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Development of an Asteroid Mission Design Software Tool for Planetary Defense

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Abstract

The impact threat of an identified potentially hazardous near-Earth objects (NEO) becomes serious, the development and design of asteroid deflection/disruption missions ceases to be an academic exercise, but a practical necessity. Several software tools are already available for mission designers to perform orbital trajectory and mission design optimization. However, this paper expands upon the development of the Asteroid Mission Design Software Tool (AMiDST), by adding a method of accommodating practical constraints on the mission design variables. Through the use of these constrained design variables, more optimally feasible missions can be designed for mitigating the impact threat of hazardous NEOs. The effectiveness of the proposed mission design tool, AMiDST, is demonstrated using several example cases, including 2012 DA14 and comet 2013 A1.

Keywords: mission design, planetary defense, precision N-body simulation

1. Introduction

The threat of asteroids impacting the Earth is very real and must be taken seriously. Instead of hoping for a successful mission to the threatening near-Earth object (NEO) when the time comes, or assuming that day will never come, demonstrations of NEO impact avoidance missions can provide knowledge and experience that may prove vital, should similar missions be needed in the future. The focus of this paper is two-fold: i) preliminary mission design for direct intercept and/or rendezvous missions to target NEOs and ii) precision, long-term N-body simulations of asteroid orbits about the Sun. In this paper, we examine such mission design and the long-term, precision orbit determination problems using 1999 RQ36, 2011 AG5, and Apophis as illustrative examples.

Previous research activities at the Asteroid Deflection Research Center (ADRC) have included asteroid target selection, preliminary hypervelocity asteroid intercept vehicle (HAIV) designs, and preliminary mission designs. [1, 2, 3] The HAIV is a baseline system concept developed to accommodate the technically challenging aspects of these missions. A baseline HAIV system consists of a leader spacecraft (kinetic impactor) and a follower spacecraft carrying an nuclear explosive device (NED) for the most effective disruption of a target NEO. The leader spacecraft would impact the NEO first and create a shallow crater. The follower spacecraft would then enter the crater and detonate the NED [4]. The preliminary mission designs using this spacecraft configuration have included decisions on the launch vehicle, OTV (orbital transfer vehicle) optimization, and initial mission orbit determination using a Lambert solver. Asteroid target selection and mission designs along with general mission analysis are components of an overall, complete mission design concept, previously left separate to focus on the individual components themselves. In this paper, target selection and preliminary mission design concepts are combined and treated as components of an overall NEO mission design tool in development at the Iowa State ADRC.

Precision orbit determination is a third component added to the mission design tool to enhance its overall strength. Precision trajectory tracking using an N-body gravitational simulator can prove to be a powerful tool,

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either to calculate impact probabilities of asteroids with Earth or find the trajectories of perturbed bodies. Together, the the asteroid target selection, preliminary mission design process, and precision orbit tracking components are integrated to create the ADRC's Asteroid Mission Design Software Tool (AMiDST) - a multi-purpose design program for asteroid deflection/disruption missions.

2. Overview of Existing Mission Design Tools

2.1. Pre-Mission Design Process Algorithm

The initial mission design program, used for the HAIV to disrupt Earth-threatening asteroids, was primarily a pre-mission design software tool. It was comprised of several functions and subroutines calculating several preliminary design variables.[5] The program assumed the HAIV was comprised of a leader and follower spacecraft carrying a nuclear explosive device (NED) for a penetrated subsurface explosion mission. Using the information about the masses of the HAIV bus and NED payload, mission ΔV or C3 needed to reach a target NEO, and class of launch vehicles to be analyzed, the algorithm begins the process of calculating the payload capacity of the launch vehicles, mission details, and analyzing the solution. A flowchart of the pre-mission design process is provided in Figure 1.[5]

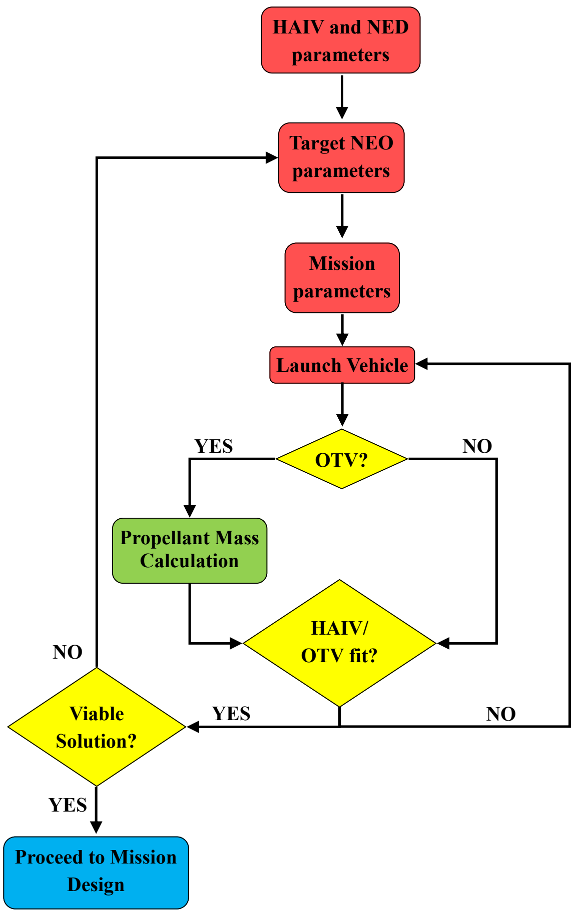

Figure 1: Flowchart Illustration of the Pre-Mission Design Process.

2.2. An On-line Tool by The Aerospace Corporation

The Aerospace Corporation is developing an on-line tool to aid in the design and understanding of deflection impulses necessary for guarding against objects that are on an Earth-impacting trajectory. Using several variables to characterize the target NEO (warning time, size/density, orbit parameters, etc.) and mitigation mission design parameters (ΔV impulse vector, number of days before impact to launch, number of days before impact to deflect, etc.), users can simulate the designed mission transfer from Earth to the target NEO and deflected NEO orbit. After the applied deflection and propagation time, the Earth miss distance would be determined on the Earth B-plane in Earth radii. This on-line tool is still under development, with the hopes of incorporating several more design variables and limitations to only allow feasible mission designs based on current launch and mission capabilities. [6]

2.3. NASA's Mission Design Software Tools

Through the In-Space Propulsion Technologies Program, in the Space Science Projects Office at NASA Glenn Research Center, several optimization tools have been developed for trajectory and mission optimization, such as MALTO, COPERNICUS, OTIS, Mystic, and SNAP. [7]

2.3.1. COPERNICUS

Originally developed by the University of Texas at Austin, under the technical direction of Johnson Space Center, Copernicus is a generalized trajectory design and optimization program that allows the user to model simple to complex missions using constraints, optimization variables, and cost functions. Copernicus can be used to model simple impulsive maneuvers about a point mass to multiple spacecraft with multiple finite and impulse maneuvers in complex gravity fields. The models of Copernicus contain an n-body tool and as a whole is considered high fidelity.

2.3.2. OTIS

The Optimal Trajectories by Implicit Simulation (OTIS) program was developed by the NASA Glenn Research Center and Boeing. OTIS is named for its original implicit integration method, but includes capabilities for explicit integration and analytic propagation. Earlier versions of OTIS have been primarily been launch vehicle trajectory and analysis programs. Since then, the program has been updated for robust and accurate interplanetary mission analyses, including low-thrust trajectories. OTIS is a high fidelity optimization and simulation program that uses SLSQP and SNOPT to solve the nonlinear programming problem associated with the solution of the implicit integration method.

2.3.3. Mystic

Mystic, developed at the Jet Propulsion Laboratory (JPL), uses a Static/Dynamic optimal control (SDC) method to perform nonlinear optimization. The tool is an n-body tool and can analyze interplanetary missions as well as planet-centered missions in complex gravity fields. One of the strengths of Mystic is its ability to automatically find and use gravity assists, and also allows the user to plan for spacecraft operation and navigation activities. The mission input and post processing can be performed using a MATLAB based GUI.

2.4. NASA's General Mission Analysis Tool

Developed by NASA Goddard Space Flight Center, the General Mission Analysis Tool (GMAT) is a space trajectory optimization and mission analysis system. Analysts use GMAT to design spacecraft trajectories, optimize maneuvers, visualize and communicate mission parameters, and understand mission trade space. GMAT has several features beyond those that are common to many mission analysis systems, features that are less common or unique to GMAT. Its main strength over other software choices is GMAT's versatility. Its scripting ability is easy to use and edit without knowledge of computer languages. And, the MATLAB plug-in allows an expansion of the user's ability to personalize each mission. [8]

2.5. Asteroid Mission Design Software Tool (AMiDST)

Building from the previously established Pre-Mission Design Algorithm, the AMiDST incorporates all elements of the pre-existing algorithm and expands upon them. Figure 2 shows a flow-chart illustration of the AMiDST. The design tool begins with a choice between analyzing a pre-determined list of target NEOs to design a mission for or build a custom mission design for a personally selected target NEO. With the pre-determined NEO target list, the software follows the Pre-Mission Design Algorithm, described previously, to analyze all launch configurations, and incorporates estimated mission cost before establishing which mission architecture is to be used for further design and analysis.

