NASA's In-Space Propulsion Program

Les Johnson

NASA Marshall Space Flight Center / TD05

In order to implement the ambitious science and exploration missions planned over the next several decades, improvements in in-space transportation and propulsion technologies must be achieved. For robotic exploration and science missions, increased efficiencies of future propulsion systems are critical to reduce overall life-cycle costs. Future missions will require 2 to 3 times more total change in velocity over their mission lives than the NASA Solar Electric Technology Application Readiness (NSTAR) demonstration on the Deep Space 1 mission. New opportunities to explore beyond the outer planets and to the stars will require unparalleled technology advancement and innovation.

NASA's In-Space Propulsion (ISP) Program is investing in technologies to meet these needs. The ISP technology portfolio includes many advanced propulsion systems. From the next generation ion propulsion system operating in the 5 - 10 kW range, to advanced cryogenic propulsion, substantial advances in spacecraft propulsion performance are anticipated. Some of the most promising technologies for achieving these goals use the environment of space itself for energy and propulsion and are generically called, "propellantless" because they do not require on-board fuel to achieve thrust. Propellantless propulsion technologies include scientific innovations such as solar and plasma sails, electrodynamic and momentum transfer tethers, and aeroassist and aerocapture. An overview of both propellantless and propellant-based advanced propulsion technologies, and NASA's plans for advancing them, will be provided.

INTRODUCTION

A vigorous and robust space science and exploration program will require a new generation of propulsion systems. Chemical propulsion, which relies on making chemical bonds to release energy and produce rocket exhaust, has been the workhorse of space exploration since its beginning. However, we have reached its performance limits and those limits are now hindering our continued exploration of space. The efficiency with which a chemical rocket uses its fuel to produce thrust, specific impulse (I_{sp}), is limited to several hundred seconds or less. In order to attain the high speeds required to reach outer planetary bodies, much less rendezvous with them, will require propulsion system efficiencies well over 1,000 sec. Chemical propulsion systems cannot meet this requirement.

The In-Space Propulsion Program was a NASA new start in Fiscal Year (FY) 2002. Significant effort was spent in the summer and early fall of 2001 preparing for FY02 implementation. Mission analysis and technology prioritization were completed in order to gain an initial understanding of the potential pay-off of each technology and their applicability to a wide range of NASA missions. This effort was called Integrated In-Space Transportation Planning (IISTP). The IISTP sought to iterate and develop future NASA requirements for In-Space transportation and perform a prioritization of relevant propulsion technologies. An agency wide team was assembled with technical experts representing over 20 different propulsion technology elements. Propulsion technologies were assessed on their ability to meet a broad spectrum of mission needs including, reliability and safety, technology maturity, development costs and risk. The Propulsion function of interest was the transportation of a payload from the Earth's vicinity to a distant location, which also included insertion maneuvers at the destination, such as orbital insertion. The highest ranked propulsion technologies were those that had a broad range of mission applications and represented an enabling or significantly enhancing capability. The results of this IISTP effort served as the basis for selecting the ISP technology sub-areas for focused development efforts.

The ISP Program currently utilizes focused Technology Assessment Groups (TAGs), one for each major in-space propulsion technology, which play an integral role in helping NASA develop a technology maturation strategy. Several ISP technology TAGs were convened in early CY02 to begin to process of developing technology roadmaps, performing technology level assessments, and recommending technology maturation strategies. The TAGs are represented by experts in NASA, industry, and academia who come together in a forum to exchange information and offer technical insight to address the challenges of advancing the state-of-the-art of ISP technologies.

The ISP Program is currently developing and evaluating a suite of propulsion technologies. Below is a brief description of the technologies along with references where more detailed information may be obtained.

ELECTRIC PROPULSION

An electric propulsion system uses electrical energy to energize the propellant to much higher exhaust velocities (V_e) than those available from chemical reactions. Ion propulsion is an electric propulsion technology that uses ionized gas as propellant. Ionized gas, such as xenon, is electrostatically accelerated to a speed of 30 km/sec and provides the "exhaust" for the propulsion system. Electric propulsion thrusters can be divided into three broad categories: (1) Electrothermal thrusters use electric energy to simply heat the propellant, (2) electrostatic thrusters use charge potential differences to accelerate propellant ions, and (3) electromagnetic thrusters use electromagnetic forces (**J X B**) to accelerate a propellant plasma.

