Spacecraft Flight Dynamics

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Flight Dynamics (Spacecraft)

Spacecraft flight dynamics is the science of space vehicle orientation and control in three dimensions. Three critical flight dynamics parameters are similar to those of aircraft: the angles of rotation in three dimensions about the vehicle's center of mass, known as *pitch*, *roll* and *yaw*. For spacecraft, there is an additional dynamic parameter which is *translation* in space, that shifts a vehicle or satellite from one defined orbit to another.

Flight dynamics in spacecraft is normally achieved by the "Attitude and Orbit control subsystem" (AOCS) and can be divided into *attitude control* and *orbit control*.

The *attitude* of a vehicle is its orientation with respect to a defined frame of reference. Satellite *attitude control* or *flight dynamics* refers to the techniques employed to keep the attitude inside a predefined range of values.

Attitude dynamics is the modeling of the changing position and orientation of a vehicle, due to external forces acting on the body. Attitude *control* is the purposeful manipulation of controllable external forces (using vehicle actuators) to establish a desired attitude, whereas attitude *determination* is the utilization of vehicle sensors to ascertain the current vehicle attitude.

Mathematical and physical treatment of the basic aspects of these topics is well-developed, but the field is quite active with respect to advanced topics and applications.

Attitude Control

Attitude control is the exercise of control over the orientation of an object with respect to an inertial frame of reference or another entity (the celestial sphere, certain fields, nearby objects, etc.).

Controlling vehicle attitude requires *sensors* to measure vehicle attitude, *actuators* to apply the torques needed to re-orient the vehicle to a desired attitude, and *algorithms* to command the actuators based on (1) sensor measurements of the current attitude and (2)

specification of a desired attitude. The integrated field that studies the combination of sensors, actuators and algorithms is called "Guidance, Navigation and Control" (GNC).

Sensors

Relative attitude sensors

Many sensors generate outputs that reflect the rate of change in attitude. These require a known initial attitude, or external information to use them to determine attitude. Many of this class of sensor have some noise, leading to inaccuracies if not corrected by absolute attitude sensors.

Gyroscopes

Gyroscopes are devices that sense rotation in three-dimensional space without reliance on the observation of external objects. Classically, a gyroscope consists of a spinning mass, but there are also "Laser Gyros" utilizing coherent light reflected around a closed path. Another type of "gyro" is a hemispherical resonator gyro where a crystal cup shaped like a wine glass can be driven into oscillation just as a wine glass "sings" as a finger is rubbed around its rim. The orientation of the oscillation is fixed in inertial space, so measuring the orientation of the oscillation relative to the spacecraft can be used to sense the motion of the spacecraft with respect to inertial space.

Motion Reference Units

Motion Reference Units are single- or multi-axis motion sensors. They utilize Micro-Electro-Mechanical-Structure (MEMS) sensor technology. These sensors are revolutionizing inertial sensor technology by bringing together micro-electronics with micro-machining technology, to make complete systems-on-a-chip with high accuracy. Typical applications for Motion Reference Units are:

- Antenna motion compensation and stabilization
- Dynamic positioning
- Heave compensation of offshore cranes
- High speed craft motion control and damping systems
- Hydro acoustic positioning
- Motion compensation of single and multibeam echosounders
- Ocean wave measurements
- Offshore structure motion monitoring
- Orientation and attitude measurements on AUVs and ROVs
- Ship motion monitoring

Absolute attitude sensors

This class of sensors sense the position or orientation of fields, objects or other phenomena outside the spacecraft.

Horizon sensor

A *horizon sensor* is an optical instrument that detects light from the 'limb' of the Earth's atmosphere, i.e., at the horizon. Thermal Infrared sensing is often used, which senses the comparative warmth of the atmosphere, compared to the much colder cosmic background. This sensor provides orientation with respect to the earth about two orthogonal axes. It tends to be less precise than sensors based on stellar observation. Sometimes referred to as an Earth Sensor.

Orbital gyrocompass

Similar to the way that a terrestrial gyrocompass uses a pendulum to sense local gravity and force its gyro into alignment with earth's spin vector, and therefore point north, an *orbital gyrocompass* uses a horizon sensor to sense the direction to earth's center, and a gyro to sense rotation about an axis normal to the orbit plane. Thus, the horizon sensor provides pitch and roll measurements, and the gyro provides yaw.

Sun sensor

A *sun sensor* is a device that senses the direction to the Sun. This can be as simple as some solar cells and shades, or as complex as a steerable telescope, depending on mission requirements.

Earth sensor

An *earth sensor* is a device that senses the direction to the Earth. It is usually an infrared camera; now the main method to detect attitude is the star tracker, but earth sensors are still integrated in satellites for their low cost and reliability.

Star tracker

A *star tracker* is an optical device that measures the position(s) of star(s) using photocell(s) or a camera.

Many models are currently available. Star trackers, which require high sensitivity, may become confused by sunlight reflected from the spacecraft, or by exhaust gas plumes from the spacecraft thrusters (either sunlight reflection or contamination of the star tracker window). Star trackers are also susceptible to a variety of errors (low spatial frequency, high spatial frequency, temporal, ...) in addition to a variety of optical sources of error (spherical aberration, chromatic aberration, ...). There are also many potential sources of confusion for the star identification algorithm (planets, comets, supernovae, the bimodal character of the point spread function for adjacent stars, other nearby satellites, point-source light pollution from large cities on Earth, ...). There are roughly 57 bright navigational stars in common use. However, for more complex missions, entire star field databases are used to determine spacecraft orientation. A typical star catalog for high-fidelity attitude determination is originated from a standard base catalog (for

example from the United States Naval Observatory) and then filtered to remove problematic stars, for example due to apparent magnitude variability, color index uncertainty, or a location within the Hertzsprung-Russell diagram implying unreliability. These types of star catalogs can have thousands of stars stored in memory on-board the spacecraft, or else processed using tools at the ground station and then uploaded.

Magnetometer

A *magnetometer* is a device that senses magnetic field strength and, when used in a three-axis triad, magnetic field direction. As a spacecraft navigational aid, sensed field strength and direction is compared to a map of the Earth magnetic field stored in the memory of an on-board or ground-based guidance computer. If spacecraft position is known then attitude can be inferred.

Algorithms

Control Algorithms are computer programs that receive data from vehicle sensors and derive the appropriate commands to the actuators to rotate the vehicle to the desired attitude. The algorithms range from very simple, e.g. proportional control, to complex nonlinear estimators or many in-between types, depending on mission requirements. Typically, the attitude control algorithms are part of the software running on the hardware which receives commands from the ground and formats vehicle data Telemetry for transmission to a ground station.

Actuators

Attitude control can be obtained by several mechanisms, specifically:

Thrusters

Thrusters are the most common, as they may be used for station keeping as well. Thrusters (often monopropellant rockets), must be organized as a Reaction control system to provide triaxial stabilization. Their limitations are fuel usage, engine wear, and cycles of the control valves. The fuel efficiency of an attitude control system is determined by its specific impulse (ISP - essentially, the rocket's exhaust velocity) and the smallest torque impulse it can provide. In practice, vehicle spin is reduced to a rate equivalent to this amount. Typically there is a tiny blip of thrust in one direction, and a few tens of seconds later, an opposing blip of thrust is needed to keep orientation errors within limits. To minimize the fuel limitation on mission duration, auxiliary attitude control systems may be used to reduce vehicle rotation to lower levels, notably smaller, lower thrust vernier thrusters that accelerate ionized gases to extreme velocities electrically, using power from solar cells.

Spin stabilization

The entire space vehicle itself can be spun up to stabilize the orientation of a single vehicle axis. This method is widely used to stabilize the final stage of a

launch vehicle. The entire spacecraft and an attached solid rocket motor are spun up about the rocket's thrust axis, on a "spin table" oriented by the attitude control system of the lower stage on which the spin table is mounted. When final orbit is achieved, the satellite may be de-spun by various means, or left spinning. Spin stabilization of satellites is only applicable to those missions with a primary axis of orientation that need not change dramatically over the lifetime of the satellite and no need for extremely high precision pointing. It is also useful for missions with instruments that must scan the star field or the Earth's surface or atmosphere.