For custom mission designs, the user begins by entering information about the target NEO of interest and the low-Earth orbit (LEO) departure radius. Then the choice is given between two types of spacecraft to be used for the mission, the HAIV concept or a Kinetic Impactor (KI). For HAIV spacecraft, information about the mass of the impactor, follower, and NED are obtained from the user, while in the KI spacecraft case the total mass of the satellite is needed. In either case, the user is prompted with a decision between three mission types: a

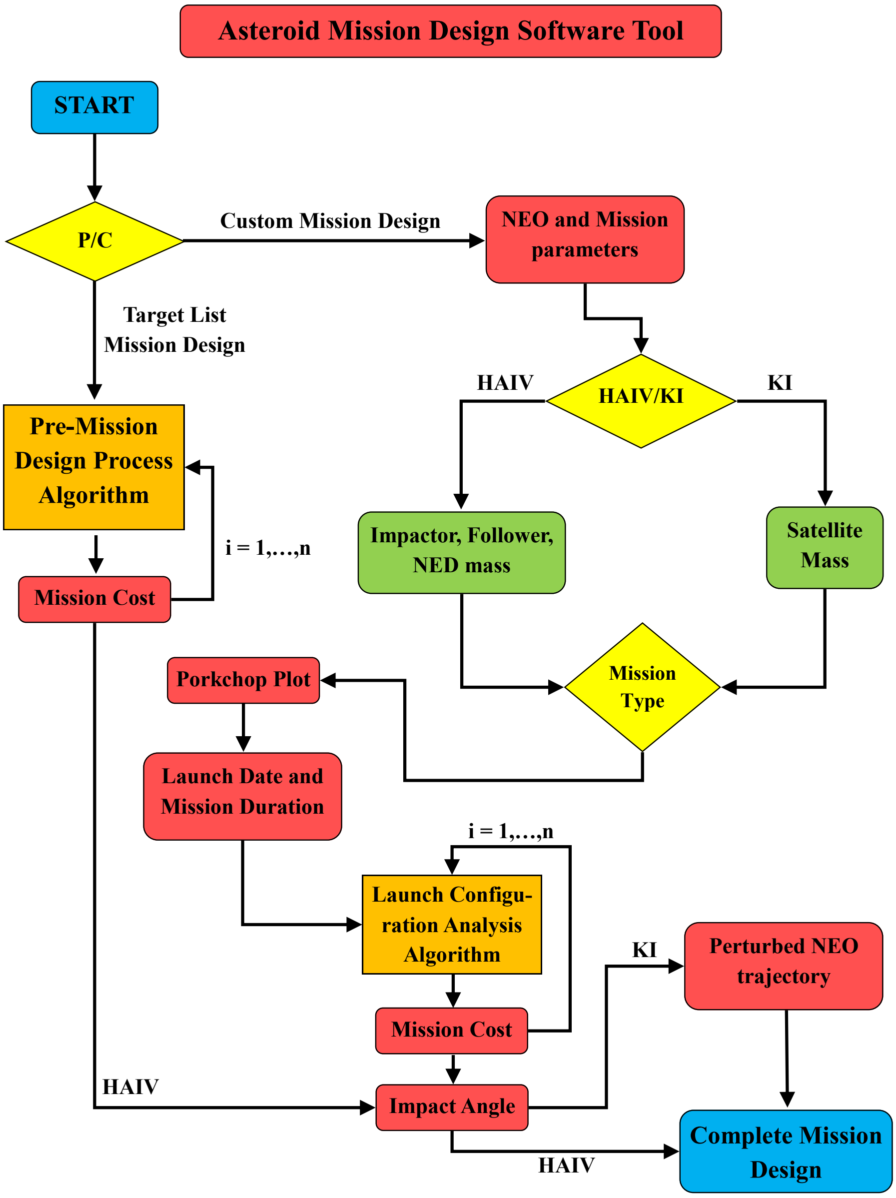

Figure 2: Flowchart Illustration of the AMiDST.

direct intercept, a direct intercept at a relative speed of 10 kilometers per second, or rendezvous. The software tool then loads the appropriate porkchop plot, showing the total required mission ΔV, where the user can select as many design points as desired, resulting in a set of launch dates and mission durations. Given the launch date(s) and mission duration(s), the transfer orbit between Earth and the target NEO is completely determined by Lambert's Problem, allowing the possible launch configurations for the mission(s) to be analyzed along with their estimated mission cost and compared to come up with the prefered launch configuration for each given mission. The resulting mission trajectories for either the HAIV or KI spacecraft are provided along with the arrival impact angles. Since the purpose of the HAIV design was total NEO disruption, the trajectory of the remaining asteroid fragments are not tracked, however in the case of the KI spacecraft the slightly perturbed NEO is propagated forward in time to see how much the orbit has changed from the original, before the impulse was applied.

2.6. Mission Design Program Comparisons

The trajectory and mission optimization tools developed through the In-Space Propulsion Technologies Program are all rather high fidelity programs. One of the common denominators of all these tools are that they primarily look at the intermediate stage of a mission, the spacecraft trajectory from one target to another. The other two mission stages are more or less overlooked in comparison to the spacecraft's mission trajectory. The

AMiDST does not currently possess the high-fidelity trajectory optimization of Copernicus, Otis, or Mystic, but instead focuses on the launch and terminal phase of an NEO mission.

Looking into several launch vehicle and spacecraft configurations to complete a given mission design to a designated target NEO, the mission design software evaluates the possible combinations based upon several evaluation criteria such as space in the launch vehicle fairing, mission ΔV requirements, and excess launch vehicle ΔV. A staple of this mission design tool is the evaluation of estimated total mission cost, the determining factor between mission configurations in the cases where more than one launch configuration can result in a successful mission.

The terminal phase of an NEO mission currently is limited to kinetic impact perturbations to a target NEO's orbital trajectory. Using the impact angle and arrival velocities of both the spacecraft and target NEO, along with both masses, the trajectory of the perturbed asteroid is tracked in order to find how much the trajectory is altered from the previous unperturbed orbit. Depending on the chosen NEO, a mission can be designed to explore the capabilities of a kinetic impactor on a target NEO or to design a mission to deflect the target NEO from its Earth-impacting trajectory.

3. Target Asteroid Examples

Near-Earth Objects are asteroids and comets with perihelion distance (q) less than 1.3 astronomical units (AU). The vast majority of NEOs are asteroids, which are referred to as Near-Earth Asteroids (NEAs). NEAs are divided into three groups (Aten, Apollo, Amor) based on their perihelion distance, aphelion distance (Q), and semi-major axes (a). Of these three classes of asteroids, Aten and Apollo type asteroids are of particular interest to this study due to their relative proximity and Earth impacting potential. Atens are Earth-crossing NEAs with semi-major axes smaller than Earth's ($a < 1.0$ AU, $Q > 0.983$ AU). Apollos are Earth-crossing NEAs with semi-major axes larger than Earth's ($a > 1.0$ AU, $q < 1.017$ AU). [9] Figure 3 shows representative orbits for the three class of asteroids in reference to Earth's orbit. With the wide array of choices to select target NEOs from, there are three asteroids

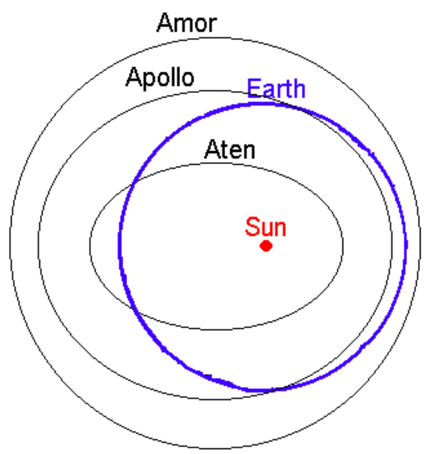

Figure 3: Typical Orbits of Apollo, Aten, and Apollo Asteroids.

mainly focused in this paper: 1999 RQ36, 2011 AG5, and Apophis, all three being Apollo class asteroids.

4. Mission Design Case Study I

In this section, results previously obtained from the AMiDST will be highlighted. The reported variables shown are those which lend significance to the overall mission design and to the ability to understand the more developed orbital missions to near-Earth asteroids and the precision orbit simulation sections presented later in this paper.

4.1. *Asteroid 1999 RQ36*

As an extension to the HAIV mission designs conducted at the ADRC in the past, an HAIV disruption mission to asteroid 1999 RQ36 was conducted using the AMiDST. Due to 1999 RQ36's large mass and size, the chosen HAIV configuration is the 1500 kg NED spacecraft. In this configuration, the HAIV has a 670 kg impactor and a 3550 kg follower carrying a 1500 kg NED. With the spacecraft configuration and mission type coordinated, the AMiDST proceeds to load the appropriate contour plot for the user to pick the desired design point. The cross-hairs and black box on Figure 4 show the region from which the design point was chosen from.