Ion propulsion is being used by commercial telecommunication satellites and has been demonstrated as a primary spacecraft propulsion system by the NSTAR demonstration on the Deep Space 1 (DS-1) mission. The successful demonstration of electric propulsion for DS-1 enabled the DAWN mission, recently selected in the Discovery Program, to baseline electric propulsion. The ISP Program is pursuing technologies to increase the performance of electrostatic thrusters by going to higher power levels and by increasing the I_{sp} on a system level.

NASA's Glenn Research Center in Cleveland, Ohio, was selected to lead development of NASA's Evolutionary Xenon Thruster (NEXT) system, which will use xenon gas and electrical power to drive future spacecraft. Additionally, a team led by Boeing Electron Dynamic Devices, Inc. of Torrance, Calif., was selected to pursue development, fabrication and testing of carbon-based ion optics -- critical components of high-power ion thrusters that have traditionally limited thruster lifetime.

The NEXT Project is a proposed two-part endeavor. Phase 1 is a one-year effort to design, build and test initial versions of ion thrusters, propellant feed systems and power processing units, which convert solar array power into forms useful for the ion engine. At the end of Phase 1, NASA may exercise a Phase 2 option to complete hardware development and integrate components into a full-scale system. Total NASA funding for Next-Generation Ion Engine system development activities is approximately $27 million.

The new ion thruster development program builds on the success of the Deep Space 1 mission, a NASA probe launched in 1998 to validate advanced flight technologies. Deep Space 1 was powered by an ion thruster just 12 inches in diameter, which accelerated the spacecraft to a velocity of 7,900 mph over a 20-month period. The NEXT ion engine will be capable of carrying significantly more payload and have a longer lifetime than the Deep Space 1 ion engine.

AEROCAPTURE

Aerocapture -- the use of a planet's atmosphere to slow down a spacecraft -- is part of a unique family of "aeroassist" technologies that will enable robust science missions to the most distant planets in our solar system. An aerocapture vehicle approaching a planet on a hyperbolic trajectory is "captured" into orbit as it passes through the atmosphere, without the use of on-board propulsion. This fuel-free method could reduce the typical mass of an interplanetary spacecraft by half, allowing for a smaller, cheaper vehicle -- one better equipped to conduct robust, long-term science at its destination.

To aerocapture, a spacecraft requires adequate drag to slow its speed and some protection from the heating environment. These two functions can be fulfilled in a variety of ways, including a traditional blunt, rigid aeroshell, such as that used during the Mars Pathfinder entry and descent in 1997; by a potentially lighter, inflatable aeroshell; or by a large, trailing "ballute," a combination parachute and balloon made of durable, thin material and stowed behind the vehicle for deployment.

The aerocapture maneuver begins with a shallow approach angle to the planet, followed by a descent to relatively dense layers of the atmosphere. Once most of the needed deceleration is reached, the vehicle maneuvers to exit the atmosphere. To account for the inaccuracies of the atmospheric entering conditions and for the atmospheric uncertainties, the vehicle needs to have guidance and control as well as maneuvering capabilities. Given the communication time delay resulting from the mission distances from Earth, the entire operation requires the vehicle to operate autonomously while in the planet's atmosphere.

NASA ISP is funding six research organizations to lead key aerocapture technology development tasks, primarily in the area of hardware development: The NASA Langley Research Center in Hampton, Virginia, tasked with development of high-temperature composite structures and adhesives; Applied Research Associates, Inc. of Englewood, Colorado, tasked with development and testing of lightweight thermal protection system ablators; the NASA Ames Research Center at Moffett Field, California, tasked with characterizing advanced thermal protection systems; the ELORET Corporation of Sunnyvale, California, tasked with development of advanced heatshield instrumentation; Lockheed Martin Astronautics of Denver, Colorado tasked with aeroshell development and integration; and Ball Aerospace Corporation of Boulder, Colorado, tasked with trailing ballute analysis and development.

SOLAR SAILS

Solar sails use photon pressure on a thin, lightweight reflective sheet to produce thrust. Sails can open up new regions of the solar system to accessibility for important science missions without the need for propellant. The chief advantage of the solar sail is its unique capability to accomplish scientific endeavors in the inner solar system. NASA is now proposing several missions to study the "Sun-Earth Connection," our planet's relationship with its parent star and the turbulent space weather it creates. Because some missions would call for the craft to hover in space, rather than orbit Earth or the Sun, the vehicle would need a constant propulsion source to hold its position. Conventional chemical propulsion or even an electric propulsion system would require too much fuel to sustain such a mission.