Momentum wheels

These are electric motor driven rotors made to spin in the direction opposite to that required to re-orient the vehicle. Since momentum wheels make up a small fraction of the spacecraft's mass and are computer controlled, they give precise control. Momentum wheels are generally suspended on magnetic bearings to avoid bearing friction and breakdown problems. To maintain orientation in three dimensional space a minimum of two must be used, with additional units providing single failure protection.

Control moment gyros

These are rotors spun at constant speed, mounted on gimbals to provide attitude control. While a CMG provides control about the two axes orthogonal to the gyro spin axis, triaxial control still requires two units. A CMG is a bit more expensive in terms of cost and mass, since gimbals and their drive motors must be provided. The maximum torque (but not the maximum angular momentum change) exerted by a CMG is greater than for a momentum wheel, making it better suited to large spacecraft. A major drawback is the additional complexity, which increases the number of failure points. For this reason, the International Space Station uses a set of four CMGs to provide dual failure tolerance.

Solar sails

Small solar sails, (devices that produce thrust as a reaction force induced by reflecting incident light) may be used to make small attitude control and velocity adjustments. This application can save large amounts of fuel on a long-duration mission by producing control moments without fuel expenditure. For example, Mariner 10 adjusted its attitude using its solar cells and antennas as small solar sails.

Gravity-gradient stabilization

In orbit, a spacecraft with one axis much longer than the other two will spontaneously orient so that its long axis points at the planet's center of mass. This system has the virtue of needing no active control system or expenditure of fuel. The effect is caused by a tidal force. The upper end of the vehicle feels less gravitational pull than the lower end. This provides a restoring torque whenever the long axis is not co-linear with the direction of gravity. Unless some means of damping is provided, the spacecraft will oscillate about the local vertical. Sometimes tethers are used to connect two parts of a satellite, to increase the

stabilizing torque. A problem with such tethers is that meteoroids as small as a grain of sand can part them.

Magnetic torquers

Coils or (on very small satellites) permanent magnets exert a moment against the local magnetic field. This method works only where there is a magnetic field to react against. One classic field "coil" is actually in the form of a conductive tether in a planetary magnetic field. Such a conductive tether can also generate electrical power, at the expense of orbital decay. Conversely, by inducing a counter-current, using solar cell power, the orbit may be raised. Due to massive variability in Earth magnetic field from an ideal radial field, control laws based on torques coupling to this field will be highly non-linear. Moreover, only two-axis control is available at any given time meaning that a vehicle reorient may be necessary to null all rates.

Pure passive attitude control

There exists two main passive control types for satellites. The first one uses gravity gradient, and it leads to four stable states with the long axis (axis with smallest moment of inertia) pointing towards the Earth. As this system has four stable states, if the satellite has a preferred orientation, e.g. a camera pointed at the planet, some way to flip the satellite and its tether end-for-end is needed. The other passive system orients the satellite along the earth magnetic field thanks to a magnet. These purely passive attitude control systems have limited pointing accuracy, because the spacecraft will oscillate around energy minima. This drawback is overcome by adding damper, which can be hysteretic materials or a viscous damper. The viscous damper is a small can or tank of fluid mounted in the spacecraft, possibly with internal baffles to increase internal friction. Friction within the damper will gradually convert oscillation energy into heat dissipated within the viscous damper.

Orbit control

In spaceflight, orbit control is the technique dealing with *orbital maneuvers*, or the use of propulsion systems to change the orbit of a spacecraft. For spacecraft far from Earth—for example those in orbits around the Sun—an orbital maneuver is called a *deep-space maneuver (DSM)*.

Orbit control is achieved via impulses named delta-*v*. This is an astrogation term used in astrodynamics and aerospace industry for velocity change (or delta-*v*) requirements for the various propulsive tasks and orbital maneuvers over phases of a space mission.

Sample delta-*v* budget will enumerate various classes of maneuvers, delta-*v* per maneuver, number of maneuvers required over the time of the mission.

In the absence of an atmosphere, the delta-*v* is typically the same for changes in orbit in either direction; in particular, gaining and losing speed cost an equal effort.

Because the delta-*v* needed to achieve the mission usually varies with the relative position of the gravitating bodies, launch windows are often calculated from porkchop plots that show delta-*v* plotted against the launch time.
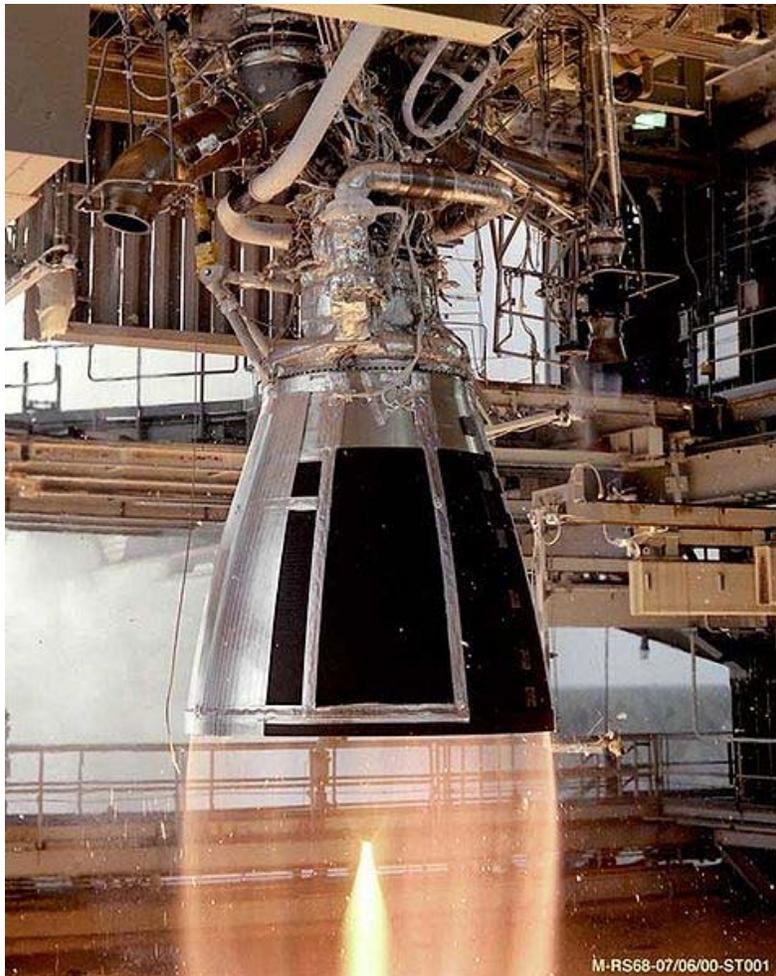
Rocket Engine

RS-68 being tested at NASA's Stennis Space Center. The nearly transparent exhaust is due to this engine's exhaust being mostly superheated steam (water vapor from its propellants, hydrogen and oxygen)

Viking 5C rocket engine

A **rocket engine**, or simply "rocket," is a jet engine that uses only propellant mass for forming its high speed propulsive jet. Rocket engines are reaction engines and obtain thrust in accordance with Newton's third law. Since they need no external material to form their jet, rocket engines can be used for spacecraft propulsion as well as terrestrial uses, such as missiles. Most rocket engines are internal combustion engines, although non combusting forms also exist.

Rocket engines as a group have the highest exhaust velocities, are by far the lightest, and are the least energy efficient of all types of jet engines.

Terminology

Chemical rockets are rockets powered by exothermic chemical reactions of the propellant.

Rocket motor (or **solid-propellant rocket motor**) is a synonymous term with rocket engine that usually refers to solid rocket engines.