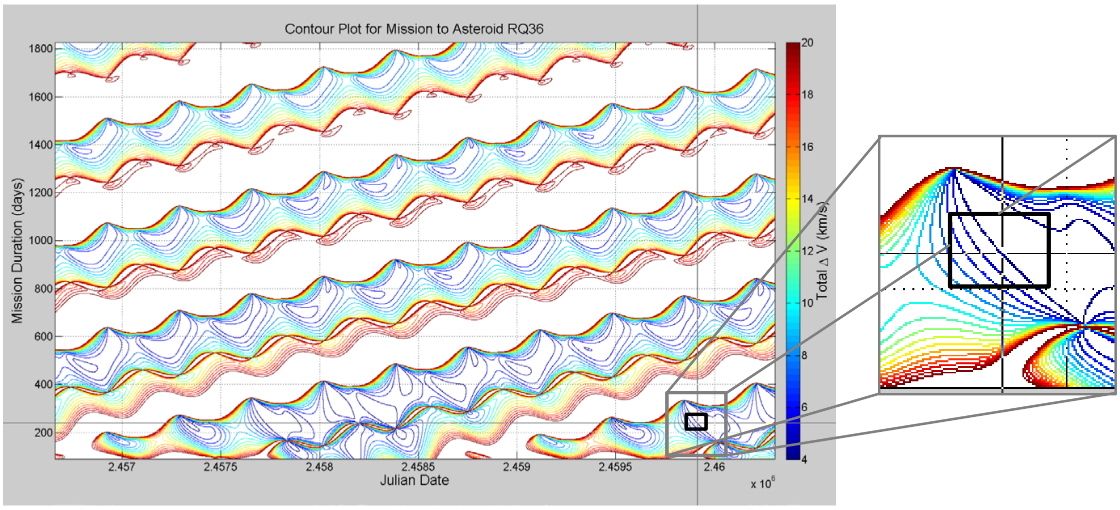

Figure 4: Selection of launch date and mission duration for 1999 RQ36 disruption mission.

The selected design point for this HAIV disruption mission is chosen to occur at a late launch date within the given launch window. The selected launch date comes out to be December 6, 2022 with a mission duration of 233 days. Given the launch date and mission duration pair, the resulting departure ΔV from the 185-km circular low-Earth orbit is just over 4 km/s. From these mission parameters, the spacecraft's trajectory is plotted in red along with the Earth's path (green line) and 1999 RQ36's trajectory (blue line) over the mission timespan in Figure 5 on the left. The HAIV would depart from Earth (red triangle) on December 6, 2022 and travel for 233 days until it would encounter the target NEO on July 27, 2023 (red circle).

On the right side of Figure 5, there is a depiction of the arrival conditions for the HAIV with respect to 1999 RQ36. Arriving at 1999 RQ36 on July 27, 2023 the HAIV would be travelling at about 26.5 km/s at a 16.1 degree angle to the target NEO's 28.7 km/s velocity, resulting in about an 8-km/s velocity difference. Thanks to the large spacecraft mass and required departure ΔV, the only launch vehicle capable of completing the given mission, from the Delta II, Atlas V, and Delta IV class vehicles analyzed, is the Delta IV Heavy. With such a powerful launch vehicle and massive spacecraft comes a large price tag as well, the estimated mission cost for this nuclear disruption mission is nearly $1.8B. Since only the Atlas V class of launch vehicles are currently able to be launched, due to the decommissioning of the Delta II and Delta IV launch vehicles, a new launch date and/or mission duration would have to be found for a feasible mission design. Based upon the given mission parameters, Table 1 gives all the pertinent HAIV mission results. [10]

4.2. *Asteroid 2011 AG5*

If asteroid 2011 AG5 were deemed a realistic threat to the survival of the planet, a deflection/disruption mission would need to be launched. The HAIV design conceived at the ADRC is used for this particular disruption mission case study. The current direct intercept mission case study has a departure date April 15, 2027 and a mission duration of 350 days. Figure 6 shows the contour plot for a direct intercept mission with 2011 AG5. The cross-hairs and black box in the diagram show the selected launch date and mission duration, which are used to design the disruption mission. With nearly a full year of transit time, the HAIV would not arrive to the target NEO until March 30, 2028, about 12 years before the estimated impact date. The orbit plot on the left of Figure 7 shows the impact between the HAIV and the target to occur inside the Earth's orbital radius. The spacecraft will depart from Earth on April 15, 2027, represented by the red triangle, and travel for 350 days until its encounter with asteroid 2011 AG5 on March 30, 2028, shown as the red circle. The spacecraft, asteroid, and Earth's orbits are depicted by the red, blue, and green lines, respectively.

The right side of Figure 7 shows the anticipated encounter between the HAIV and target NEO. Arrival at 2011 AG5 from the given trajectory will result in an impact angle of about 14.3 degrees, the angle between the

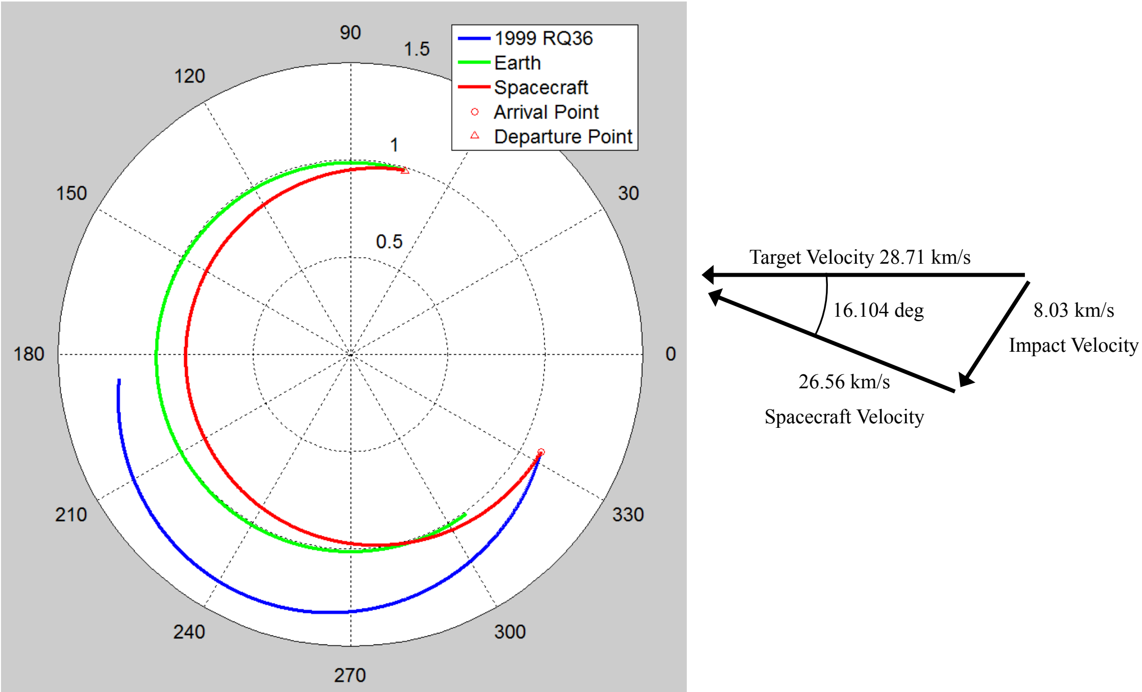

Figure 5: Left: Orbit diagram of transfer trajectory from Earth to 1999 RQ36. Right: Speeds and angle between spacecraft and 1999 RQ36 at impact.

Table 1: Mission design parameters for intercept with Asteroid 1999 RQ36.

