generate the required velocity change to capture into the target's orbit (see Figure 9). Based upon the detection information for the target listed in Table 2, an approximate position for D'Artagnon was determined at the date of detection.

It was assumed that the Earth-To-Orbit (ETO) launch vehicle would nominally be the Delta IV-Heavy, will provide the needed velocity to achieve earth escape (with $c_3 = 0 \text{ km}^2/\text{s}^2$). A Delta IV-Heavy (4250H-19) vehicle can launch approximately 9,305 kg to a c_3 of $0 \text{ km}^2/\text{s}^2$ to achieve earth escape¹³.

From earth escape, a simple two-burn transfer was assumed to capture into the orbit of the target. These two burns consist of a transfer orbit/earth escape injection (performed at perihelion of the transfer orbit) and an impactor capture burn (performed at aphelion of the transfer orbit). The perihelion of the transfer orbit was assumed to be the distance of the Earth from the Sun at detection date. Impactor orbit capture was performed at the perihelion of the impactor's heliocentric orbit. Given these simplifying assumptions (along with a 10% margin), the total ΔV for the in-space portion of the trajectory to capture into the target's orbit was determined to be 5.66 km/s. This will

be the velocity change required by the in-space transfer stage (ISTS) to get a MADMEN spacecraft to the target. Additional ΔV required for the MADMEN spacecraft themselves for cruise stage egress and impactor landing was set to 50 and 100 m/s respectively.

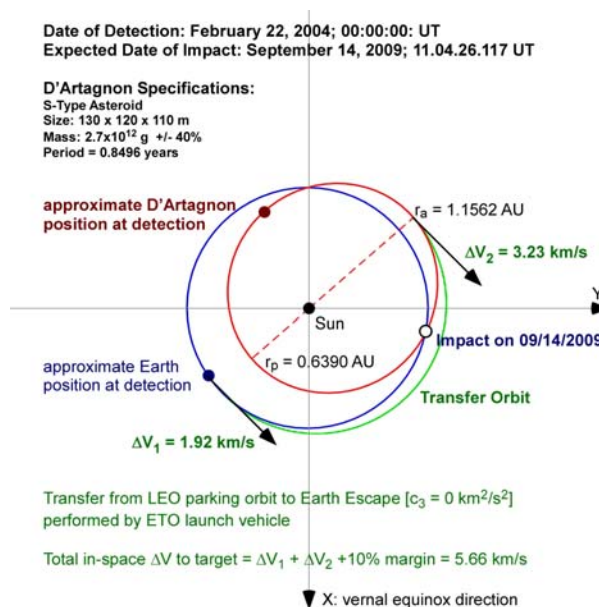


Figure 9. D'Artagnon Trajectory Profile

System Sizing

The ISTS was physically sized in the ROSETTA model described previously in this paper. Parametric sizing models were created for the ISTS and several associated subsystems (notably telecommunications). The initial transfer stage design was designed to use a liquid oxygen / liquid hydrogen propulsion system with an Isp of 433 seconds.

The ISTS sizing process took the mass of the MADMEN spacecraft as an input. Since the mass of each of those spacecraft was relatively large (over 1 MT each) and the payload of the Delta IV-Heavy is about 9.3 MT, only one spacecraft was placed on each transfer stage. Given this payload for the ISTS, total stack mass on the Delta IV-Heavy is around 7.8 MT as seen in Table 6, well within the limits of the launch vehicle to a c_3 of zero (earth escape).

**Table 6. Baseline In-Space Transfer Stage (ISTS)
 Mass Breakdown Statement (MBS)**

Item	Mass (kg)
1.0 LH2 Tank Structure	81
2.0 LH2 Tank Insulation	62
3.0 LOX Tank Structure	31
4.0 LOX Tank Insulation	33
5.0 Engine Weight	188
6.0 Telecommunications	8
7.0 Subsystems	30
8.0 Other Structure	43
9.0 Margin (+15%)	65
Total Dry Mass	541
Total Payload Mass	1,343
Impactor Arrival Mass	1,885
Required Propellant	5,763
Unusable Propellant	179
Pre-Injection Mass	7,827

Note: Any errors due to rounding

Given the particular asteroid threat for this analysis, D'Artagnon, 329 MADMEN lander spacecraft are required to change the approximately 100 m wide asteroid's velocity by 9.5 m/s for a surface operation time of 60 days. This correlates to 329 Delta IV-Heavy launches. Generally, the launch capacity of current expendable launch vehicles (fewer than 10 MT mass to earth escape) precludes any more massive systems than the MADMEN lander spacecraft shown.