Liquid rockets (or **liquid-propellant rocket engine**) use one or more liquid propellants that are held in tanks prior to burning.
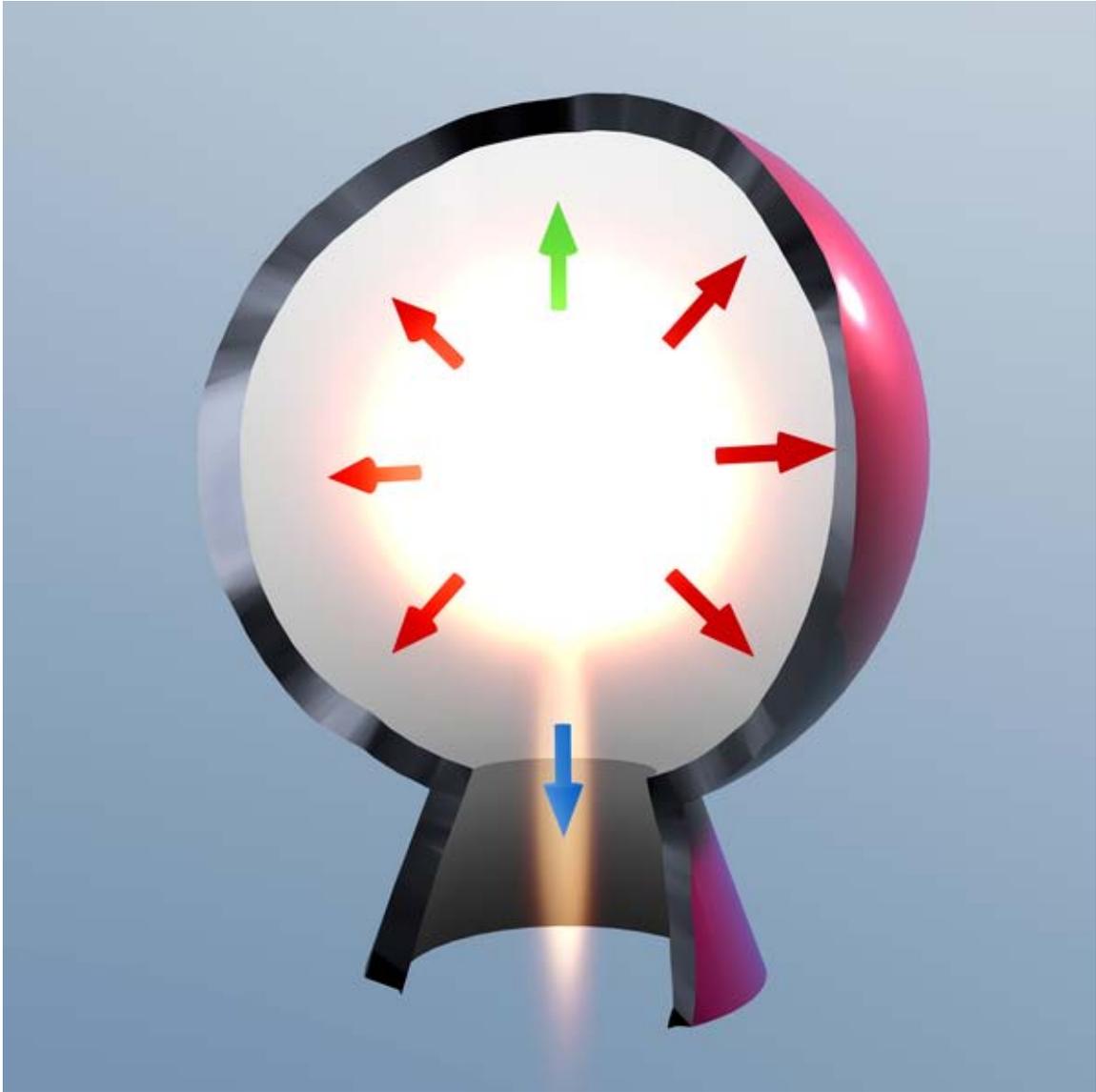
Hybrid rockets have a solid propellant in the combustion chamber and a second liquid or gas propellant is added to permit it to burn.

Thermal rockets are rockets where the propellant is inert, but is heated by a power source such as solar or nuclear power or beamed energy.

Principle of operation
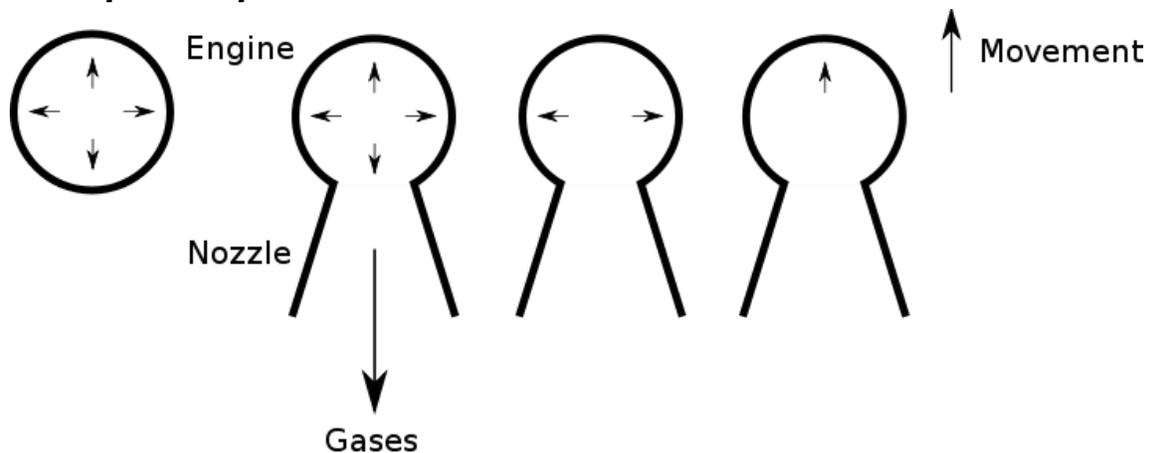
How rocket engines work

Rocket engines give part of their thrust due to unopposed pressure on the combustion chamber

Rocket engines produce thrust by the expulsion of a high-speed fluid exhaust. This fluid is nearly always a gas which is created by high pressure (10-200 bar) combustion of solid or liquid propellants, consisting of fuel and oxidiser components, within a combustion chamber.

The fluid exhaust is then passed through a supersonic propelling nozzle which uses heat energy of the gas to accelerate the exhaust to very high speed, and the reaction to this pushes the engine in the opposite direction.

In rocket engines, high temperatures and pressures are highly desirable for good performance as this permits a longer nozzle to be fitted to the engine, which gives higher exhaust speeds, as well as giving better thermodynamic efficiency.

Introducing propellant into a combustion chamber

Rocket propellant is mass that is stored, usually in some form of propellant tank, prior to being ejected from a rocket engine in the form of a fluid jet to produce thrust.

Chemical rocket propellants are most commonly used, which undergo exothermic chemical reactions which produce hot gas which is used by a rocket for propulsive purposes. Alternatively, a chemically inert reaction mass can be heated using a high-energy power source via a heat exchanger, and then no combustion chamber is used.
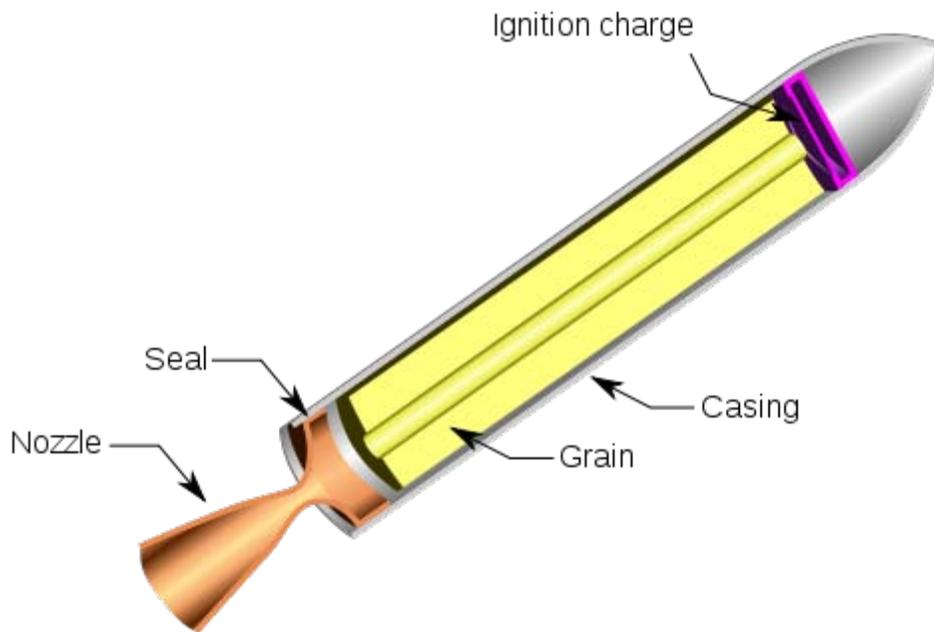
A solid rocket motor.