Mission Parameter	Value
Asteroid	1999 RQ36
Asteroid Mass (kg)	1.4E+11
LEO altitude (km)	185
Spacecraft Designation	HAIV
NED Mass (kg)	1500
Impactor Mass (kg)	670
Follower Mass (kg)	3550
Total HAIV Mass (kg)	5720
Departure ΔV (km/s)	4.002
C3 (km^2/s^2)	17.669
Launch Vehicle	Delta IV Heavy
Departure Date	December 6, 2022
Mission Duration (days)	233
Arrival Angle (deg)	16.104
Impact Velocity (km/s)	8.03
Arrival Date	July 27, 2023
Estimated Mission Cost ($)	1797.66M

asteroid and spacecraft's velocity vectors at the time of impact. Such an arrival angle results in a relative velocity between the asteroid and the HAIV of over 9 km/s. High relative impact velocities, similar to the one present in this mission, are the reasons why the ADRC has been developing the HAIV concept. The pertinent mission parameters for this direct intercept disruption mission are given in Table 2. The departure ΔV for this case study is rather high, at just under 6 km/s. Given such a large ΔV, an Atlas V 551 launch vehicle is smallest launch vehicle from the Delta II, Atlas V, and Delta IV classes capable of imparting the required change in velocity from low-Earth orbit. And, since the decommissioning of the Delta II and Delta IV launch vehicles, the Atlas V 551 is the only launch vehicle available, and capable, of completing the aforementioned mission. The estimated mission cost for this particular mission design is nearly $1B. It is interesting to note that while there are several regions where a feasible mission can be designed, there are many more design points where there is no feasible launch

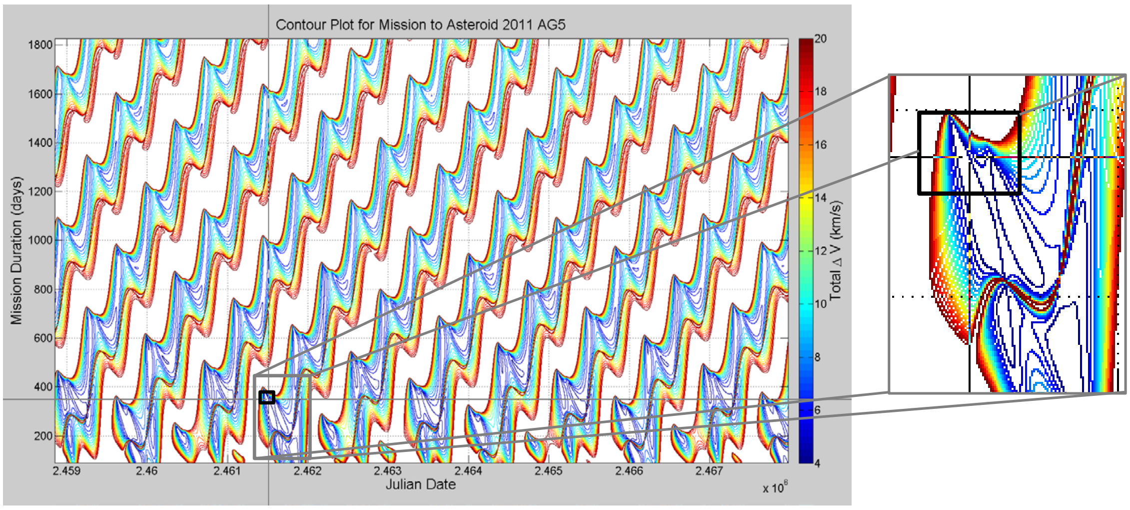

Figure 6: Selection of launch date and mission duration for 2011 AG5 disruption mission.

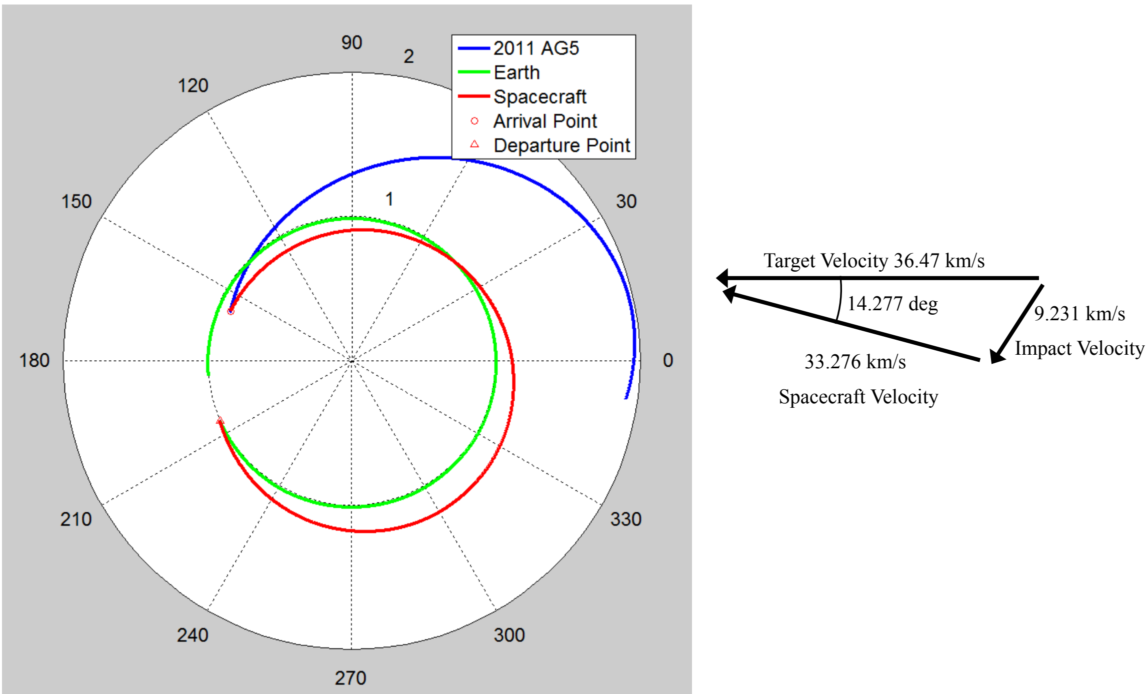

Figure 7: Left: Orbit diagram of transfer trajectory from Earth to 2011 AG5. Right: Speeds and angle between spacecraft and 2011 AG5 at impact.

configuration that will apply enough ΔV to inject the spacecraft into the required direct transfer orbit. [10]

5. Mission Design Case Study II

To this point, the mission archictectures designed in AMiDST have been fairly unconstrained - merely ensuring the mission is feasible. Now, let's apply some additional constraints such as limitations on flight time and time between asteroid impact and NEO flyby/impact on a couple new targets that have been in the media recently. It is important to remember while going through these examples that some of the initial assumptions are not possible anymore, but the missions are being used as exercises to show the capabilities of the AMiDST.

5.1. Comet 2013 A1

Comet 2013 A1, an Oort cloud comet, was discovered January 3, 2013 at the Siding Spring Observatory. The significance of this discovering lies in its anticipated trajectory through our Solar System. On October 19, 2014,

Table 2: Mission design parameters for intercept with Asteroid 2011 AG5.

Mission Parameter	Value
Asteroid	2011 AG5
Asteroid Mass (kg)	4.1E+9
LEO altitude (km)	185
Spacecraft Designation	HAIV
NED Mass (kg)	300
Impactor Mass (kg)	360
Follower Mass (kg)	1183
Total HAIV Mass (kg)	1843
Departure ΔV (km/s)	5.961
C3 (km^2/s^2)	67.709
Launch Vehicle	Atlas V 551
Departure Date	April 15, 2027
Mission Duration (days)	350
Arrival Angle (deg)	14.277
Impact Velocity (km/s)	9.231
Arrival Date	March 30, 2028
Estimated Mission Cost ($)	860.340M

2013 A1 is projected to have a close-encounter with Mars. The nucleus of the comet is estimated to be between one and three kilometers, traveling about 56 kilometers per second. If the comet were to hit Mars, the amount of impact energy would be about a third of the energy from the asteroid that killed off the dinosaurs and about 80 million times more energy than the tiny asteroid that exploded over Russia this past February. [11]

Table 3 shows the prominent orbital elements of Comet 2013 A1. Given that 2013 A1 is a hyperbolic asteroid,

Table 3: The orbital elements of Comet 2013 A1 that dictate its orbital shape. [9]

Orbital Element	Value	Uncertainty (1-σ)	Units
a	-3842.815	646.13	AU
e	1.000364	6.1198e-05	
i	129.0223	0.002152	deg

there is a limited window in which we could design a feasible mission to the body. Figure 8 shows the believed orbit of the hazardous comet.

So, let's assume that it is currently the beginning of January 2013 and Comet 2013 A1 has just been discovered and based on the simulations it will impact Mars in October 2014. Also, let us assume that we would not want to watch Mars get hit by this comet, implying that we would like to have a disruption mission to this body that would have enough dispersion time for the debris before Mars encounter. And to make this scenario more feasible, let's also assume that we are mission capable at the time of discovery. These criteria are not realistic and are merely put in place for the benefit of the exercise that it would provide. Given what is available and these constraints/requirements it can be easily seen that the problem has limited possible solutions.

From the information given on the 2013 A1 and the requirements set on mission to impact the comet and allow time for dispersion of the debris before the anticipated date of its Mars encounter, an established timeline from January of 2013 to October of 2014 has been set. During this time, spacecraft would have to be launched, intercept the target, and allow time for the disrupted body to disperse. To help visualize this established launch window, Figure 9 shows the corresponding $\Delta V's$ for a given launch date and mission duration. From previously constructed missions to other NEOs, the feasible mission $\Delta V's$ were generally less than seven kilometers per second. If this is taken to be true for this body as well, then the mission launch window becomes rather small, with mission durations of about 200 days or more.