A solar sail, however, could carry out such missions for an extended duration. It would be uniquely suited, for instance, to hover at the so-called "sub-L1 point." The L1 point is a location in space where the position in space the gravitational forces of Earth and the Sun are in balance. A position in the Earth-Sun line closer than L1, hence sub-L1, would require a constant thrust force to maintain this non-Keplerian orbital motion. A spacecraft at the sub-L1 point could provide early warning of large-scale geomagnetic storms that might threaten satellites in Earth orbit or disrupt and damage communications systems and power grids on the planet.

Sailing in space has only become a real possibility in the last few years, with the advent of strong, lightweight materials. The sail itself could vary in size -- depending on the distance to its destination -- from the length of the Space Shuttle to that of a football field. The sail would be thinner than cellophane, with a density of just 5-10 grams per square meter. NASA and its partners are now evaluating sail hardware and materials to understand how well they will survive the harsh environment of space.

PLASMA SAILS

A novel new approach to spacecraft propulsion using a virtual sail composed of low-energy plasma might harness the energy of the solar wind to propel a spacecraft anywhere in the solar system and beyond. Such plasma sails will affect their momentum transfer with the plentiful solar wind streaming from the Sun. Plasma sails use a plasma chamber attached to a spacecraft as the primary propulsion system. Solar cells and solenoid coils would power the creation of a dense magnetized plasma, or ionized gas, that would inflate an electromagnetic field up to 19 km in radius around the spacecraft. In the future, fission power could be used. The field would interact with and be dragged by the solar wind. Creating this virtual sail will be analogous to raising a giant physical sail and harnessing the solar wind, which moves at speeds more than 1million km/hr.

Such an idea was first proposed by science fiction writer Carl Wiley in 1951, and advanced as a scientific possibility by physicist Richard Garwin later that decade. But it wasn't until the mid-1990s that practical research into harnessing plasma -- or the super-energized gas that would serve as the foundation of such a unique propulsion system -- were undertaken.

MOMENTUM-EXCHANGE ELECTRODYNAMIC REBOOST TETHERS

An Earth-orbiting, spinning tether system can be used to boost payloads into higher orbits with a Hohmann-type transfer. A tether system would be anchored to a relatively large mass in LEO, awaiting rendezvous with a payload delivered to orbit. The uplifted payload would meet with the tether facility which then begins a slow spin-up using electrodynamic tethers (for propellantless operation) or another low thrust, high I_{sp} thruster. At the proper moment and tether system orientation, the payload is released into a transfer orbit, potentially to geostationary transfer orbit (GTO) or lunar transfer orbit.

Following spin-up of the tether and satellite system, the payload is released at the local vertical. The satellite is injected into a higher orbit with perigee at the release location; the orbital tether platform is injected into a lower orbit with apogee at the release location. Momentum is transferred to the satellite from the orbiting tether boost station. The satellite then enters a GTO trajectory and accomplishes the transfer in as little as 5 hr. The platform then reboosts to its operational altitude. The system thus achieves transfer times comparable to a chemical upper stage with the efficiencies of electric propulsion. This type of system could be used to reduce launch vehicle requirements or to increase injected payload mass for any interplanetary mission.

ADVANCED CHEMICAL PROPULSION

These technologies may provide new solutions for interplanetary travel. NASA is investigating promising new chemical fuels, including non-toxic monopropellants and advanced hydrocarbons, as well as new means of improving chemical fuel efficiency through development of lightweight components, cryogenic fluid management technologies and other improvements to fuel storage and delivery systems.

SUMMARY

The coming generation of scientific exploration missions presents NASA with unique challenges. Chief among these: fast access throughout the solar system and the ability to rendezvous with, orbit and conduct *in situ* exploration of planets, satellites and small bodies. It is the mission of the In-Space Propulsion Program to develop propulsion technologies that will benefit future NASA science missions by significantly reducing travel times required for transit to distant bodies; to increase their capability by reducing the mass of the propulsion system; and to enable new destinations and new vantage points for science.

At the forefront of this effort is research now being conducted by NASA's In-Space Propulsion Program, managed by the Office of Space Science in Washington, D.C., and implemented for NASA by the Marshall Space Flight Center in Huntsville, Ala. The In-Space Propulsion program is also supported by Ames Research Center in Moffett Field, Calif.; Glenn Research Center in Cleveland, Ohio; the Jet Propulsion Laboratory in Pasadena, Calif.; Johnson Space Center in Houston, Texas; and Langley

Research Center in Hampton, Va. NASA also partners with government, industry and academic organizations around the nation to pursue its in-space propulsion goals.