Solid rocket propellants are prepared as a mixture of fuel and oxidizing components called 'grain' and the propellant storage casing effectively becomes the combustion chamber. Liquid-fueled rockets typically pump separate fuel and oxidiser components into the combustion chamber, where they mix and burn. Hybrid rocket engines use a combination of solid and liquid or gaseous propellants. Both liquid and hybrid rockets use *injectors* to introduce the propellant into the chamber. These are often an array of simple jets- holes through which the propellant escapes under pressure; but sometimes may be more complex spray nozzles. When two or more propellants are injected the jets usually deliberately collide the propellants as this breaks up the flow into smaller droplets that burn more easily.

Combustion chamber

For chemical rockets the combustion chamber is typically just a cylinder, and flame holders are rarely used. The dimensions of the cylinder are such that the propellant is able to combust thoroughly; different propellants require different combustion chamber sizes for this to occur. This leads to a number called L^*:

$$L^* = \frac{V_c}{A_t}$$

where:

- V_c is the volume of the chamber
- A_t is the area of the throat

L* is typically in the range of 25–60 inches (0.63–1.5 m).

The combination of temperatures and pressures typically reached in a combustion chamber is usually extreme by any standards. Unlike in air-breathing jet engines, no atmospheric nitrogen is present to dilute and cool the combustion, and the temperature can reach true stoichiometric. This, in combination with the high pressures, means that the rate of heat conduction through the walls is very high.

Rocket nozzles
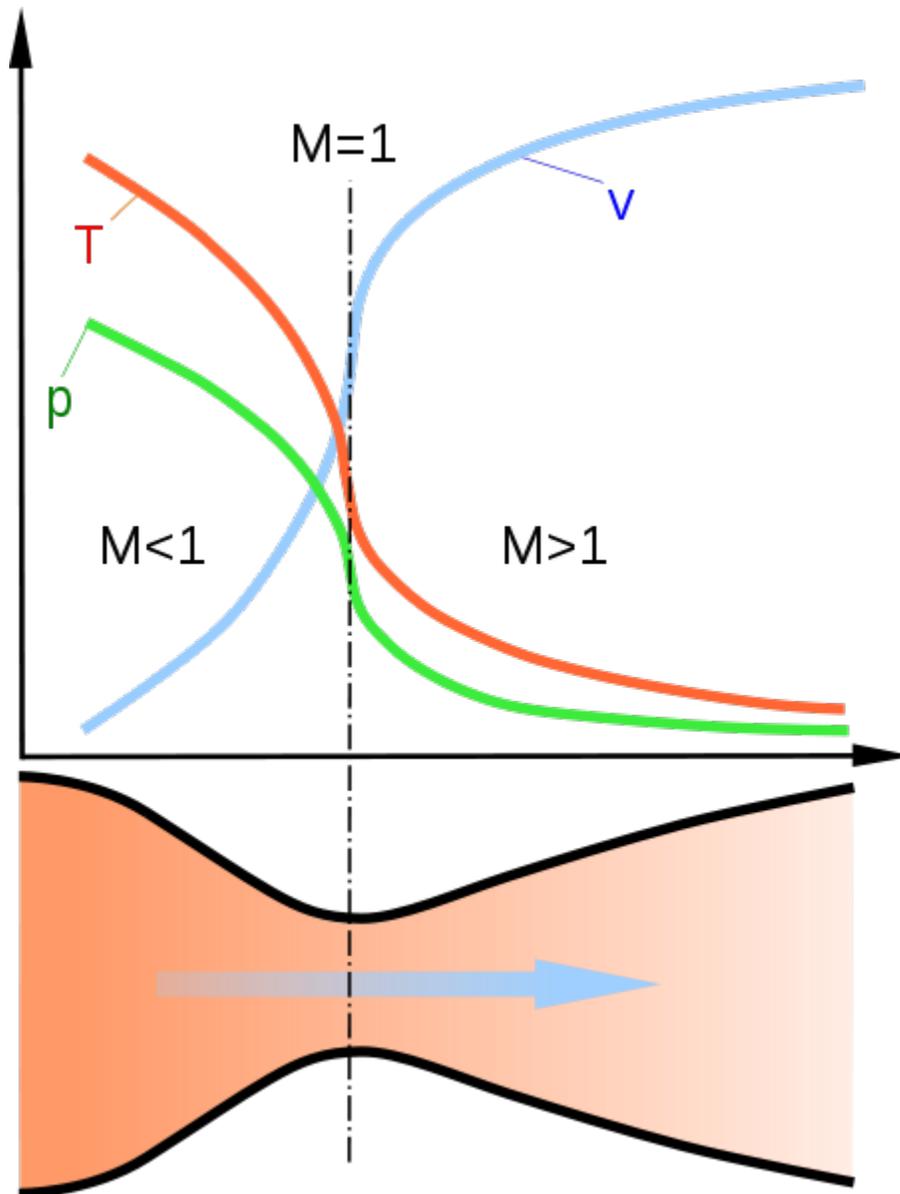
Typical temperatures (T) and pressures (p) and speeds (v) in a De Laval Nozzle

The large bell or cone shaped expansion nozzle gives a rocket engine its characteristic shape.

In rockets the hot gas produced in the combustion chamber is permitted to escape from the combustion chamber through an opening (the "throat"), within a high expansion-ratio 'de Laval' nozzle.

Provided sufficient pressure is provided to the nozzle (about 2.5-3x above ambient pressure) the nozzle *chokes* and a supersonic jet is formed, dramatically accelerating the gas, converting most of the thermal energy into kinetic energy.

The exhaust speeds vary, depending on the expansion ratio the nozzle is designed to give, but exhaust speeds as high as ten times the speed of sound of sea level air are not uncommon.
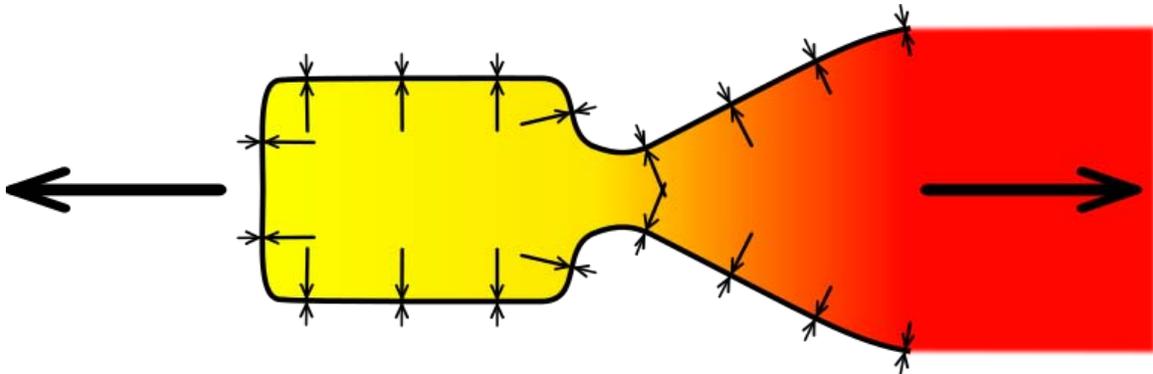
Rocket thrust is caused by pressures acting in the combustion chamber and nozzle. From Newton's third law, equal and opposite pressures act on the exhaust, and this accelerates it to high speeds.

About half of the rocket engine's thrust comes from the unbalanced pressures inside the combustion chamber and the rest comes from the pressures acting against the inside of the nozzle. As the gas expands (adiabatically) the pressure against the nozzle's walls forces the rocket engine in one direction while accelerating the gas in the other.