Obviously, the best mission would require the smallest amount of ΔV, which would imply that a given launch vehicle could lift more mass into orbit, so the limitation of total ΔV previously discussed is not really a constraint as much as an interesting bit of information to keep in mind during the design process. The important constraints

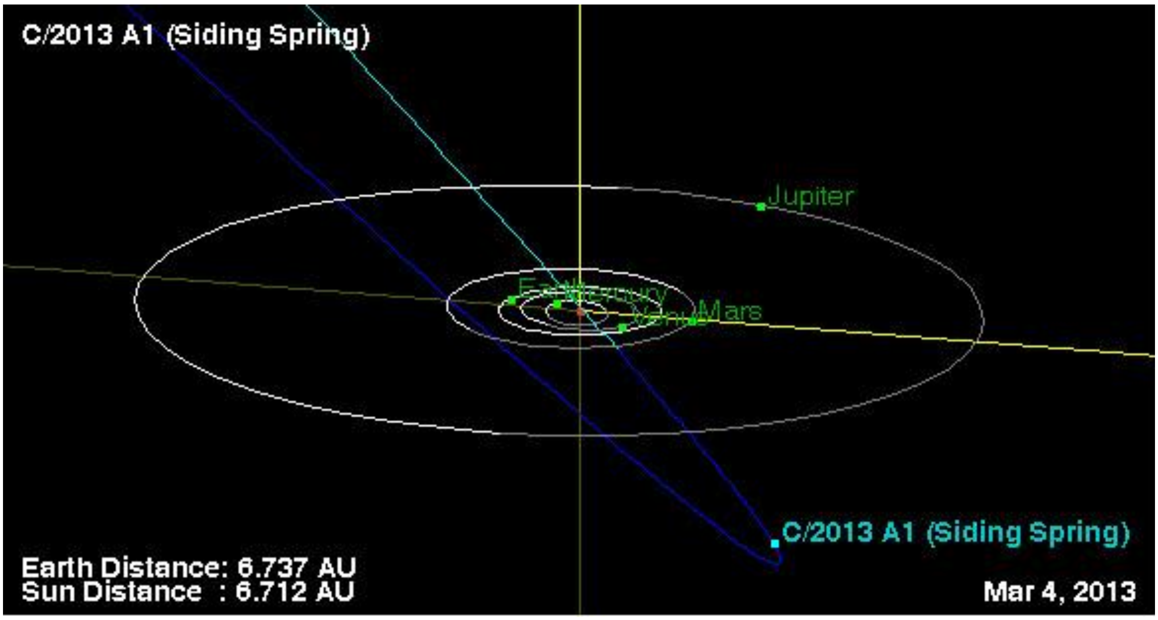

Figure 8: Orbital diagram of Comet 2013 A1, with respect to Jupiter and the inner planets.

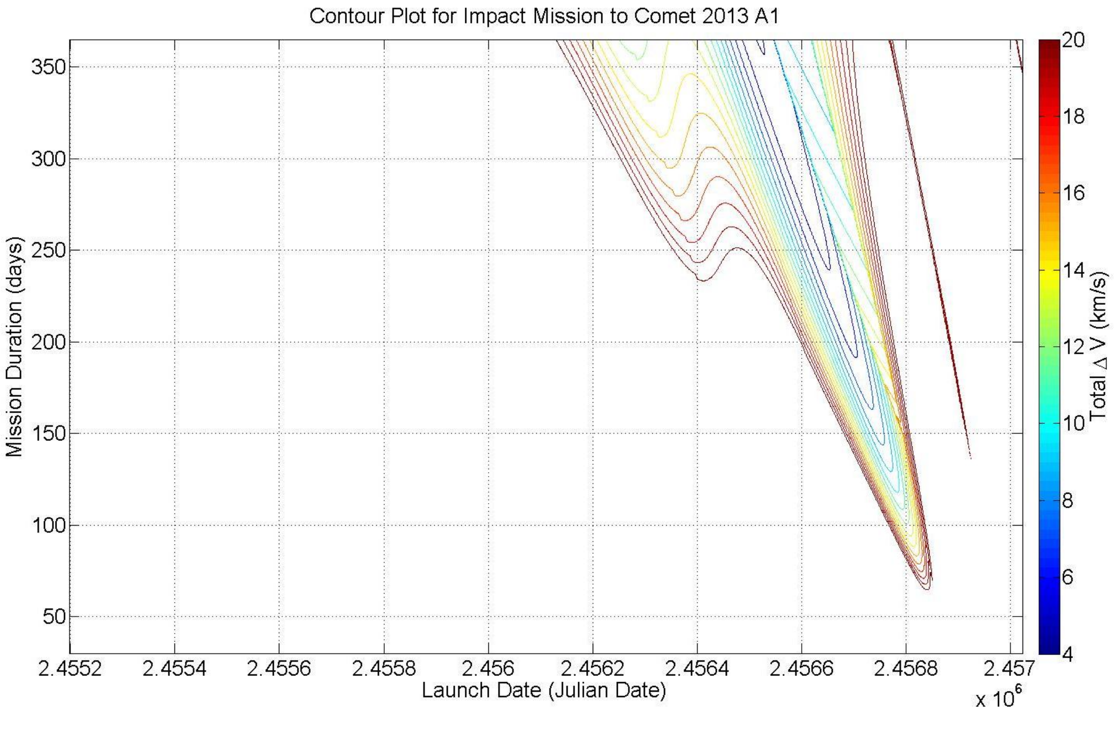

Figure 9: Contour plot showing total mission ΔV based on launch date and mission flight time. The departure dates are from January 2010 to January 2015, and mission durations vary from 30 days to one year.

that will limit the mission feasibility window are the launch date and mission duration resulting in an impact date that allows for dispersion of the disrupted debris. So, the launch date cannot occur before the discovery date, meaning that the departure date cannot be before January 3, 2013. Taking a pretty relaxed approach to the mission constraints, let the minimum dispursion time be at least 15 days and the maximum flight time be a year. The optimal mission parameters for an impact mission to Comet 2013 A1 are shown in Table 4.

The resulting optimal mission parameters that meet the established constraints show a departure date a little more than eight months after discovery and a year long mission flight time, requiring a departure ΔV of just under four kilometers per second. After the year long transit from Earth to Comet 2013 A1, the spacecraft would impact

Table 4: Optimal constrained mission parameters for impact mission to Comet 2013 A1.

Parameter	Value
Departure Date	August 15, 2013
Flight Time (days)	365
Departure ΔV (km/s)	3.963
Dispersion time (days)	65

the comet about 65 days before the expected close approach with Mars. Using these parameters as the basis for an impact mission to Comet 2013 A1, the resulting mission design parameters are summarized in Table 5. The design

Table 5: Mission design parameters for intercept mission to Comet 2013 A1.

Mission Parameter	Value
Comet	2013 A1
LEO altitude (km)	185
Spacecraft Designation	HAIV
Total HAIV Mass (kg)	1800
Departure ΔV (km/s)	3.963
C3 (km^2/s^2)	16.7407
Launch Vehicle	Delta IV Medium
Departure Date	August 15, 2013
Mission Duration (days)	365
Arrival Angle (deg)	85.2868
Impact Velocity (km/s)	35.1673
Arrival Date	August 15, 2014
Estimated Mission Cost ($)	842.26M

of the launched spacecraft is based upon the ADRC's two-body HAIV. Assuming the total mass of the spacecraft is 1800 kg, the smallest launch vehicle that can place the HAIV into the 16.74 km^2/s^2 C3 orbit necessary to meet the comet is the Delta IV Medium. Given that the Delta IV class launch vehicles have been decommissioned, the smallest Atlas V launch vehicle (Atlas V 401) could be used to complete the mission. The Atlas V 401 is a larger rocket than the Delta IV Medium, so it would be too powerful given this mission architecture, but it would do the job just as well.

Upon arriving at Comet 2013 A1, on August 15, 2014, the spacecraft would have a relative impact speed of over 35 km/s at an impact angle of about 85.3°. Meaning that the comet and the spacecraft's velocity vectors, at the time of impact, would be nearly perpendicular to each other. Depending on whether or not such an impact would be desirable or not, trajectory correction maneuvers could perhaps be applied to have an impact that is more along the line of the asteroid's velocity vector. To gain a visual of what the transfer orbit from Earth to the comet would look like, Figure 10 shows the orbits of the Earth, 2013 A1, and the spacecraft, in green, blue, and red respectively, in the Earth's orbital plane. This two dimensional representation of the orbits does not show a lot of information about the comet or spacecraft's orbits, given that the comet has a highly inclined orbit with respect to the ecliptic. Looking at a three dimensional representation of the orbits tells a better story (Figure 11). It can be seen that the comet's orbit (blue) is travelling up toward the ecliptic, and the spacecraft's orbit has to travel below the ecliptic to meet it before it crosses the ecliptic, and Mars. Once the HAIV impacts 2013 A1, there will be 65 days for the disrupted comet debris to disperse before its encounter with Mars.

