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Propulsion Systems for Interstellar Exploration

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Abstract

The idea of manned spaceships exploring nearby star systems, although difficult and unlikely in this generation or the next, is becoming less a tale of science fiction and more a concept of rigorous scientific interest. In 2003, NASA sent two rovers to Mars and returned images and data that would change our view of the planet forever. Already, scientists and engineers are proposing concepts for manned missions to the Red Planet. As we prepare to visit the planets in our solar system, we dare to explore the possibilities and venues to travel beyond. With NASA's count of known exoplanets now over 3,000 and growing, interest in interstellar science is being renewed as well. In this work, the authors discuss the benefits and deficiencies of current and emerging technologies in electric propulsion for outer planet and extrasolar exploration and propose innovative and daring concepts to further the limits of present engineering. The topics covered include solar and electric sails and beamed energy as propulsion systems.

I. Introduction

Te Puke is the name for the voyaging canoe that the Polynesians developed to sail across vast distances in the Pacific Ocean at the turn of the first millennium. This primitive yet sophisticated canoe, made of two hollowed out tree trunks and crab claw sails woven together from leaves, allowed Polynesian sailors to navigate the open ocean by studying the stars. Polynesians settled hundreds of islands in a few hundred years and may have even landed in the Americas long before Columbus. The vast ocean was no barrier to these sailors and, likewise, we believe that the vastness of space beyond our solar system shall be no barrier to study and settle distant planets.

Earth is plentiful with energy sources. In propulsion, various forms of energy conversion are utilized: wind and ocean currents for sailing, wind turbines and solar panels for power generation, combustion of gas-phase and solid-fuels for heat production, etc. In contrast, outerspace is a desert barren of these options for energy. A craft attempting to cross this desert must carry its own

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or have means for accessing distant sources of energy. Traditional means of propulsion are either unavailable or not feasible. For instance, availability of energy from the sun quickly decreases as the craft leaves the solar system. Carrying chemical propellants would mean massive payloads making it difficult to achieve the necessary speeds - a fraction of the speed of light.

In this report, we summarize some of the latest innovative ideas for interstellar navigation that address some of the issues above. They include bizarre laser and particle beam propulsion mechanisms as well as controversial EM drive and nuclear reactor based systems. Finally, we will present our vision for the future of interstellar exploration.

II. Interstellar Propulsion Mechanisms

i. Light Sail Design

If a spacecraft or probe meant to explore nearby solar systems is unable to carry its own propellant, perhaps having means for providing it with energy from far away is useful. The original concept for the light sail was first proposed by Robert L. Forward [1] and consists of two major components: first, a laser system capable of focusing a high-power beam over vast distances. The effective distance over which the laser is able to propel the spacecraft is limited by its focus, since beam losses over distance will make it progressively difficult to direct the full beam onto the target spacecraft as it travels away from the beam source. Due to scattering, the system must operate in space or on a body without an atmosphere, such as the Moon, to prevent scattering and thus loss of the beam energy. Forward's simplest design for an Alpha Centauri fly-by mission involves a 65 GW laser system with a Fresnel zone lens 1000 km in diameter [1].

Recent designs for the laser system include high power beams using a single lens and arrays of lasers with lower power. Pulsed or continuous beams are used depending on the laser design and its power requirements [1].

The second major component in this design is a low density reflective sail of sufficient radius for the laser beam to strike. Forward's design requires a sail 3.6 km in diameter [1]. As the laser strikes the sail, there is a small transfer in momentum upon reflection that produces acceleration in the spacecraft in the direction of the beam. Although the transfer from each photon would be very small, the accumulation of many over long periods of time would propel the vehicle to speeds far greater than chemical propellants.

Keeping the weight of the craft its sail low is very important. Current concepts use sails made of aluminized Mylar, but designs using a layered graphene structure have also been proposed that may prove to be a feasible alternative [2]. Materials of lower density would reduce the overall spacecraft weight or allow for larger sails that provide a better target for the laser. Material with higher reflectivity would increase the force of acceleration provided by the beam [3].

The main challenges in this design are the requirements for the laser and stability of the beam-riding sails. Constructing and powering a laser in outerspace with such requirements would require a concerted effort of great significance - not to mention an enormous lens. Additional challenges include the stability of the craft as the beam accelerates it. If the beam does not strike the sail uniformly, it could result in spin or misdirection [4]. Lastly, further studies need to be conducted to address the optimal sail geometry for this type of design.

ii. Mini-Magnetospheric Plasma Propulsion

Building on the concept of a light sail, and seeking to avoid some of its drawbacks, Landis developed a design for a particle beam sail that replaces the light sail with a magnetic field [5].

Early designs used a physical sail consisting of a loop of superconducting cable 64 km in diameter. Current flowing through the sail results in a large magnetic field [6]. While still utilizing a heavy physical sail (the superconducting loop), the higher momentum per energy unit offered by a particle beam would provide greater acceleration than a light beam [5].

Recently, techniques have been developed to generate a magnetic field without the use of the large sail. Winglee et al. proposed replacing the heavy physical sail with a mini magnetosphere. The mini-magnetospheric plasma propulsion (M2P2) system would be sufficiently small to fit on the spacecraft itself, rather than being attached by tethers, and generate a magnetic bubble, or sphere, surrounding the the vehicle. The system was originally designed to use the magnetosphere's interaction with the solar wind to generate thrust [7]. Landis proposed using a particle beam to push the magnetic field in addition to using the solar wind. The charged beam is directed at the target and immediately neutralizes to prevent dissipation of the beam due to electrostatic propulsion on its way to the target. The particles are ionized again by the vehicle and reflect off the sail to provide thrust [5].