Propellant efficiency

For a rocket engine to be propellant efficient, it is important that the maximum pressures possible be created on the walls of the chamber and nozzle by a specific amount of propellant; as this is the source of the thrust. This can be achieved by all of:

- heating the propellant to as high a temperature as possible (using a high energy fuel, containing hydrogen and carbon and sometimes metals such as aluminium, or even using nuclear energy)
- using a low specific density gas (as hydrogen rich as possible)
- using propellants which are, or decompose to, simple molecules with few degrees of freedom to maximise translational velocity

Since all of these things minimise the mass of the propellant used, and since pressure is proportional to the mass of propellant present to be accelerated as it pushes on the engine, and since from Newton's third law the pressure that acts on the engine also reciprocally acts on the propellant, it turns out that for any given engine the speed that the propellant leaves the chamber is unaffected by the chamber pressure (although the thrust is proportional). However, speed is significantly affected by all three of the above factors and the exhaust speed is an excellent measure of the engine propellant efficiency. This is termed *exhaust velocity*, and after allowance is made for factors that can reduce it, the

effective exhaust velocity is one of the most important parameters of a rocket engine (although weight, cost, ease of manufacture etc. are usually also very important).

For aerodynamic reasons the flow goes sonic ("chokes") at the narrowest part of the nozzle, the 'throat'. Since the speed of sound in gases increases with the square root of temperature, the use of hot exhaust gas greatly improves performance. By comparison, at room temperature the speed of sound in air is about 340 m/s while the speed of sound in the hot gas of a rocket engine can be over 1700 m/s; much of this performance is due to the higher temperature, but additionally rocket propellants are chosen to be of low molecular mass, and this also gives a higher velocity compared to air.

Expansion in the rocket nozzle then further multiplies the speed, typically between 1.5 and 2 times, giving a highly collimated hypersonic exhaust jet. The speed increase of a rocket nozzle is mostly determined by its area expansion ratio—the ratio of the area of the throat to the area at the exit, but detailed properties of the gas are also important. Larger ratio nozzles are more massive but are able to extract more heat from the combustion gases, increasing the exhaust velocity.

Nozzle efficiency is affected by operation in the atmosphere because atmospheric pressure changes with altitude; but due to the supersonic speeds of the gas exiting from a rocket engine, the pressure of the jet may be either below or above ambient, and equilibrium between the two is not reached at all altitudes.

Back pressure and optimal expansion

For optimal performance the pressure of the gas at the end of the nozzle should just equal the ambient pressure: if the exhaust's pressure is lower than the ambient pressure, then the vehicle will be slowed by the difference in pressure between the top of the engine and the exit; on the other hand, if the exhaust's pressure is higher, then exhaust pressure that could have been converted into thrust is not converted, and energy is wasted.

To maintain this ideal of equality between the exhaust's exit pressure and the ambient pressure, the diameter of the nozzle would need to increase with altitude, giving the pressure a longer nozzle to act on (and reducing the exit pressure and temperature). This increase is difficult to arrange in a lightweight fashion, although is routinely done with other forms of jet engines. In rocketry a lightweight compromise nozzle is generally used and some reduction in atmospheric performance occurs when used at other than the 'design altitude' or when throttled. To improve on this, various exotic nozzle designs such as the plug nozzle, stepped nozzles, the expanding nozzle and the aerospike have been proposed, each providing some way to adapt to changing ambient air pressure and each allowing the gas to expand further against the nozzle, giving extra thrust at higher altitudes.

When exhausting into a sufficiently low ambient pressure (vacuum) several issues arise. One is the sheer weight of the nozzle- beyond a certain point, for a particular vehicle, the extra weight of the nozzle outweighs any performance gained. Secondly, as the exhaust

gases adiabatically expand within the nozzle they cool, and eventually some of the chemicals can freeze, producing 'snow' within the jet. This causes instabilities in the jet and must be avoided.

On a De Laval nozzle, exhaust gas flow detachment will occur in a grossly over-expanded nozzle. As the detachment point will not be uniform around the axis of the engine, a side force may be imparted to the engine. This side force may change over time and result in control problems with the launch vehicle.

Thrust vectoring

Many engines require the overall thrust to change direction over the length of the burn. A number of different ways to achieve this have been flown:

- The entire engine is mounted on a hinge or gimbal and any propellant feeds reach the engine via low pressure flexible pipes or rotary couplings.
- Just the combustion chamber and nozzle is gimbled, the pumps are fixed, and high pressure feeds attach to the engine
- multiple engines (often canted at slight angles) are deployed but throttled to give the overall vector that is required, giving only a very small penalty
- fixed engines with vernier thrusters
- high temperature vanes held in the exhaust that can be tilted to deflect the jet

Overall rocket engine performance

Rocket technology can combine very high thrust (meganewtons), very high exhaust speeds (around 10 times the speed of sound in air at sea level) and very high thrust/weight ratios (>100) *simultaneously* as well as being able to operate outside the atmosphere, and while permitting the use of low pressure and hence lightweight tanks and structure.

Rockets can be further optimised to even more extreme performance along one or more of these axes at the expense of the others.

Specific impulse

The most important metric for the efficiency of a rocket engine is impulse per unit of propellant, this is called specific impulse (usually written I_{sp}). This is either measured as a speed (the *effective exhaust velocity* V_e in metres/second or ft/s) or as a time (seconds). An engine that gives a large specific impulse is normally highly desirable.

The specific impulse that can be achieved is primarily a function of the propellant mix (and ultimately would limit the specific impulse), but practical limits on chamber pressures and the nozzle expansion ratios reduce the performance that can be achieved.

Typical performances of common propellants

Propellant mix	Vacuum Isp (seconds)	Effective exhaust velocity (m/s)
liquid oxygen/ liquid hydrogen	455	4462
liquid oxygen/ kerosene (RP-1)	358	3510
nitrogen tetroxide/ hydrazine	305	2993

n.b. All performances at a nozzle expansion ratio of 40

Net thrust

Below is an approximate equation for calculating the net thrust of a rocket engine:

$$F_n = \dot{m}\, V_e = \dot{m}\, V_{e-act} + A_e(P_e - P_{amb})$$

where:

$\dot{m}$ = exhaust gas mass flow
V_e = effective exhaust velocity
V_{e-act} = actual jet velocity at nozzle exit plane
A_e = flow area at nozzle exit plane (or the plane where the jet leaves the nozzle if separated flow)
P_e = static pressure at nozzle exit plane
P_{amb} = ambient (or atmospheric) pressure

Since, unlike a jet engine, a conventional rocket motor lacks an air intake, there is no 'ram drag' to deduct from the gross thrust. Consequently the net thrust of a rocket motor is equal to the gross thrust (apart from static back pressure).

The $\dot{m}\, V_{e-act}$ term represents the momentum thrust, which remains constant at a given throttle setting, whereas the $A_e(P_e - P_{amb})$ term represents the pressure thrust term. At full throttle, the net thrust of a rocket motor improves slightly with increasing altitude, because as atmospheric pressure decreases with altitude, the pressure thrust term increases. At the surface of the Earth the pressure thrust may be reduced by up to 30%, depending on the engine design. This reduction drops roughly exponentially to zero with increasing altitude.

