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Electric micropropulsion systems

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ABSTRACT

With the development of microspacecraft, the field of electrical micropropulsion is a rapidly expanding discipline. New ideas are being explored constantly and a review of the current state of technological development in the field will be useful. This review deals with electrostatic and electromagnetic micropropulsion systems that are either miniaturization attempts of existing technologies or novel systems in their own right. A brief discussion of the development of microspacecraft and a general overview of the types of micropropulsion are given. The essential mechanism of operation of each electrical micropropulsion system is described and recent progress in the development of these systems is explored, giving latest available data of their performance parameters.

Contents

1. Introduction

Requirements of modern space missions are tending towards the use of smaller spacecraft. Both civilian [1–4] and military space organizations [5] have begun proposing missions which involve small spacecraft able to execute complex maneuvers such as

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de-orbiting, orbit raising and formation flying [6] and capabilities to maintain precise attitude control [7]. A major motivating factor for exploring smaller spacecraft is cost. By reducing the size of satellites and spacecraft, the mass that needs to be launched into space is much reduced, thereby resulting in reduced launch costs. Manufacturing costs are reduced due to fewer material requirements and potential reductions in complexity of the spacecraft [8]. This allows for the possibility of more frequent launches and space missions will be more accessible to the private sector. A reduction in spacecraft size further allows for a greater flexibility in space missions by using many small craft with a distributed work load as opposed to a single large one [9].

The advantages of smaller space craft bring with them a new set of technological challenges. Many complex and essential spacecraft systems require miniaturization which is often difficult. Such systems include power generating and processing systems [10] and apparatus for performing scientific measurements [11]. Another area of active research is miniaturization of spacecraft propulsion systems. Over the years, numerous large scale propulsion technologies have been developed and successfully implemented [12,13]. These technologies have found use in missions ranging from manned space flight [14] to robotic space probes used for scientific exploration [15,16]. As one possible option, researchers attempt to miniaturize these well understood systems, but many conventional propulsion systems suffer from scaling problems [17] and in some cases are physically prohibited from operating effectively on a small scale. These issues can be overcome, but often result in more complicated designs requiring, for example, the use of additional magnetic fields to operate [18]. Some of these problems require new approaches to be overcome.

Another option is to explore new technologies that utilize novel physical and chemical mechanisms [19]. In order to compare the performance of different propulsion systems, a set of requirements for micropropulsion systems must be defined. This in turn requires that a definition of a small spacecraft and different classification systems are proposed [9,20].

It is generally agreed that the mass of the spacecraft is a crucial factor when categorising small spacecraft. In general, a microspacecraft should have a mass less than 100 kg. In this work we will consider the classification of Mueller [9] who groups small spacecraft into three distinct categories:

- Microspacecraft – these craft have masses in the range of 5 kg - 20 kg.
- Nanospacecraft – these craft have masses in the range of 1 kg - 5 kg.
- Picospacecraft – these craft have masses less than 1 kg.

These mass restrictions place constraints on the physical dimensions of the spacecraft and the on-board power supplies that can be used. These power supplies are generally limited to 100 W [9]. Developing these spacecraft systems with such tight restrictions on mass and power consumption has led to new production techniques the first use of which being reported in 1991 [21]. Microfabrication techniques such as photolithography and plasma etching have lead to the development of microelectromechanical systems (MEMS). These have provided an invaluable resource for the development of new technologies for small spacecraft [22–24].

A number of missions have been proposed prior to the year 2000 to test current micropropulsion systems and some future missions will rely even more on these technologies. These missions include the TechSat21 space-based radar test flight which was to use pulsed plasma thrusters (PPTs) for primary propulsion and attitude control [8]; the PRISMA satellite mission used to demonstrate formation flying which was to use a cold gas thruster system [25]; the CanX Nanosatellite program which tested new miniaturized technology for microspacecraft and formation flying techniques using a cold gas thruster system [26] and commercially available CubeSats which are a new and affordable nanosatellite platform for academic and private institutions to perform research from orbit [27]. CubeSats typically have the dimensions of 10 cm $\times$ 10 cm $\times$ 10 cm and have a mass of approximately 1 kg, but larger structures consisting of such modules have been built.

TechSat21 was cancelled in 2003 due to budget over-run issues and no results were obtained [28]. The PRISMA satellite mission was launched in 2010 and as of 2013 the satellites are still operational [29]. At the time of writing, the mission was in its final phase. Previous iterations of the CanX program, CanX-1 and CanX-2, were amongst the smallest satellites launched to date (CanX-1 has a mass less than 5 kg) and have been used as a test bed for miniaturized space technology. Further iterations of the program promise the use of more advanced technologies, paving the way for nanosatellite applications in more advanced areas outside of the simple proof-of-concept arena [30]. A number of successful CubeSat missions have been launched by countries without well established space programs [31]. Typically CubeSats do not feature propulsion systems, but some propulsion designs such as electrospray/colloid thrusters [32] and vacuum arc thrusters [33] have been proposed for future missions.

2. Types of micropropulsion

The types of micropropulsion systems are broadly divided into two categories based on their primary mechanism of thrust generation. This classification scheme is identical to larger propulsion systems [34,35]. The two categories are chemical and electrical propulsion systems and both are considered for primary propulsion and attitude control in microspacecraft [17]. A third category of propulsion system, nuclear propulsion, could be of interest for larger space craft, but it is not yet a viable option for microspacecraft [36].

2.1. Chemical micropropulsion

Chemical propulsion systems utilize the thrust generated from the exothermic combustion or decomposition of some form of chemical fuel [37,38]. Propulsion systems which use the force exerted by an inert gas stored under high pressure and allow it to escape through a nozzle are also classed under this propulsion type even though a chemical reaction does not always take place [39,40].

The major systems classed as chemical propulsion include mono-propellant thrusters [41], bi-propellant thrusters [42], tri-propellent thrusters [43], cold gas thrusters [44], warm gas thrusters [45], solid propellant thrusters [46], and hybrid thrusters [47].

Many of these systems have been used as primary propulsion systems in larger spacecraft [48] as they are relatively simple to construct and utilize [49], however, they are prone to setbacks when miniaturization efforts are made [50]. The thrust and specific impulses obtained from these systems decrease rapidly while the physical size and mass remain prohibitively large [17]. In the case of gas and liquid propellant thrusters, leakage of propellant is an issue which is more problematic after miniaturization as the amount of propellant that can be stored is reduced and losses have a much greater impact on the lifetime and usability of the system [51]. These and other issues such as the toxicity of propellants all effect the viability of using chemical thrusters in micropropulsion systems.