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Cosmic Explorers: Space Propulsion Systems

Beyond Chemical Rockets

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This free sample contains the Introduction and Chapter 1. The complete book contains the full contents above.

Introduction

Spacecraft propulsion is any method used to accelerate spacecraft and artificial satellites. In-space propulsion is used in the vacuum of space after launch vehicle has lifted the spacecraft into outer space. Several methods of pragmatic spacecraft propulsion have been developed, each having its own drawbacks and advantages.

Most satellites have simple reliable chemical thrusters (often monopropellant rockets) or resistojet rockets for orbital station-keeping, while a few use momentum wheels for attitude control.

Russian and antecedent Soviet bloc satellites have used electric propulsion for decades, and newer Western geo-orbiting spacecraft are starting to use them for north, south station-keeping and orbit raising. Interplanetary vehicles mostly use chemical rockets as well, although a few have used electric propulsion such as ion thrusters and Hall-effect thrusters.

Various technologies need to support everything from small satellites and robotic deep space exploration to space stations and human missions to Mars.

Hypothetical in-space propulsion technologies describe propulsion technologies that could meet future space science and exploration needs. These propulsion technologies are intended to provide effective exploration of the Solar System and may permit mission designers to plan missions to "fly anytime, anywhere, and complete a host of science objectives at the destinations" and with greater reliability and safety.

With a wide range of possible missions and candidate propulsion technologies, the question of which technologies are "best" for future missions is a difficult one; expert opinion now holds that a portfolio of propulsion technologies should be developed to provide optimum solutions for a diverse set of missions and destinations. A spacecraft propulsion system provides propulsive force for orbital transfer, interplanetary trajectories, and potentially for landing and ascent.

In orbit, any additional impulse, even tiny, will result in a change in the orbit path, in three ways, corresponding to the three dimensions of space; the first chapter takes them in turn.

Earth's surface is situated fairly deep in a gravity well; the escape velocity required to leave its orbit is 11.2 kilometers per second. Thus for destinations beyond, propulsion systems need enough propellant and to be of high enough efficiency. The same is true for other planets and moons, albeit some have

lower gravity wells.

The impulse per unit weight-on-Earth, the quantity engineers call specific impulse, is the field's standard yardstick. Measured against Earth's gravity, the figure equals the effective exhaust velocity of the engine, the speed at which spent propellant leaves the nozzle, and either reading tells the same story.

Chapter 01: The Discovery of Space Propulsion Systems

A spacecraft can spend its impulse in any of three directions, and each buys a different orbit. Pushing towards or away from the body being orbited alters the eccentricity. The home planet sits well down inside its own gravity well, and climbing out demands roughly 11.2 kilometers per second of speed before a craft can break free of Earth's hold; farther destinations ask a propulsion system to carry enough propellant and to spend it well. Other worlds impose the same tax at gentler rates, and a few have wells deeper than ours.

As human beings evolved in a gravitational field of "one g" (9.81 m/s2), it would be most comfortable for a human spaceflight propulsion system to provide that acceleration continuously (though human bodies can tolerate much larger accelerations over short periods).

The occupants of a rocket or spaceship having such a propulsion system would be free from the ill effects of free fall, such as nausea, muscular weakness, reduced sense of taste, or leaching of calcium from their bones.

Almost all types of spacecraft propulsion are reaction engines, which produce thrust by expelling reaction mass, in accordance with Newton's third law of motion. The Tsiolkovsky rocket equation shows, using the law of conservation of momentum, that for a rocket engine propulsion method to change the momentum of a spacecraft, it must change the momentum of something else in the opposite direction.

In other words, the rocket must exhaust mass opposite the spacecraft's acceleration direction, with such exhausted mass called propellant or reaction mass.

For this to happen, both reaction mass and energy are needed. The impulse provided by launching a particle of reaction mass with mass m at velocity v is mv. But (following Newton's second law of motion) this particle has kinetic energy 1/2mv2, which must come from somewhere.

In a conventional solid, liquid, or hybrid rocket, fuel is burned, providing the energy, and the reaction products are allowed to flow out of the engine nozzle, providing the reaction mass.

In an ion thruster, electricity is used to accelerate ions behind the spacecraft. Here other sources must provide the electrical energy (e.g. The rate of change of velocity is called acceleration and the rate of change of momentum is called force.

To reach a given velocity, one can apply a small acceleration over a long period of time, or a large acceleration over a short time; similarly, one can achieve a given impulse with a large force over a short time or a small force over a long time.