Maximum thrust for a rocket engine is achieved by maximizing the momentum contribution of the equation without incurring penalties from over expanding the exhaust. This occurs when $P_e = P_{amb}$. Since ambient pressure changes with altitude, most rocket engines spend very little time operating at peak efficiency.
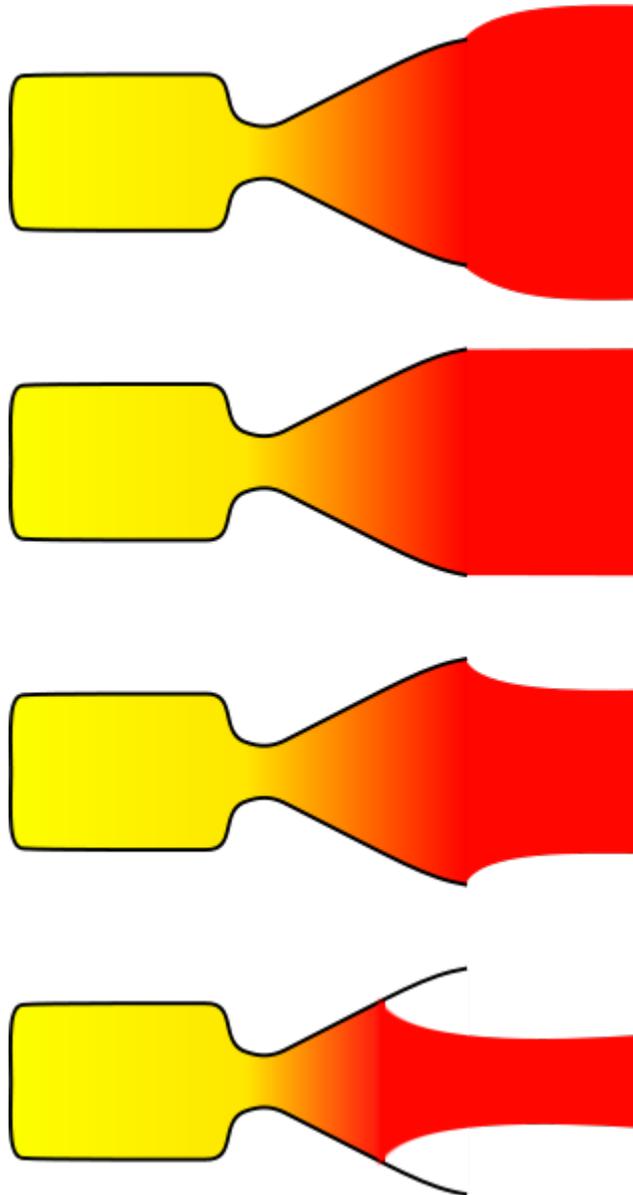
If the pressure of the exhaust jet varies from atmospheric pressure, nozzles can be said to be (top to bottom):

Underexpanded
Ambient
Overexpanded
Grossly overexpanded

If under or overexpanded then loss of efficiency occurs, grossly overexpanded nozzles lose less efficiency, but can cause mechanical issues with the nozzle. Rockets become progressively more underexpanded as they gain altitude. Note that almost all rocket engines will be momentarily grossly overexpanded during startup in an atmosphere.

Vacuum Isp

Due to the specific impulse varying with pressure, a quantity that is easy to compare and calculate with is useful. Because rockets choke at the throat, and because the supersonic exhaust prevents external pressure influences travelling upstream, it turns out that the pressure at the exit is ideally exactly proportional to the propellant flow $\dot{m}$, provided the mixture ratios and combustion efficiencies are maintained. It is thus quite usual to rearrange the above equation slightly:

$$F_{vac} = C_f \dot{m} c^*$$

and so define the *vacuum Isp* to be:

$$V_{evac} = C_f c^*$$

Where:

$c^* =$ the speed of sound constant at the throat

$C_f =$ the thrust coefficient constant of the nozzle (typically about 2)

And hence:

$$F_n = \dot{m} V_{evac} - A_e P_{amb}$$

Throttling

Rockets can be throttled by controlling the propellant combustion rate $\dot{m}$ (usually measured in kg/s or lb/s). In liquid and hybrid rockets, the propellant flow entering the chamber is controlled using valves, in solid rockets it is controlled by changing the area of propellant that is burning and this can be designed into the propellant grain (and hence cannot be controlled in real-time).

Rockets can usually be throttled down to an exit pressure of about one-third of ambient pressure (often limited flow separation in nozzles) and up to a maximum limit determined only by the mechanical strength of the engine.

In practice, the degree to which rockets can be throttled varies greatly, but most rockets can be throttled by a factor of 2 without great difficulty; the typical limitation is combustion stability, as for example, injectors need a minimum pressure to avoid triggering damaging oscillations (chugging or combustion instabilities); but injectors can often be optimised and tested for wider ranges. Solid rockets can be throttled by using shaped grains that will vary their surface area over the course of the burn.

Energy efficiency
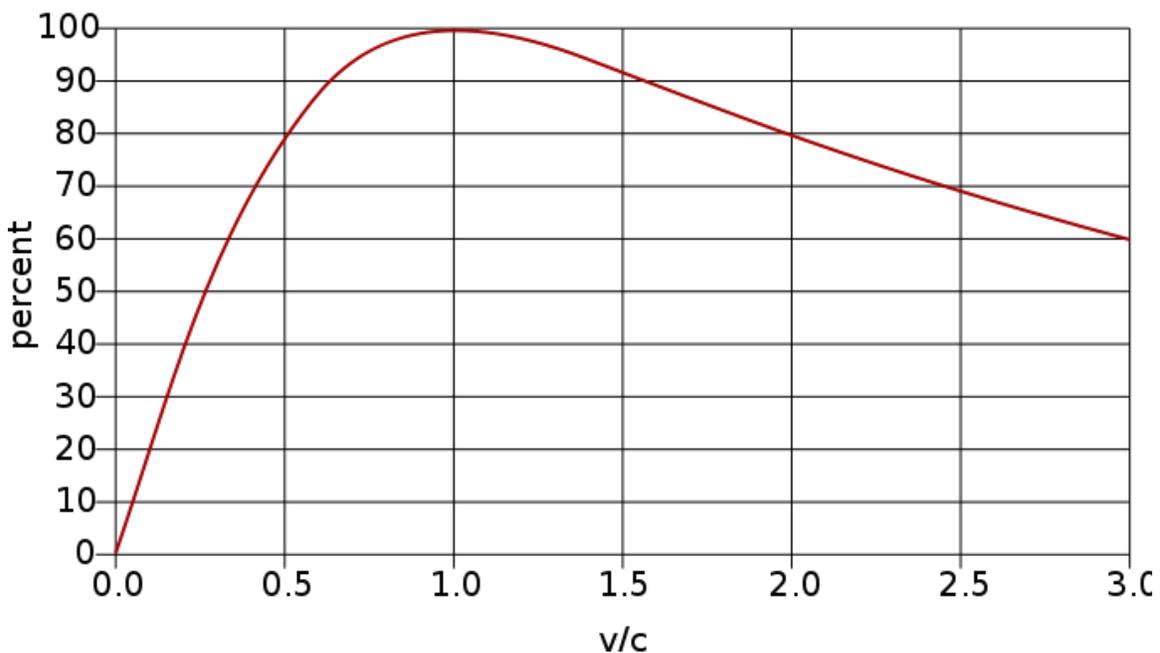
Rocket energy efficiency as a function of vehicle speed divided by effective exhaust speed

Rocket engine nozzles are surprisingly efficient heat engines for generating a high speed jet, as a consequence of the high combustion temperature and high compression ratio. Rocket nozzles give an excellent approximation to adiabatic expansion which is a reversible process, and hence they give efficiencies which are very close to that of the Carnot cycle. Given the temperatures reached, over 60% efficiency can be achieved with chemical rockets.

For a *vehicle* employing a rocket engine the energetic efficiency is very good if the vehicle speed approaches or somewhat exceeds the exhaust velocity (relative to launch); but at low speeds the energy efficiency goes to 0% at zero speed (as with all jet propulsion.)

Thrust to weight ratio

Rockets, of all the jet engines, indeed of essentially all engines, have the highest thrust to weight ratio. This is especially true for liquid rocket engines.

This high performance is due to the small volume of pressure vessels that make up the engine- the pumps, pipes and combustion chambers involved. The lack of inlet duct and the use of dense liquid propellant allows the pressurisation system to be small and

lightweight, whereas duct engines have to deal with air which has a density about one thousand times lower.

Jet or Rocket engine	Mass, kg	Jet or rocket thrust, kN	Thrust-to-weight ratio
RD-0410 nuclear rocket engine	2000	35.2	1.8
J-58 (SR-71 Blackbird jet engine)	2722	150	5.2
Concorde's Rolls-Royce/Snecma Olympus 593 turbojet with reheat	3175	169.2	5.4
RD-0750 rocket engine, three-propellant mode	4621	1413	31.2
RD-0146 rocket engine	260	98	38.5
Space Shuttle's SSME **rocket engine**	3177	2278	73.2
RD-180 rocket engine	5393	4152	78.6
F-1 (Saturn V first stage)	8391	7740.5	94.1
NK-33 rocket engine	1222	1638	136.8

Of the liquid propellants used, density is worst for liquid hydrogen. Although this propellant is marvellous in many ways, it has a very low density, about one fourteenth that of water. This makes the turbopumps and pipework larger and heavier, and this is reflected in the thrust-to-weight ratio of engines that use it (for example the SSME) compared to those that do not (NK-33).