BASELINE SENSITIVITY ANALYSIS

Some causes of these large launch rates include the large mass of the MADMEN spacecraft themselves, the large ΔV to be applied to the target, and the length of mass driver surface operations of the spacecraft. A sensitivity analysis can be performed to examine the nature of the architecture with regards to these parameters. Figure 10 relates the sensitivity of the total number of MADMEN lander spacecraft required versus the total surface mass driver operation time and the deflection distance (a proxy for the applied ΔV on the target). There is generally a linear relationship between deflection distance and number of lander spacecraft required for the target. At lower surface operation times there is non-linear relationship with respect towards number of lander spacecraft, which changes to a more linear one at higher operation times. For example, increasing surface operation time by 200 days and reducing miss/deflection distance to 0.3 LD, results in only 60 lander spacecraft needed for the target. Thus there may be a possibility to substantially reduce the number of lander spacecraft or develop smaller, lower

power versions if longer surface times or lower miss distances are possible than those postulated for the baseline architecture. These preliminary results do not reflect a complete system optimized solution to the planetary deflection issue. Additional options and architecture variations could reduce the spacecraft size and subsequent number of required ETO launches.

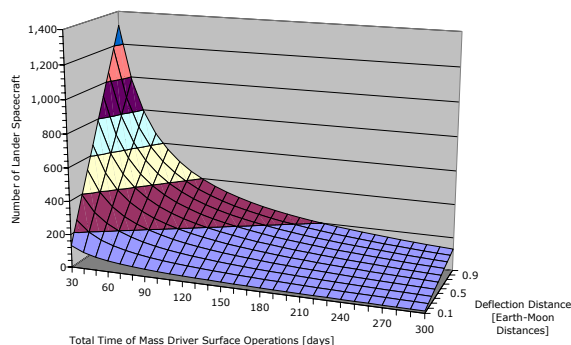


Figure 10. MADMEN Lander Spacecraft Sensitivity

FUTURE WORK

SEI will continue to develop and analyze the swarm planetary defense concept. Future work will include detailed analysis of the architecture including increasing the fidelity and depth of the lander and transfer stage design. A more complex and realistic transfer trajectory model will be developed and integrated with the parametric ROSETTA model. With this coupled analysis, a complex optimization can be performed to minimize the launch mass required to deflect an incoming NEO. The trade between delaying launch time for smaller ΔV 's to the rendezvous and increased numbers of landers required for shorter times on the impactor will be studied. Additionally, trade studies will be performed on lander system components such as the mining system, ejection system, and reactor; as well as for the transfer stage, including electric propulsion options. Specific trade studies to be addressed during the Phase I study are listed in Table 7.

One of the primary objectives of these further refinements of the baseline modeling capability and trade studies will be to attempt to reduce the total spacecraft mass required per asteroid and to examine the specific sensitivity of these parameters to target detection time/transfer time and on-site excavation time.

Table 7. Proposed Trade Studies for Phase 1 NIAC Effort

Trade Study Type	Options
Pre-Deployment	Earth-Moon L2, Earth-Sun L1, Earth-Sun L2, or Ground versus simple rapid response from the Earth
Boost Propulsion to Target	Solid, Liquid, Electric (high thrust versus low thrust)
MADMEN Power	Nuclear, Solar
Mass Driver Velocity	Variable (approx 50 m/s – 500 m/s)
Mining technology	Mechanical, Acoustic, etc.
Landing configuration	Impact landing vs. "soft-land"
Mass Driver Power (per spacecraft)	Variable (500 W – 50 kW)
Launch Vehicle	Delta IV, Atlas V, RLV, etc.

SUMMARY

This analysis has presented a novel and potentially valuable technique for NEO deflection. The potential solution described here considers not only the need to move a specific impactor’s orbit, but also the need to have a highly reliable, robust, and scaleable architecture that is cost effective, easy to manufacture, easy to launch, and practical to intercept most incoming threats. This preliminary assessment has indicated that several tens to hundreds of MADMAN lander spacecraft, each with a mini mass driver system, can deflect a local/regionally-devastating incoming asteroid that is in an orbit generally close to the Earth. Substantial reductions can be made in the total number of spacecraft and/or spacecraft mass if both surface operation time and deflection distance are traded-off in the analysis. Specific use was made of fictional threat scenarios to present a case study of this planetary defense architecture. Future trade studies are presented that will be part of the completed Phase I NASA Institute for Advanced Concept (NIAC) study.

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