This means that for maneuvering in space, a propulsion method that produces tiny accelerations for a long time can often produce the same impulse as another which produces large accelerations for a short time.

However, when launching from a planet, tiny accelerations cannot overcome the planet's gravitational pull and so cannot be used. Some designs however, operate without internal reaction mass by taking advantage of magnetic fields or light pressure to change the spacecraft's momentum.

When discussing the efficiency of a propulsion system, designers often focus on the effective use of the reaction mass, which must be carried along with the rocket and is irretrievably consumed when used.

Spacecraft performance can be quantified in amount of change in momentum per unit of propellant consumed, also called specific impulse. This is a measure of the amount of impulse that can be obtained from a fixed amount of reaction mass. The higher the specific impulse, the better the efficiency.

Ion propulsion engines have high specific impulse (~3000 s) and low thrust whereas chemical rockets like monopropellant or bipropellant rocket engines have a low specific impulse (~300 s) but high thrust.

The impulse per unit weight-on-Earth (typically designated by I sp

Because the weight on Earth of the reaction mass is often unimportant when discussing vehicles in space, specific impulse can also be discussed in terms of impulse per unit mass, with the same units as velocity (e.g., meters per second). This measure is equivalent to the effective exhaust velocity of the engine, and is typically designated v e.

Either the change in momentum per unit of propellant used by a spacecraft, or the velocity of the propellant exiting the spacecraft, can be used to measure its specific impulse. The two readings differ only by the standard acceleration due to gravity, the bookkeeping value 9.80665 meters per second squared, a unit conversion rather than a physical difference

In contrast to chemical rockets, electrodynamic rockets use electric or magnetic fields to accelerate a charged propellant. What the approach buys is exhaust speed: figures more than ten times those of a chemical engine come within reach, and the engine then delivers its thrust in a steady whisper while sipping propellant.

With a conventional chemical propulsion system, 2% of a rocket's total mass might make it to the destination, with the other 98% having been consumed as fuel.

With an electric propulsion system, 70% of what is aboard in low Earth orbit can make it to a deep-space destination. However, there is a trade-off.

Chemical rockets transform propellants into most of the energy needed to propel them, but their electromagnetic equivalents must carry or produce the power required to create and accelerate propellants.

Because there are currently practical limits on the amount of power available on a spacecraft, these engines are not suitable for launch vehicles or when a spacecraft needs a quick, large impulse, such as when it brakes to enter a capture orbit.

In addition, propulsion is needed for orienting and positioning the spacecraft in route as well as orbit maintenance (reaction control, station keeping, precision pointing, and orbital maneuvering).

Prograde/retrograde (i.e. Perpendicular to orbital plane, which changes orbital inclination. Radially, i.e.

Even so, because electrodynamic rockets offer very high, mission planners are increasingly willing to sacrifice power and thrust (and the extra time it will take to get a spacecraft where it needs to go) in order to save large amounts of propellant mass. Spacecraft operate in many areas of space. These include orbital maneuvering, interplanetary travel, and interstellar travel.

Artificial satellites are first launched into the desired altitude by conventional liquid/solid propelled rockets, after which the satellite may use onboard propulsion systems for orbital stationkeeping.

Once in the desired orbit, they often need some form of attitude control so that they are correctly pointed with respect to the Earth, the Sun, and possibly some astronomical object of interest. They are also subject to drag from the thin atmosphere, so that to stay in orbit for a long period of time some form of propulsion is occasionally necessary to make small corrections (orbital station-keeping).

Many satellites need to be moved from one orbit to another from time to time, and this also requires propulsion. A satellite's useful life is usually over once it has exhausted its ability to adjust its orbit. For interplanetary travel, a spacecraft can use its engines to leave Earth's orbit.

It is not explicitly necessary as the initial boost given by the rocket, gravity

slingshot, monopropellant/bipropellent attitude control propulsion system are enough for the exploration of the solar system (see New Horizons).

Once it has done so, it must make its way to its destination. Current interplanetary spacecraft do this with a series of short-term trajectory adjustments. In between these adjustments, the spacecraft typically moves along its trajectory without accelerating. The most fuel-efficient means to move from one circular orbit to another is with a Hohmann transfer orbit: the spacecraft begins in a roughly circular orbit around the Sun.

A short period of thrust in the direction of motion accelerates or decelerates the spacecraft into an elliptical orbit around the Sun which is tangential to its previous orbit and also to the orbit of its destination. The spacecraft falls freely along this elliptical orbit until it reaches its destination, where another short period of thrust accelerates or decelerates it to match the orbit of its destination.