Cooling

For efficiency reasons, and because they physically can, rockets run with combustion temperatures that can reach ~3500 K (~5800 °F)(~3227 °C).

Most other jet engines have gas turbines in the hot exhaust. Due to their larger surface area, they are harder to cool and hence there is a need to run the combustion processes at much lower temperatures, losing efficiency. In addition duct engines use air as an oxidant, which contains 80% largely unreactive nitrogen, which dilutes the reaction and lowers the temperatures. Rockets have none of these inherent disadvantages.

Therefore in rockets temperatures employed are very often far higher than the melting point of the nozzle and combustion chamber materials, two exceptions are graphite and tungsten (~1200 K for copper), however both are subject to oxidation if not protected. Indeed many construction materials can make perfectly acceptable propellants in their own right. It is important that these materials be prevented from combusting, melting or vaporising to the point of failure. This is sometimes somewhat facetiously termed an 'engine rich exhaust'. Materials technology could potentially place an upper limit on the exhaust temperature of chemical rockets.

Alternatively, rockets may use more common construction materials such as aluminium, steel, nickel or copper alloys and employ cooling systems that prevent the construction material itself becoming too hot. Regenerative cooling, where the propellant is passed through tubes around the combustion chamber or nozzle, and other techniques, such as curtain cooling or film cooling, are employed to give longer nozzle and chamber life. These techniques ensure that a gaseous thermal boundary layer touching the material is kept below the temperature which would cause the material to catastrophically fail.

In rockets, the heat fluxes that can pass through the wall are among the highest in engineering, fluxes are generally in the range of 1-200 MW/m^2. The strongest heat fluxes are found at the throat, which often sees twice that found in the associated chamber and nozzle. This is due to the combination of high speeds (which gives a very thin boundary layer), and although lower than the chamber, the high temperatures seen there.

In rockets the coolant methods include:

1. uncooled (used for short runs mainly during testing)
2. ablative walls (walls are lined with a material that is continuously vaporised and carried away).
3. radiative cooling (the chamber becomes almost white hot and radiates the heat away)
4. dump cooling (a propellant, usually hydrogen, is passed around the chamber and dumped)
5. regenerative cooling (liquid rockets use the fuel, or occasionally the oxidiser, to cool the chamber via a cooling jacket before being injected)
6. curtain cooling (propellant injection is arranged so the temperature of the gases is cooler at the walls)
7. film cooling (surfaces are wetted with liquid propellant, which cools as it evaporates)

In all cases the cooling effect that prevents the wall from being destroyed is caused by a thin layer of insulating fluid (a boundary layer) that is in contact with the walls that is far cooler than the combustion temperature. Provided this boundary layer is intact the wall will not be damaged.

Disruption of the boundary layer may occur during cooling failures or combustion instabilities, and wall failure typically occurs soon after.

With regenerative cooling a second boundary layer is found in the coolant channels around the chamber. This boundary layer thickness needs to be as small as possible, since the boundary layer acts as an insulator between the wall and the coolant. This may be achieved by making the coolant velocity in the channels as high as possible.

In practice, regenerative cooling is nearly always used in conjunction with curtain cooling and/or film cooling.

Liquid fueled engines are often run fuel rich, which results in lower temperature combustion. Cooler exhaust reduces heat loads on the engine allowing lower cost materials, a simplified cooling system, and a lower performance engine.

Mechanical issues

Rocket combustion chambers are normally operated at fairly high pressure, typically 10-200 bar (1 to 20 MPa, 150-3000 psi). When operated within significant atmospheric pressure, higher combustion chamber pressures give better performance by permitting a larger and more efficient nozzle to be fitted without it being grossly overexpanded.

However, these high pressures cause the outermost part of the chamber to be under very large hoop stresses – rocket engines are pressure vessels.

Worse, due to the high temperatures created in rocket engines the materials used tend to have a significantly lowered working tensile strength.

In addition, significant temperature gradients are set up in the walls of the chamber and nozzle, these cause differential expansion of the inner liner that create internal stresses.

Acoustic issues

In addition, the extreme vibration and acoustic environment inside a rocket motor commonly result in peak stresses well above mean values, especially in the presence of organ pipe-like resonances and gas turbulence.

Combustion instabilities

The combustion may display undesired instabilities, of sudden or periodic nature. The pressure in the injection chamber may increase until the propellant flow through the injector plate decreases; a moment later the pressure drops and the flow increases, injecting more propellant in the combustion chamber which burns a moment later, and again increases the chamber pressure, repeating the cycle. This may lead to high-amplitude pressure oscillations, often in ultrasonic range, which may damage the motor. Oscillations of ±200 psi at 25 kHz were the cause of failures of early versions of the Titan II missile second stage engines. The other failure mode is a deflagration to detonation transition; the supersonic pressure wave formed in the combustion chamber may destroy the engine.

The combustion instabilities can be provoked by remains of cleaning solvents in the engine, reflected shock wave, initial instability after ignition, explosion near the nozzle that reflects into the combustion chamber, and many more factors. In stable engine designs the oscillations are quickly suppressed; in unstable designs they persist for prolonged periods. Oscillation suppressors are commonly used.

Periodic variations of thrust, caused by combustion instability or longitudinal vibrations of structures between the tanks and the engines which modulate the propellant flow, are known as "pogo oscillations" or "pogo", named after the pogo stick.

Three different types of combustion instabilities occur:

Chugging

This is a low frequency oscillation at a few Hertz in chamber pressure usually caused by pressure variations in feed lines due to variations in acceleration of the vehicle. This can cause cyclic variation in thrust, and the effects can vary from merely annoying to actually damaging the payload or vehicle. Chugging can be minimised by using gas-filled damping tubes on feed lines of high density propellants.

Buzzing

This can be caused due to insufficient pressure drop across the injectors. It generally is mostly annoying, rather than being damaging. However, in extreme cases combustion can end up being forced backwards through the injectors – this can cause explosions with monopropellants.

Screeching

This is the most immediately damaging, and the hardest to control. It is due to acoustics within the combustion chamber that often couples to the chemical combustion processes that are the primary drivers of the energy release, and can lead to unstable resonant "screeching" that commonly leads to catastrophic failure due to thinning of the insulating thermal boundary layer. Such effects are very difficult to predict analytically during the design process, and have usually been addressed by expensive, time consuming and extensive testing, combined with trial and error remedial correction measures.

Screeching is often dealt with by detailed changes to injectors, or changes in the propellant chemistry, or vaporizing the propellant before injection, or use of Helmholtz dampers within the combustion chambers to change the resonant modes of the chamber.

Testing for the possibility of screeching is sometimes done by exploding small explosive charges outside the combustion chamber with a tube set tangentially to the combustion chamber near the injectors to determine the engine's impulse response and then evaluating the time response of the chamber pressure- a fast recovery indicates a stable system.

Exhaust noise

For all but the very smallest sizes, rocket exhaust compared to other engines is generally very noisy. As the hypersonic exhaust mixes with the ambient air, shock waves are formed. The Space Shuttle generates over 200 dB(A) of noise around its base.

The Saturn V launch was detectable on seismometers a considerable distance from the launch site. The sound intensity from the shock waves generated depends on the size of the rocket and on the exhaust velocity. Such shock waves seem to account for the characteristic crackling and popping sounds produced by large rocket engines when heard live. These noise peaks typically overload microphones and audio electronics, and so are generally weakened or entirely absent in recorded or broadcast audio reproductions. For large rockets at close range, the acoustic effects could actually kill.

More worryingly for space agencies, such sound levels can also damage the launch structure, or worse, be reflected back at the comparatively delicate rocket above. This is why so much water is typically used at launches. The water spray changes the acoustic qualities of the air and reduces or deflects the sound energy away from the rocket.

Generally speaking noise is most intense when a rocket is close to the ground, since the noise from the engines radiates up away from the plume, as well as reflecting off the ground. Also, when the vehicle is moving slowly, little of the chemical energy input to the engine can go into increasing the kinetic energy of the rocket (since useful power P transmitted to the vehicle is $P = F * V$ for thrust F and speed V). Then the largest portion of the energy is dissipated in the exhaust's interaction with the ambient air, producing noise. This noise can be reduced somewhat by flame trenches with roofs, by water injection around the plume and by deflecting the plume at an angle.