An important point to make note of in the mission design for this particular body is the mission flight time. The mission duration tends to reach the upper bound, where given the other constraints of this problem tend to have lower changes in velocity. In other words, the more tightly the mission duration is bound the larger the total mission ΔV becomes, the more likely the missions are to be infeasible.

5.2. *Asteroid 2012 DA14*

Asteroid 2012 DA14 is an Aten class near-Earth asteroid with an estimated mass of about 30 meters. The NEO was discovered on February 23, 2012 in Spain. Upon initial observation, the odds of 2012 DA14 impacting

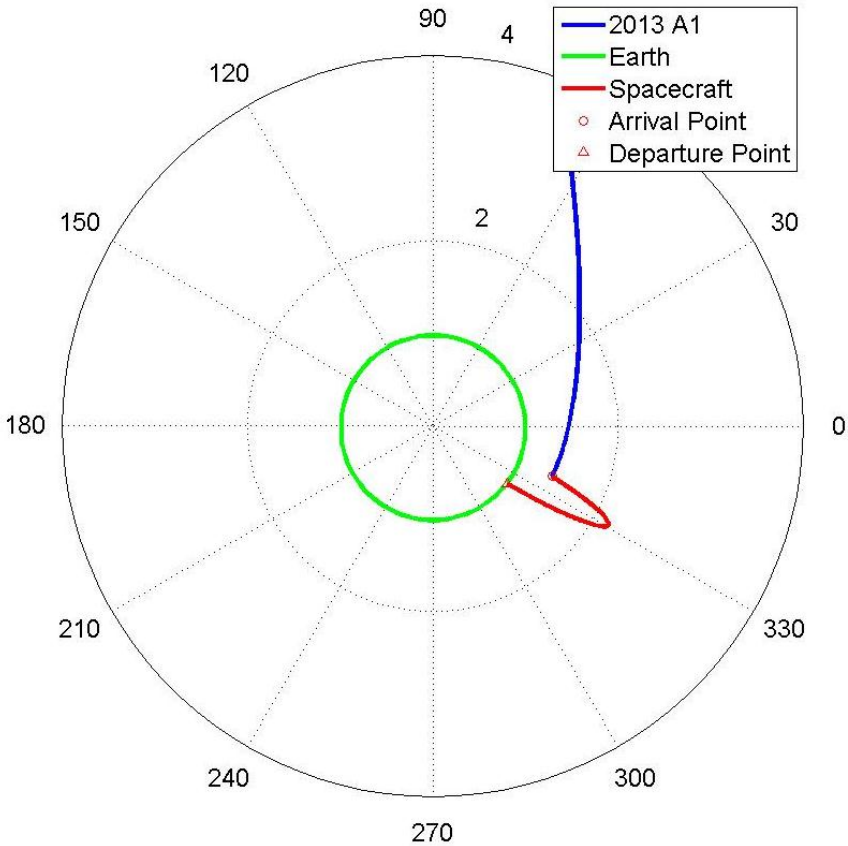

Figure 10: Two-dimensional depiction of the spacecraft's orbit trajectory from Earth to intercept Comet 2013 A1.

Earth between 2026 and 2069 were about 1-in-3000, with no possibility of the asteroid hitting Earth during its close-encounter in 2013. Table 6 shows the orbital elements of the asteroid.

Table 6: The orbital elements of asteroid 2012 DA14 at an epoch of April 18, 2013. [9]

Orbital Element	Value	Units
a	0.91032	AU
e	0.0894	
i	11.6081	deg
ω	195.5346	deg
Ω	146.996	deg
M	231.097	deg

Similar to the exercise conducted with Comet 2013 A1, let's assume that the current date is around the end of February 2012, and asteroid 2012 DA14 was just discovered, it has a high likelihood of impacting Earth on February 15, 2013, and that we are launch ready at this point in time. Once again, these pieces of information are/were not true, but we assume them to be true for the sake of the problem that they establish.

With the impact date set with respect to the discovery date, a mission window is established where the spacecraft has to be launched after discovery, travel to meet the asteroid, and allow time for the disrupted pieces of the asteroid to disperse before the anticipated impact date. This mission timeline is much more stringent than the one for 2013 A1 since everything has to occur within one year. Given that the asteroid is a near Earth object, there should be more options for missions to it, either long-term or short-term. Figure 12 depicts a contour plot of total mission ΔV in terms of launch date and mission flight time. The porkchop plot agrees with the earlier assessment that upon initial views there are plenty of feasible mission options for this asteroid.

Due to the wide range of mission possibilities within the one year timeline that has been established for 2012

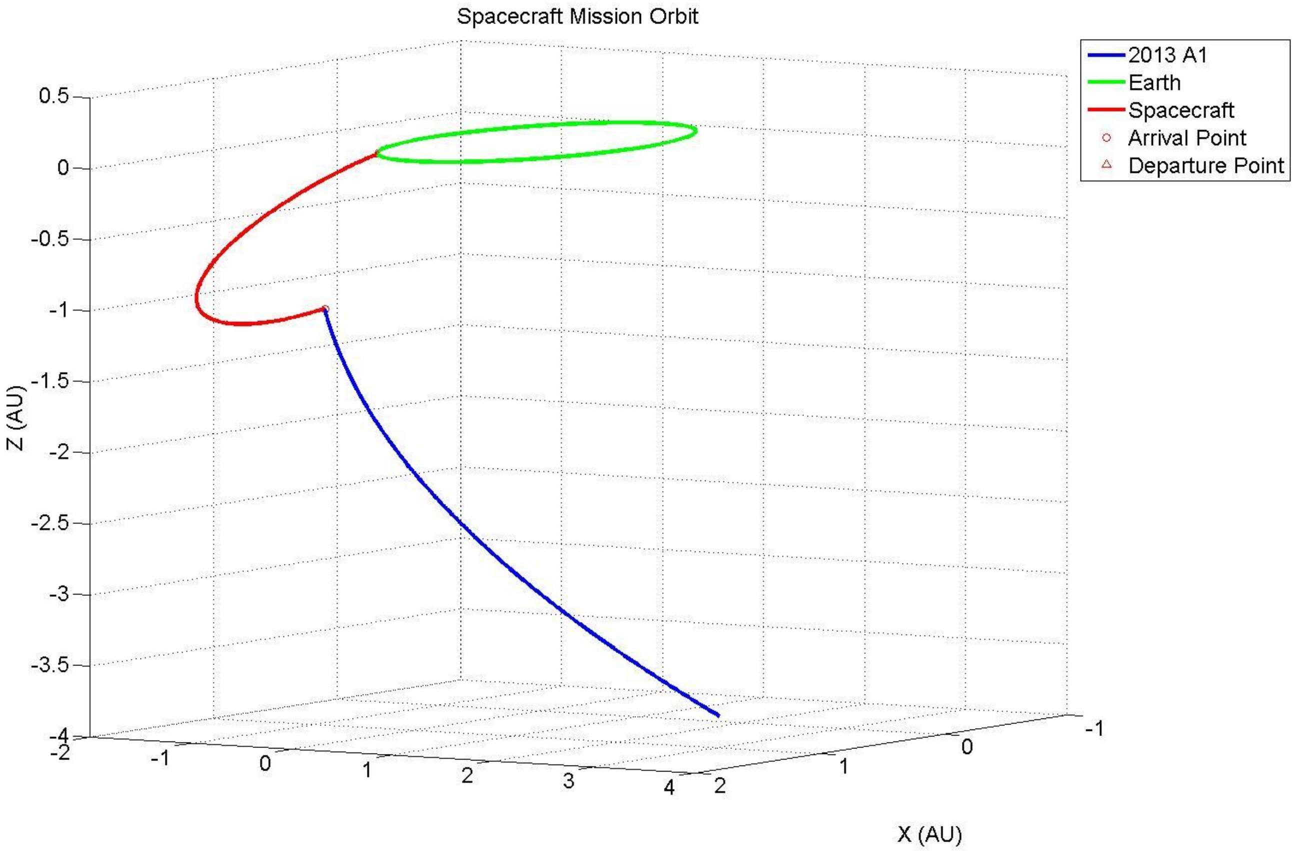

Figure 11: Three-dimensional depiction of the spacecraft's orbit trajectory from Earth to intercept Comet 2013 A1.