Special methods such as aerobraking or aerocapture are sometimes used for this final orbital adjustment.

Some spacecraft propulsion methods such as solar sails provide very low but inexhaustible thrust; an interplanetary vehicle using one of these methods would follow a rather different trajectory, either constantly thrusting against its direction of motion in order to decrease its distance from the Sun, or constantly thrusting along its direction of motion to increase its distance from the Sun.

The concept has been successfully tested by the Japanese IKAROS solar sail spacecraft.

Because interstellar distances are great, a tremendous velocity is needed to get a spacecraft to its destination in a reasonable amount of time. Acquiring such a velocity on launch and getting rid of it on arrival remains a formidable challenge for spacecraft designers. No spacecraft capable of short duration (compared to human lifetime) interstellar travel has yet been built, but many hypothetical designs have been discussed.

The four conventional and widely used types of spacecraft propulsion are cold gas, monopropellant, bipropellant, and solid motor systems.

Spacecraft propulsion technology can be of several types, such as chemical, electric or nuclear. They are distinguished based on the physics of the propulsion system and how thrust is generated. Other experimental and more theoretical types are also included, depending on their technical maturity.

Additionally, there may be credible meritorious in-space propulsion concepts

not foreseen or reviewed at the time of publication, and which may be shown to be beneficial to future mission applications.

A large fraction of rocket engines in use today are chemical rockets; that is, they obtain the energy needed to generate thrust by chemical reactions to create a hot gas that is expanded to produce thrust. Many different propellant combinations are used to obtain these chemical reactions, including, for example, hydrazine, liquid oxygen, liquid hydrogen, nitrous oxide, and hydrogen peroxide. They can be used as a monopropellant or in bi-propellant configurations.

Rocket engines provide essentially the highest specific powers and high specific thrusts of any engine used for spacecraft propulsion. Most rocket engines are internal combustion heat engines (although non-combusting forms exist). Rocket engines generally produce a high-temperature reaction mass, as a hot gas, which is achieved by combusting a solid, liquid or gaseous fuel with an oxidiser within a combustion chamber.

The extremely hot gas is then allowed to escape through a high-expansion ratio bell-shaped nozzle, a feature that gives a rocket engine its characteristic shape. The effect of the nozzle is to accelerate the mass, converting most of the thermal energy into kinetic energy, where exhaust speeds reaching as high as 10 times the speed of sound at sea level are common.

Read either way, specific impulse separates by nothing more than the standard acceleration due to gravity, the fixed value 9.80665 meters per second squared, a matter of bookkeeping rather than physics. Even so, because electrodynamic rockets offer exhaust speeds that chemical flames cannot match, their advantage compounds with every month of a long voyage

Non-toxic 'green' alternatives are now being developed to replace hydrazine. Nitrous oxide-based alternatives are garnering traction and government support, with development being led by commercial companies Dawn Aerospace, Impulse Space, and Launcher.

The first nitrous oxide-based system flown in space was by D-Orbit onboard their ION Satellite Carrier (space tug) in 2021, using six Dawn Aerospace B20 thrusters, launched upon a SpaceX Falcon 9 rocket.

Rather than relying on high temperature and fluid dynamics to accelerate the reaction mass to high speeds, a whole family of methods uses electrostatic or electromagnetic forces to accelerate the reaction mass directly, and the reaction mass in these designs is usually a stream of ions.

There is a fitting bookend to this chapter in a Massachusetts cabbage patch.

On a March day in 1926, Robert Goddard flew the first liquid-propellant rocket, a machine thinner than a stovepipe that climbed for two and a half seconds, reached about the height of a two-story house, and splashed into a snow crust. The newspapers had a fine time with it; one editorial cartoonist drew him checking the moon off a shorter list. Yet every engine in this book, from the gentlest ion thruster to the loudest booster core, is descended from that flight, because it proved the working principle in metal: an engine is not a flame, it is a reaction, and the reaction does not care whether the chamber is elegant, only whether the mass goes one way so the craft goes the other.

The discovery that propulsion is bookkeeping, not fireworks, is the founding one, and it still surprises people. Nothing in a rocket pushes against the air. A rocket works in a vacuum for the same reason a rowboat works on a still lake: you throw mass behind you, and the universe, keeping its ledger exact, moves you forward.

End of free sample. The full book is available at putrabooks.github.io

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.