Acta Astronautica 101 (2014) 1–15

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Near-Earth object intercept trajectory design for planetary defense

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ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form
3 March 2014
Accepted 6 April 2014
Available online 13 April 2014

Keywords:
Mission design
Planetary defense
Gravitational simulator
Encounter geometry
Keyholes

ABSTRACT

Tracking the orbit of asteroids and planning for asteroid missions have ceased to be a simple exercise, and become more of a necessity, as the number of identified potentially hazardous near-Earth asteroids increases. Several software tools such as Mystic, MALTO, Copernicus, SNAP, OTIS, and GMAT have been developed by NASA for spacecraft trajectory optimization and mission design. However, this paper further expands upon the development and validation of an Asteroid Mission Design Software Tool (AMiDST), through the use of approach and post-encounter orbital variations and analytic keyhole theory. Combining these new capabilities with that of a high-precision orbit propagator, this paper describes fictional mission trajectory design examples of using AMiDST as applied to a fictitious asteroid 2013 PDC-E. During the 2013 IAA Planetary Defense Conference, the asteroid 2013 PDC-E was used for an exercise where participants simulated the decision-making process for developing deflection and civil defense responses to a hypothetical asteroid threat.

1. Introduction

Traditional trajectory and mission optimization tools (such as Mystic, MALTO, Copernicus, SNAP, OTIS, and GMAT) are high-fidelity computer programs being developed by NASA [1,2]. A commonality of all these tools is that they primarily look at the intermediate stage of a mission, the mission trajectory from the current location to desired target – more or less overlooking the other two stages of any mission design, in comparison. An on-line mission design tool to aid in the design and understanding of kinetic impactors necessary for guarding against objects on an Earth-impacting trajectory is being developed at The Aerospace Corporation [3]. Still under development, this on-line tool has hopes of incorporating several specific design variables and limitations to allow for only feasible mission designs based on current launch and mission capabilities.

The Asteroid Mission Design Software Tool (AMiDST) being developed at the Asteroid Deflection Research Center (ADRC) at Iowa State University [4–6] does not yet have the high fidelity as many existing optimization-based packages. However, the focus of the program lies on the launch and terminal phase of a near-Earth object (NEO) mission rather than finding the optimal mission trajectory. Looking into several launch vehicle and spacecraft configurations to complete a given mission design to a designated target NEO, the AMiDST evaluates the possible combinations based upon several evaluation criteria such as launch vehicle mass capacity, mission ΔV requirements, and excess launch vehicle ΔV. In addition to these features, it also provides the estimated total mission cost, used as a main determining factor between mission configurations.

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http://dx.doi.org/10.1016/j.actaastro.2014.04.006

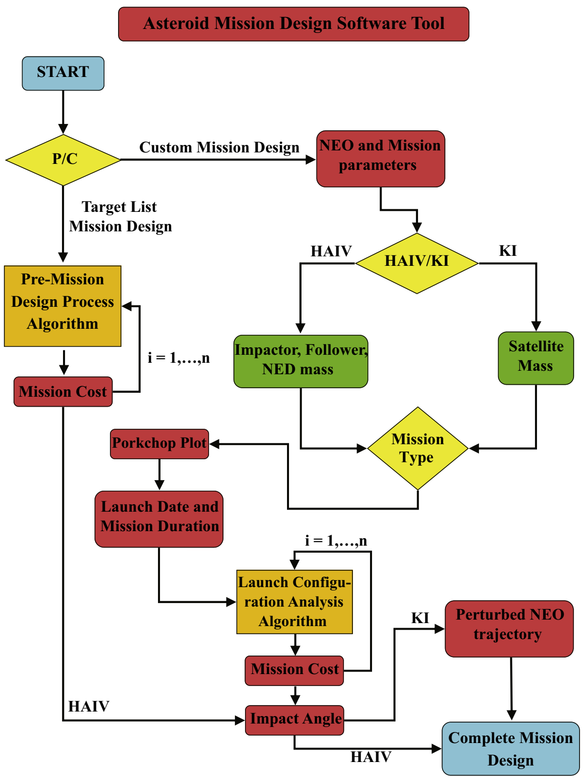

Fig. 1. Flowchart illustration of the AMiDST.

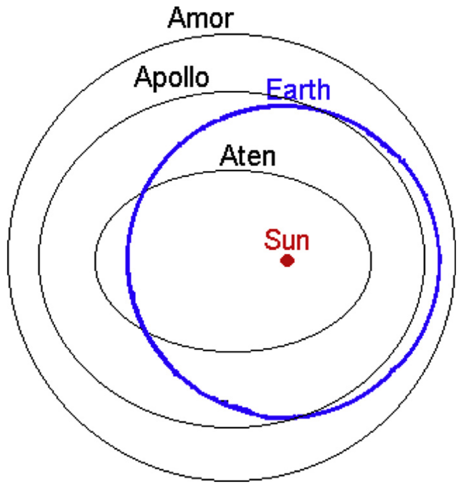

Fig. 2. Typical orbits of Apollo, Aten, and Apollo asteroids.

A flowchart illustration of the basic algorithms used by AMiDST is presented in Fig. 1. In this figure, HAIV stands for Hypervelocity Asteroid Intercept Vehicle and KI for Kinetic Impactor, and NED for Nuclear Explosive Device, described in detail by Pitz et al. [7,8].

For a current version of AMiDST, the terminal phase of a NEO mission is limited, at this time, to kinetic impact perturbations applied to the target NEO's orbital trajectory. Taking the output of the mission analysis of relative impact angle and velocities of both the spacecraft and target NEO, along with the mass of both objects, the trajectory of the perturbed asteroid would be tracked in order to find how much the trajectory is altered from the previous unperturbed orbit. In addition to simply tracking the NEO to a future time, a resonance and keyhole analysis would be performed to see the likelihood the body would have a further future threat to the Earth.

2. Intercept trajectory design for asteroids with no keyholes

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]. Fig. 2 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 have been many objects studied through the use of AMiDST [4–6]. The most notable targets being Apophis, 1999 RQ36, 2011 AG5, 2012 DA14, and comet 2013 A1.

In 1990, Congress directed NASA to increase the rate of discovery of near Earth objects [10]. Through those efforts, at times objects of significant size have been found to be on a potential Earth-impacting trajectory. The accurate prediction of such Earth-impacting trajectories could be obtained through the use of high-fidelity N-body models, also containing the effects of non-gravitational orbital perturbations such as solar radiation pressure (SRP). From such highly precise asteroid orbits, many advantages can be had: more specific mission planning, higher certainty of the target's location, and more accurate impact probability.

2.1. Orbit simulation

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

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

where $\mu = \mathrm{GM}$ is the gravitational parameter of the Sun, n is the number of perturbing bodies, μ_k and $\mathbf{r}_k$ are the gravitational parameter and heliocentric position vector of perturbing body k, respectively, and $\mathbf{f}$ 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, Earth's Moon, Pluto, Ceres, Pallas, and Vesta.

Previous studies performed at the ADRC were concerned with the impact probability of potential Earth-impacting asteroids, such as Apophis, 1999 RQ36, and 2011 AG5 due to their proximity to Earth and their relatively high impact