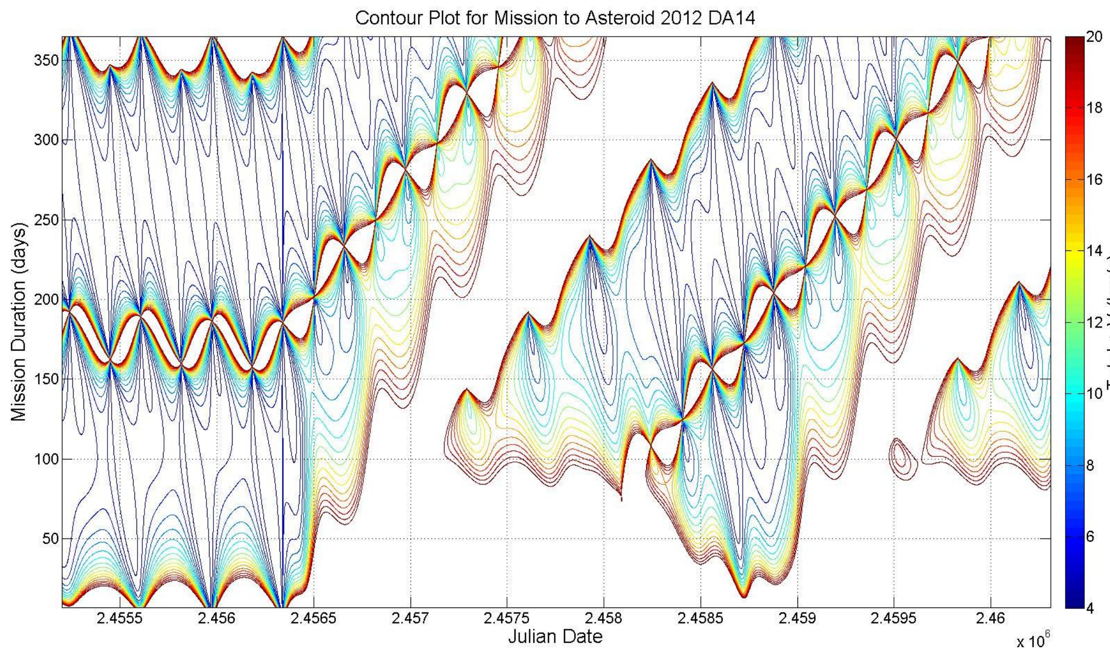

Figure 12: Mission contour plot of total ΔV in terms of launch date and mission flight time for asteroid 2012 DA14.

DA14, three mission case studies will be analyzed. The three mission case studies are: (1) an early launch, short-term mission, (2) an early launch, long-term mission, and (3) a late launch, short-term mission. Each case study will be analyzed from the stand point of the mission parameters that make the mission feasible and the resulting orbital parameters.

5.2.1. Early launch, short-term mission

One of the big assumptions made for this exercise is that we are launch ready at the time of discovery of asteroid 2012 DA14. If the main point of the mission design process is to maximize the dispersion time, with the lowest mission ΔV, by keeping the mission flight time to 60 days or less, then this course of action would indicate an early mission launch with a short flight time. Because a longer mission duration would result in lower $\Delta V's$, the mission duration seems to run into the upper bound. The resulting early launch date and short mission flight time parameters are shown in Table 7.

Table 7: Optimal constrained mission parameters for early launch, short-term impact mission to asteroid 2012 DA14.

Parameter	Value
Departure Date	February 24, 2012
Flight Time (days)	60
Departure ΔV (km/s)	5.036
Dispersion time (days)	297

Given the long dispersion time associated with this mission architecture, a smaller spacecraft can be used to impact the asteroid body. Using the associated mission parameters, the overall mission construction can be summarized in Table 8. With the small size of asteroid 2012 DA14, the spacecraft type that would be used in these

Table 8: Mission design parameters for a early launch, short-term intercept mission to asteroid 2012 DA14.

Mission Parameter	Value
Asteroid	2012 DA14
LEO altitude (km)	185
Spacecraft Designation	HAIV
Total HAIV Mass (kg)	1000
Departure ΔV (km/s)	5.036
C3 (km^2/s^2)	43.121
Launch Vehicle	Delta IV M+(4,2)
Departure Date	February 24, 2012
Mission Duration (days)	60
Arrival Angle (deg)	2.001
Impact Velocity (km/s)	0.9571
Arrival Date	April 24, 2012
Estimated Mission Cost ($)	601.376M

situations would be a kinetic impactor. But, with the small relative impact velocity a kinetic impactor may not be able to disrupt the asteroid enough, if at all, to be effective. So, a smaller scaled version of the ADRC's HAIV would be the spacecraft of choice for this mission. Due to the higher departure ΔV for this mission, a midsize Delta IV launch vehicle is chosen for this mission. With the spacecraft intercepting the asteroid on April 24, 2012, there would be almost 300 days for the fragments of the disrupted body to disperse before February 15, 2013.

5.2.2. Early launch, long-term mission

Again, assuming that we are launch ready from the time of discovery for an early launch date, but lower mission ΔV is valued over dispersion time, then the mission construction would lean toward a longer mission duration. So, the constraint on dispersion time is relaxed with respect to the constraints put in place for the first case study. The transfer trajectory parameters for this early launch, long-term mission design are shown in Table 9.

By allowing a longer mission flight time, the departure ΔV drops to about 3.6 km/s to inject into an orbit to intercept asteroid 2012 DA14. With such a low departure velocity a smaller launch vehicle can be used to conduct

Table 9: Optimal constrained mission parameters for early launch, long-term impact mission to asteroid 2012 DA14.

Parameter	Value
Departure Date	April 27, 2012
Flight Time (days)	263
Departure ΔV (km/s)	3.602
Dispersion time (days)	31

the mission. Launching on April 27, 2012 with a 263 day flight time results in asteroid intercept on January 15, 2013 - allowing for 31 days of dispersion time for the disrupted asteroid.

Table 10: Mission design parameters for a early launch, long-term intercept mission to asteroid 2012 DA14.

Mission Parameter	Value
Asteroid	2012 DA14
LEO altitude (km)	185
Spacecraft Designation	Kinetic Impactor
Total Spacecraft Mass (kg)	1400
Departure ΔV (km/s)	3.602
C3 (km^2/s^2)	8.383
Launch Vehicle	Delta IV Medium
Departure Date	April 27, 2012
Mission Duration (days)	263
Arrival Angle (deg)	10.901
Impact Velocity (km/s)	6.049
Arrival Date	January 15, 2013
Estimated Mission Cost ($)	717.658M

5.2.3. Late launch, short-term mission

In the case where there is no possibility for an early launch, there are still feasible missions to disrupt the threatening body and allow for at least a little time for the fragments to disperse. If the mission flight time is limited to 30 days or less and dispersion time of 15 days or more, the situation that arises is the worst case scenario for Earth in which something can still be done to the threatening body. Given these constraints to the mission design, the following mission parameters are obtained: While there is a limited amount of time for the disrupted pieces of

Table 11: Optimal constrained mission parameters for late launch, short-term impact mission to asteroid 2012 DA14.

Parameter	Value
Departure Date	December 31, 2012
Flight Time (days)	30
Departure ΔV (km/s)	3.789
Dispersion time (days)	16

the body to scatter expected impact date, that time would allow for some fragments to miss the planet and only a subset of the entire body to impact the Earth, hopefully resulting in most of smaller pieces burning up in Earth's atmosphere. The complete mission architecture for such a scenario is summarized in Table 12. This mission scenario results in the largest relative impact velocity of the case studies discussed, despite the small departure ΔV. The reason for this is because of where the asteroid is being intercepted. The asteroid is approaching its perihelion, meaning that its speed is increasing as it crosses Earth-orbit, and since there is not a long flight time for the spacecraft it would not have lost a lot of its launch energy, making for a more energetic collision.

Table 12: Mission design parameters for a late launch, short term intercept mission to asteroid 2012 DA14.

Mission Parameter	Value
Asteroid	2012 DA14
LEO altitude (km)	185
Spacecraft Designation	Kinetic Impactor
Total Spacecraft Mass (kg)	1800
Departure ΔV (km/s)	3.789
C3 (km^2/s^2)	12.6798
Launch Vehicle	Delta IV Medium
Departure Date	December 31, 2012
Mission Duration (days)	30
Arrival Angle (deg)	17.481
Impact Velocity (km/s)	9.371
Arrival Date	January 30, 2013
Estimated Mission Cost ($)	842.26M

5.2.4. Case Study Conclusions

While all three missions are completely feasible and would probably result in the salvation of the planet, each mission has its own time and place. The early launch, short term mission scenario should always be the first option. Making an attempt on the threatening body as early as possible would give some time afterwards in case something were to go wrong and the mission were to fail. But, this mission construction makes the assumption that we are ready to launch a spacecraft upon discovering a threat, if not, then this scenario is worthless. It would be this author's opinion that the second option mission scenario would be an early launch, with a longer mission flight time. In the event that the body threatening Earth were similar to Comet 2013 A1 with a highly energetic and inclined orbit, launching early and intercepting the body as far from Earth as possible would be the best option, and that would likely require a longer mission duration. If neither of the first two options are available, or fail, the last option should be a late launch with a short flight time mission scenario. This mission construction would be a last resort option, and should not be thought of as the first choice in hopes that new data would prove the NEO is no longer a threat. Regardless of the option chosen given the situation, any action would be better than inaction.

