Progress in Aerospace Sciences 100 (2018) 1–17

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

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

Asteroid engineering: The state-of-the-art of Near-Earth Asteroids science and technology

Niklas Anthony [a], M. Reza Emami [a,b,*]

[a] Space Technology Division, Luleå University of Technology, Kiruna 98128, Sweden
[b] Institute for Aerospace Studies, University of Toronto, Toronto M3H 5T6, Canada

ARTICLE INFO

Keywords:
Near-Earth Asteroids
Space resource utilization
Asteroid mining
Asteroid detection
Asteroid redirection
Asteroid deflection

ABSTRACT

This paper presents a comprehensive review of the science and technology of accessing near-Earth asteroids (NEAs), or making them accessible, for obtaining both information and resources. The survey is divided into four major groups of NEA study, namely **a)** discovery (population estimation and detection), **b)** Exploration (identification and characterization), **c)** deflection and redirection, and **d)** mining (prospecting, excavation, processing, refining, storage.). Recent research and development advancements from both industry and academia are discussed in each group, and certain specific future directions are highlighted. Some concluding remarks are made at the end, including the need for creating new educational programs to train competent engineers and researchers for the taskforce in the new field of asteroid engineering in near future.

1. Introduction

Asteroid mining is poised to be likely the most profitable industry in the history of mankind, and has already drawn interest from private funding entities like Goldman Sachs [1]. There are millions of Near Earth Objects (NEOs), containing untold riches that can be used here on Earth or in space. The term NEO refers to any asteroid or comet that has a perihelion distance of less than 1.3 Astronomical Units (AUs), i.e., approximately 195 million km. This paper will focus on Near-Earth Asteroids (NEAs) as near-Earth comets tend to spend most of their orbits very far away from Earth. While humans have been mining resources on Earth for millennia, technology to prospect, extract and refine resources in the micro-gravity, vacuous environment of space has yet to be developed.

There are three main drivers behind the interest in NEAs: the expected scientific return, planetary defense, and mining. Scientists can glean information about the formation of the Solar System by studying the composition and structure of NEAs. Most of NEAs have peculiar orbits that scientists study to reveal orbital change processes. These objects might also contain organic compounds that could have kick-started life on Earth [2]. In addition to originating life, they could also destroy it. It is evident that a ten-kilometer-wide impactor caused the Cretaceous-Paleocene extinction event, when it made the Chicxulub crater over 64 million years ago [3]. More recently, the Chelyabinsk bolide in February 2013, which caused massive property damage and injured around 1500 people, was only 20 m wide, weighed 12,000 metric tons, and entered our atmosphere at a relative speed of 19 km/s [4]. It is, therefore, imperative that technologies be developed to divert such potentially hazardous objects away from collision courses with Earth. Nevertheless, most asteroids are not considered as a threat to us: countless science fiction tales and scientific papers alike rely on using materials from asteroids to build the infrastructure necessary for mass exploration and colonization of the Solar System. The company Deep Space Industries (DSI) believes that NEA 2012 DA14 could be worth up to $195 billion, for example [5]. The asteroid passed within geostationary orbit distance in 2013, and it is estimated to be 45 m wide [6].

To facilitate the emergence of these technologies, it is argued that a new field of asteroid engineering must be founded, characterized as “the science and technology of exploring, accessing asteroids and/or making them accessible to avoid collision with Earth and to retrieve and process both information and raw materials from them for scientific activities as well as Earth and space developments” [7].

Asteroids are best found by using wide-angle optical or infrared (IR) telescopes using streak-detection software. There are fundamental limitations when looking for small, dim, and distant objects using ground-based telescopes; not only are they difficult to find, the information about these NEAs is incredibly limited as well. There are methods to remotely determine a NEA's physical properties, but their requirements

* Corresponding author. Space Technology Division, Luleå University of Technology, Kiruna 98128, Sweden.
E-mail address: reza.emami@ltu.se (M.R. Emami).

https://doi.org/10.1016/j.paerosci.2018.05.001
Received 22 February 2018; Received in revised form 19 April 2018; Accepted 3 May 2018

Abbreviations

NEO	Near-Earth Object
AU	Astronomical Unit
NEA	Near-Earth Asteroid
DSI	Deep Space Industries
IR	Infrared
ARM	Asteroid Redirect Mission
H	Absolute Magnitude
WISE	Wide-Field Infrared Survey Explorer
PHO	Potentially Hazardous Object
CNEOS	Center for NEO Studies
SFD	Size-Frequency Distribution
CCD	Charge-Coupled Device
BSSD	Blind Search Streak Detection
LSST	Large Synoptic Survey Telescope
COTS	Commercial Off-The-Shelf
ISS	International Space Station
CSS	Catalina Sky Survey
SSS	Sliding Spring Survey
MLS	Mt. Lemmon Survey
PanSTARRS	Panoramic Survey Telescope and Rapid Response System
NEOCam	Near-Earth Object Camera
PDO	Palmer Divide Observatory
TCO	Temporarily-Captured Object
TRL	Technology Readiness Level
JPL	Jet Propulsion Laboratory
DART	Double Asteroid Redirection Test
AIM	Asteroid Impact Mission
LEO	Low-Earth Orbit
IBRM	Ion Beam Redirection Method
SERT	Space Electric Rocket Test
DRO	Distant Retrograde Orbit
PGM	Platinum-Group Metal
LIBS	Laser-Induced Breakdown Spectroscopy
CAVoR	Carbonaceous Asteroid Volatile Recovery System
LOX	Liquid Oxygen
LH2	Liquid Hydrogen
ZBO	Zero Boil-Off