The particle beam itself offers a number of advantages over the laser required for the light sail. The power requirements are six orders of magnitude lower to generate the particle beam; the particle beam is easier to focus, eliminating the need for a massive lens and enabling beam propulsion at longer distances; the particle beam imparts less heat on the target vehicle and can be operated for longer periods of time; and the force generated per kW of beam power on the target vehicle is significantly higher with a particle beam than with a laser [5, 8].

Another advantage of the M2P2 system is that the same propulsion system can be used to slow down at the destination star [6]. The light sail cannot use the solar wind to produce thrust, and so requires an additional system to change velocity and achieve orbit at its destination. The M2P2 system, however, can use the solar wind to decelerate as long as it is moving against the solar wind. From the point it enters the heliopause of the target star to its periapsis above that star, it will be able to decelerate to ensure orbital capture.

iii. EMDrive

There may be, however, an opportunity to generate momentum in space without the need of beams from far away. For the past few of decades, scientists have been studying microwave-driven resonant cavity thrusters which are said to generate micro-Newtons of thrust *out of thin air*. As if out of science fiction, these resonant cavity thrusters appear to generate thrust, not by an exchange in momentum with a traditional propellant, photons or a particle beam but rather by interacting with the quantum vacuum virtual plasma [9, 10].

At the turn of the second millennium, Brady proposed a propellantless propulsion system called the EMDrive. It consists of a strong electromagnetic source coupled with a tapered, conical cavity of high reflectivity in the inside walls. According to Brady, the group velocity of microwaves vary with the diameter of the waveguide resulting in a radiation pressure differential along the axis of the cavity. The radiation pressure differential, because of Newton's Third Law, results in thrust. This, of course, is a highly controversial claim because it also violates the Law of Conservation of Momentum. Nevertheless, various experiments have been conducted to confirm or refute this design and so far results are inconclusive at best [11, 9, 10].

This nascent technology has a long way to go before becoming a viable means of propulsion. Tests must first be conducted in outerspace where thermal effects can be better isolated. Furthermore, cavity geometries for optimal coupling with the waveguide must be explored. A definitive physical theory must be proposed and tested so as to continue building on this technology.

An additional major difficulty with this technology is the power requirement. The electromagnetic source must be anywhere between 20 to 700 W to produce thrust [9, 11]. Having to carry sufficient energy to power the electromagnetic source may be a show-stopper.

iv. Project Daedalus - Nuclear Pulse Rockets

Although, with today's technology, it would be impossible to carry enough chemical propellant to propel a spacecraft to the nearest solar system, perhaps there is a different type of prollenat more suitable for the task. In the 1970s, the British Interplanetary Society began to design an unmanned probe to explore nearby star systems for planets with the potential to sustain life - Project Daedalus. The concept required the use of two-stage nuclear pulse rockets to create sufficient acceleration so as to reach a star system 5.9 lightyears away within a human lifetime [12]. The rockets would work on a principle similar to chemical rockets in that tiny explosions within a chamber are expelled through a nozzle creating thrust. The fuel for this type of rocket are pellets made up of deuterium and helium-3. When radiated by high-powered electron beams, the pellets create fusion in the rocket's chamber and these tiny explosions produce thrust when expelled through a magnetic field nozzle.

In this design, nuclear rockets are key to propel the spaceship towards our neighboring star. Helium-3 is difficult to find on Earth. However, it is believed to be abundant in Jupiter's atmosphere. Therefore, in order to fulfill the requirements for this design, separate efforts must be made to harvest the helium-3 needed or the probe could be designed to make a stop in Jupiter on its way out of the solar system. Furthermore, due to the environmental concerns resulting from the nuclear rocket, the unmanned probe would have to be constructed in orbit. Like the beam laser in outerspace, this is no trivial task.

For various reasons, including the daunting tasks mentioned, the project did not move forward. However, the concepts developed remain useful and, as we continue to explore our solar system, harvesting raw materials from nearby planets may soon be a reality.

III. The Future of Electric Propulsion

As in a *Te Puke* that uses the wind to propel itself across the ocean, the light sail spacecrafts and M2P2 craft use laser and particle beams, respectively, to propel themselves across the vastness of space. The EMDrive technology, however, produces its own thrust on board the vessel. And lastly, nuclear rockets are synonymous to chemical propellents in that they must be brought on board but are much more efficient and powerful.

Although we have not covered every conceivable approach to crossing the barren desert between our solar system and the nearest one, we have briefly presented some of the major ones that have caught our attention. None of them are without their complications and limitations.

Barring a major breakthrough in physics that would provide us with the capability of teleporting matter, the future of electric propulsion will depend on daring, innovative and expensive ideas such as the ones discussed. Based on what is currently available, the most feasible concept to reach the nearest solar system appears to be the mini-magnetosphere approach. Its advantages over a light sail are clear. Also, it addresses a major problem in this endeavor - the need to slow down once the spacecraft has reached the solar system. Of course, the necessary technology is not yet fully mature. Designing and building the particle beam in space would be a major task. As expensive and daunting as it would be, the task is not impossible.

If further studies show that the EMDrive is a reality and not a result of experimental error, perhaps a more suitable approach would be to design a spacecraft that could maneuver in outerspace by exchanging momentum with the quantum vacuum virtual plasma powered by a nuclear reactor. The concept for a nuclear rocket propels requires large amounts of helium-3 from Jupiter's atmosphere as fuel. A more compact and lighter nuclear reactor could be designed with the goal to power the EMDrive rather than propel the craft. In a similar effort, Shawyer proposes the design of an interstellar probe powered by a 200 kW nuclear generator [13]. The design is daring, innovative and expensive indeed.

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