6. Precision Orbit Simulation

NASA had to find ways to increase the rate of discovery of near Earth objects (NEOs), by decree of Congress in 1990. On occasion, objects of significant size, have been found to be on a potential Earth-impacting trajectory, through those efforts. Often requiring high-fidelity N-body models, containing the effects of non-gravitational orbital perturbations such as solar radiation pressure (SRP), the accurate prediction of such Earth-impacting trajectories could be found. Such highly precise asteroid orbits allows mission designers to take advantage of more specific mission planning, higher certainty of the target's location, and more accurate impact probability.

6.1. Orbit Simulation

The orbital motion of an asteroid is governed by a so-called Standard Dynamical Model (SDM) of the form [18]

$$\frac{d^2\vec{r}}{dt^2} = -\frac{\mu}{r^3}\vec{r} + \sum_{k=1}^{n}\mu_k\left(\frac{\vec{r}_k - \vec{r}}{|\vec{r}_k - \vec{r}|^3} - \frac{\vec{r}_k}{r_k^3}\right) + \vec{f} \quad (1)$$

where μ = GM is the gravitational parameter of the Sun, n is the number of perturbing bodies, μ_k and $\vec{r}_k$ are the gravitational parameter and heliocentric position vector of perturbing body k, respectively, and $\vec{f}$ represents other non-conservative orbital perturbation acceleration. The gravitational model used in orbit propagation takes into account the effects of the Sun, all eight planets, Pluto, Ceres, Pallas, and Vesta.

Previous studies performed at the ADRC were concerned with the impact probability of potential Earth-impacting asteroids, such as 99942 Apophis. Using commercial software such as NASA's General Mission Analysis Tool (GMAT), AGI's Satellite Tool Kit (STK), and Jim Baer's Comet/asteroid Orbit Determination and Ephemeris Software (CODES), the ADRC conducted precision orbital simulation studies to compare with JPL's Sentry program [19].

At the moment, the three asteroids of study at the ADRC for high precision orbit propagation are Apophis, 1999 RQ36, and 2011 AG5, due to their proximity to Earth and their relatively high impact probability. Apophis and 2011 AG5, recently declared to have virtually no threat to Earth, are primarily used for validation of the numerical integration and orbit propagation schemes in the ADRC's N-body simulator.

6.2. Previous Work

Taking Apophis as a reference NEO, simulations have been run from an an initial epoch of August 27, 2011 until January 1, 2037 to show the capabilities of the ADRC's N-body code in calculating precise, long-term orbit trajectories. A preliminary test was conducted for the period of May 23, 2029 to May 13, 2036 show the relative errors of GMAT and STK to JPL's Sentry (Horizons), as well as the error of the N-body code with respect to Sentry. The error in the radial position of Apophis between the N-body code to that of JPL's Sentry is much lower than that of both GMAT and STK. The N-body simulator used to obtain the aforementioned results uses a Runge-Kutta Fehlberg (RKF) 7(8) fixed-time-step method, including the orbital perturbations of all eight planets, Pluto, and Earth's Moon, in the form of constant orbital element rates coupled with the nominal element values provided updated position and velocity data for the perturbation bodies. [10]

6.3. Current Work and Capabilities

Expanding upon the work done on the numerical integration scheme used to obtain the results previously shown, the fixed-time-step numerical integration algorithm has been changed to a variable step method. The Runge-Kutta Fehlberg method is used for approximating the solution of a differential equation $\dot{x}(t) = f(x,t)$ with initial condition $x(t_0)$. The implementation evaluates $f(x,t)$ thirteen times per step using embedded seventh order and eight order Runge-Kutta estimates to estimate not only the solution but also the error. By specifying the interval in which the results of the integration should be reported and the acceptable local error tolerance, the algorithm takes as many error controlled steps as necessary to calculate the state vector at the desired time.

Using ephemeris data from the NASA Jet Propulsion Laboratory (JPL) Horizons website, orbital data from all these bodies is taken for a given period of time to construct a planetary state vector (X, Y, Z, V_X, V_Y, V_Z) database. In order to accommodate the need to retrieve data at any specified date within the propagation time, a Lagrange interpolation scheme is constructed. Using the Julian Date of the available state vector data for each planet as the distinct independent variables of an n^{th} degree Lagrange interpolating polynomial, a unique polynomial P(x) is created for each timestep, which is then applied to each body.

As far as non-conservative perturbations, the three most well-known are solar radiation pressure (SRP), relativistic effects, and the Yarkovsky effect, the former two being the most prevalent effects. Solar radiation pressure provides a radial outward force on the asteroid body from the interaction of the Sun's photons impacting the asteroid surface. The equation for SRP is given by

$$a_{SRP} = (K)(C_R)\left(\frac{A_R}{M}\right)\left(\frac{L_S}{4\pi c r^2}\right) \quad \Rightarrow \quad \vec{a}_{SRP} = (K)(C_R)\left(\frac{A_R}{M}\right)\left(\frac{L_S}{4\pi c r^3}\right)\vec{r} \tag{2}$$

where $\vec{a}_R$ and a_R are the acceleration vector and magnitude of the solar radiation pressure acceleration, respectively, C_R is the coefficient for solar radiation, A_R is the cross-sectional area presented to the Sun, M is the mass of the asteroid, K is the fraction of the solar disk visible at the asteroid's location, L_S is the luminosity of the Sun, c is the speed of light, and $\vec{r}$ and r is the distance vector and magnitude of the asteroid from the Sun, respectively.

The relativistic effects of the body are included because for many objects, especially those with small semimajor axes and large eccentricities, those effects introduce a non-negligible radial acceleration toward the Sun. One form of the relativistic effects is represented by

$$\vec{a}_R = \frac{k^2}{c^2 r^3}\left[\frac{4k^2\vec{r}}{r} - \left(\dot{\vec{r}} \cdot \dot{\vec{r}}\right)\vec{r} + 4\left(\vec{r} \cdot \dot{\vec{r}}\right)\dot{\vec{r}}\right] \tag{3}$$

where $\vec{a}_R$ is the acceleration vector due to relativistic effects, k is the Gaussian constant, $\vec{r}$ is the position vector of the asteroid, and $\dot{\vec{r}}$ is the velocity vector of the asteroid. With the introduction of such non-conservative forces the error within the system will increase, but these effects need to be included in calculations in order to maintain consistency with the planetary ephemeris. A more complete dynamical model will allow the accurate calculation of asteroid impact probabilities and gravitational keyholes, leading to more effective mission designs [15].

7. Future Work

While there have been improvements made to the AMiDST, the work is far from done on this program. Work is being done to expand the numerical integration scheme used for the N-body simulator from the current RKF7(8) method to an Adams-Bashforth variable timestep numerical integration scheme. The Runge-Kutta-Fehlberg method is used for approximating the solution of a differential equation $\dot{x}(t) = f(x,t)$ with initial condition

$x(t_0) = c$. The implementation evaluates $f(x,t)$ thirteen times per step using embedded seventh order and eight order Runge-Kutta estimates to estimate not only the solution but also the error. The Adams-Bashforth numerical integrator solves the initial value problem for stiff or nonstiff systems of first order Ordinary Differential Equations (ODEs).

In addition to the major planetary perturbations, non-gravitational orbital perturbations such as solar radiation pressure and the Yarkovsky effect will be added into the pre-existing N-body gravitation model in order to have a more encompassing dynamical model. With the introduction of such non-conservative forces the error within the system will increase, but the expected increase in orbital accuracy should out-weigh the benefits of leaving them out of the dynamical model. A more complete dynamical model will allow the accurate calculation of asteroid impact probabilities and gravitational keyholes, leading to more effective mission designs.

With the multitude of variables to track and optimize in order to find the optimal design for a mission to a target NEO, the use of a genetic algorithm will be utilized in conjuction with the AMiDST program to find the optimal mission design. [20] Genetic algorithms are a stochastic optimization method, which means that it requires no initial guess to find solutions. Through the use of a genetic algorithm, a pre-determined cost function would be able to evaluate the randomly generated and evolved solutions, taking into account the launch date, mission trajectory, transfer duration, launch vehicle, estimated mission cost, etc. all at once instead of component by component, to arrive at the globally optimal solution.

8. Conclusions

This paper has shown the part of the growth and development of the ADRC's Asteroid Mission Design Software Tool for the preliminary design of asteroid deflection/disruption missions. Beyond simply creating missions to other bodies near Earth with no constraint on the parameters used in the design process, the AMiDST has added a level of optimization to its design by taking into account bounds and constraints on some of those design variables. The first design study examples (1999 RQ36 and 2011 AG5) discussed in this paper showed the AMiDST's ability to construct a mission given a particular body and wide time frame. The second study cases (Comet 2013 A1 and Asteroid 2012 DA14) introduced the addition of a set of boundary conditions to a mission's design variables in order to obtain a more optimal mission architecture. With this enhancement of the mission design process, added to the high fidelity of the orbit simulator for deflection missions, the overall capability and fidelity of the AMiDST is increased to the point that the results from the program have a certain amount of credibility.

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