limit the number of investigatable asteroids to close-approaching or well-observed ones. To reliably gather detailed information about a NEA, a spacecraft must be sent to explore it. Only then can we accurately determine the NEA's size, shape, spin-vector, mass distribution, and composition. In-situ exploration of an asteroid can be done through either rendezvousing with the asteroid in its natural orbit, which is typically unstable and far from Earth, or first bringing the asteroid into a closer and more stable orbit in the Earth-Moon system before the exploration phase, a mission called asteroid redirection.

Many unique asteroid redirection methods have been suggested over the years, ranging from landing rockets on an asteroid's surface to detonating a nuclear warhead near, on, or in an asteroid. As of 2016 though, there is no developed technology to carry out any of those redirections, but there are a few promising plans. For instance, NASA proposed the Asteroid Redirect Mission (ARM) in 2013, which sought to either find and redirect a small (under 8 m in diameter) asteroid, or to physically grab a small boulder (under 4 m) from the surface of a large asteroid and bring it to a distant retrograde orbit around the Moon in 2021. It would then be the target of a human exploration phase as the next step in getting humans to Mars [8]. In late 2017, however, the mission was officially cancelled in order to develop the Orion capsule and Space Launch System [9]. Companies like DSI and Planetary Resources are interested in moving asteroids around in the future, but do not have any redirection missions planned yet.

The country of Luxembourg announced in early 2016 that it plans to invest several hundred million euros into the asteroid mining industry [10]. Later that year, they invited asteroid mining companies and interested parties to a workshop to answer questions about the future use of space resources [11]. The general science gaps that they identified were centered on detecting a large enough sample size, figuring out what they were made of before sending a spacecraft to asteroid, and regolith dynamics. What is clear among almost every extra-terrestrial mining operation is that water is the desired resource. There are countless papers on extracting and using or selling water from asteroids, the Moon, and even Mars. While asteroids might contain promising platinum-group metals, there is no technology capable of refining these metals in space.

This paper will be organized into four sections; Section 1 will discuss the latest NEA detection capabilities, Section 2 will review the most promising asteroid redirection methods, Section 3 will analyze various asteroid mining technologies, and Section 4 will convey some conclusions and suggestions.

2. Asteroid discovery

Astronomers have been discovering asteroids since the 1800s, with Giuseppe Piazzi's discovery of 1 Ceres, an object in the main asteroid belt with a diameter of nearly 1000 km, in 1801. However, it was not until early 1970s when NASA began to take interest in NEOs by sending Pioneer 10 to Jupiter through the main asteroid belt [12]. Most NEOs appear to have originated from the main asteroid belt through a combination of processes, including planetary perturbations, collisions, thermal forces, and solar wind pressure. Such processes could have shifted asteroids into resonant orbits with planets, most notably Jupiter, which can drastically change their orbit and send them into the near-Earth environment [13].

In 1994, the US Congress mandated NASA to “identify and catalogue within 10 years the orbital characteristics of all comets and asteroids that are greater than 1 kilometer in diameter and are in an orbit around the sun that crosses the orbit of the Earth” [14]. To facilitate the completion of this mandate, NASA started its NEO Observations Program in 1998 [15], but was unable to fulfil the mandate until 2011 [16]. The Congress further mandated NASA in 2005 to “detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act” [17]. Both mandates revolve around absolute size, in meters, of NEOs, which is an indirect metric because when any extraterrestrial object is detected it appears as a bright dot or streak, the intensity of which is given by a metric known as absolute magnitude. The Absolute Magnitude (H) of an extraterrestrial object is a measure of how bright the object is to an observer if it were placed 1 AU away (from the observer) and 1 AU from the Sun, at a zero phase angle. Accordingly, larger values of H represent dimmer objects in a logarithmic scale. This metric can be used to estimate an object's size, but is also dependent on the object's albedo, i.e., the percentage of light that the object reflects, depending on its size, shape, spin rate, and composition. Most asteroids' bolometric luminosity is concentrated in the IR spectrum [18], which is why optical and IR telescopes are used to search for them. Larger asteroids that rotate quickly, or have high thermal inertias, exhibit IR profiles similar to smaller objects [19]. By studying data on 419 NEAs from the 2010 Wide-field Infrared Survey Explorer (WISE) mission and follow-up optical observations, it was found