Testing

Rocket engines are usually statically tested at a test facility before being put into production. For high altitude engines, either a shorter nozzle must be used, or the rocket must be tested in a large vacuum chamber.

Safety

Rockets have a reputation for unreliability and danger; especially catastrophic failures. Contrary to this reputation, carefully designed rockets can be made arbitrarily reliable. In military use, rockets are not unreliable. However, one of the main non-military uses of rockets is for orbital launch. In this application, the premium is on minimum weight, and it is difficult to achieve high reliability and low weight simultaneously. In addition, if the number of flights launched is low, there is a very high chance of a design, operations or manufacturing error causing destruction of the vehicle. Essentially all launch vehicles are test vehicles by normal aerospace standards (as of 2006).

The X-15 rocket plane achieved a 0.5% failure rate, with a single catastrophic failure during ground test, and the SSME has managed to avoid catastrophic failures in over 350 engine-flights.

Chemistry

Rocket propellants require a high specific energy (energy per unit mass), because ideally all the reaction energy appears as kinetic energy of the exhaust gases, and exhaust velocity is the single most important performance parameter of an engine, on which vehicle performance depends.

Aside from inevitable losses and imperfections in the engine, incomplete combustion, etc., after specific reaction energy, the main theoretical limit reducing the exhaust velocity obtained is that, according to the laws of thermodynamics, a fraction of the chemical energy may go into rotation of the exhaust molecules, where it is unavailable for producing thrust. Monatomic gases like helium have only three degrees of freedom, corresponding to the three dimensions of space, {*x,y,z*}, and only such spherically symmetric molecules escape this kind of loss. A diatomic molecule like H_2 can rotate about either of the two axes perpendicular to the one joining the two atoms, and as the equipartition law of statistical mechanics demands that the available thermal energy be divided equally among the degrees of freedom, for such a gas in thermal equilibrium 3/5 of the energy can go into unidirectional motion, and 2/5 into rotation. A triatomic molecule like water has six degrees of freedom, so the energy is divided equally among rotational and translational degrees of freedom. For most chemical reactions the latter situation is the case. This issue is traditionally described in terms of the ratio, gamma, of the specific heat of the gas at constant volume to that at constant pressure. The rotational energy loss is largely recovered in practice if the expansion nozzle is large enough to allow the gases to expand and cool sufficiently, the function of the nozzle being to convert the random thermal motions of the molecules in the combustion chamber into the unidirectional translation that produces thrust. As long as the exhaust gas remains in equilibrium as it expands, the initial rotational energy will be largely returned to translation in the nozzle.

Although the specific reaction energy per unit mass of reactants is key, low mean molecular weight in the reaction products is also important in practice in determining exhaust velocity. This is because the high gas temperatures in rocket engines pose serious problems for the engineering of survivable motors. Because temperature is proportional to the mean *energy per molecule*, a given amount of energy distributed among more molecules of lower mass permits a higher exhaust velocity at a given temperature. This means low atomic mass elements are favoured. Liquid hydrogen (LH2) and oxygen (LOX, or LO2), are the most effective propellants in terms of exhaust velocity that have been widely used to date, though a few exotic combinations involving boron or liquid ozone are potentially somewhat better in theory if various practical problems could be solved.

It is important to note in computing the specific reaction energy, that the *entire mass of the propellants, including both fuel and oxidizer*, must be included. The fact that air-breathing engines are typically able to obtain oxygen "for free" without having to carry it along, accounts for one factor of why air-breathing engines are very much more propellant-mass efficient, and one reason that rocket engines are far less suitable for most

ordinary terrestrial applications. Fuels for automobile or turbojet engines, utilize atmospheric oxygen and so have a much better effective energy output per unit mass of propellant that must be carried, but are similar per unit mass of fuel.

Computer programs that predict the performance of propellants in rocket engines are available.

Ignition

With liquid and hybrid rockets, immediate ignition of the propellant(s) as they first enter the combustion chamber is essential.

With liquid propellants (but not gaseous), failure to ignite within milliseconds usually causes too much liquid propellant to be within the chamber, and if/when ignition occurs the amount of hot gas created will often exceed the maximum design pressure of the chamber. The pressure vessel will often fail catastrophically. This is sometimes called a *hard start*.

Ignition can be achieved by a number of different methods; a pyrotechnic charge can be used, a plasma torch can be used, or electric spark plugs may be employed. Some fuel/oxidizer combinations ignite on contact (hypergolic), and non-hypergolic fuels can be "chemically ignited" by priming the fuel lines with hypergolic propellants (popular in Russian engines).

Gaseous propellants generally will not cause hard starts, with rockets the total injector area is less than the throat thus the chamber pressure tends to ambient prior to ignition and high pressures cannot form even if the entire chamber is full of flammable gas at ignition.

Solid propellants are usually ignited with one-shot pyrotechnic devices.

Once ignited, rocket chambers are self sustaining and igniters are not needed. Indeed chambers often spontaneously reignite if they are restarted after being shut down for a few seconds. However, when cooled, many rockets cannot be restarted without at least minor maintenance, such as replacement of the pyrotechnic igniter.

Plume physics

Armadillo aerospace's quad vehicle showing visible banding (shock diamonds) in the exhaust plume

Rocket plume varies depending on the rocket engine, design altitude, altitude, thrust and other factors.

Carbon rich exhausts from kerosene fuels are often orange in colour due to the black body radiation of the unburned particles, in addition to the blue Swan bands. Peroxide oxidiser based rockets and hydrogen rocket plumes contain largely steam and are nearly invisible to the naked eye but shine brightly in the ultraviolet and infrared. Plumes from solid rockets can be highly visible as the propellant frequently contains metals such as elemental aluminium which burns with an orange-white flame and adds energy to the combustion process.

Some exhausts, notably alcohol fuelled rockets, can show visible shock diamonds. These are due to cyclic variations in the plume pressure relative to ambient creating shock waves that form 'mach disks'.

The shape of the plume varies from the design altitude, at high altitude all rockets are grossly under-expanded, and a quite small percentage of exhaust gases actually end up expanding forwards.

Types of rocket engines

Physically powered

Type	Description	Advantages	Disadvantages
water rocket	Partially filled pressurised carbonated drinks container with tail and nose weighting	Very simple to build	Altitude typically limited to a few hundred feet or so (world record is 623 meters/2044 feet)
cold gas thruster	A non combusting form, used for vernier thrusters	Non contaminating exhaust	Extremely low performance
hot water rocket	Hot water is stored in a tank at high temperature/pressure and turns to steam in nozzle	Simple, fairly safe, under 200 seconds Isp	Low overall performance due to heavy tank

Chemically powered

Type	Description	Advantages	Disadvantages
Solid rocket	Ignitable, self sustaining solid fuel/oxidiser mixture ("grain") with central hole and nozzle	Simple, often no moving parts, reasonably good mass fraction, reasonable I_{sp}. A thrust schedule can be designed into the grain.	Once lit, extinguishing it is difficult although often possible, cannot be throttled in real time; handling issues from ignitable mixture, lower performance than liquid rockets, if grain cracks it can block nozzle with disastrous results, cracks burn and widen during burn. Refuelling grain harder than simply filling tanks, Lower specific Impulse than Liquid Rockets.
Hybrid rocket	Separate oxidiser/fuel, typically oxidiser is liquid and kept in a tank, the other solid with central hole	Quite simple, solid fuel is essentially inert without oxidiser, safer; cracks do not escalate, throttleable and easy to switch off.	Some oxidisers are monopropellants, can explode in own right; mechanical failure of solid propellant can block nozzle (very rare with rubberised propellant), central hole widens over burn and negatively affects mixture ratio.

Monopropellant rocket	Propellant such as Hydrazine, Hydrogen Peroxide or Nitrous Oxide, flows over catalyst and exothermically decomposes and hot gases are emitted through nozzle	Simple in concept, throttleable, low temperatures in combustion chamber	catalysts can be easily contaminated, monopropellants can detonate if contaminated or provoked, I_{sp} is perhaps 1/3 of best liquids
Liquid Bipropellant rocket	Two fluid (typically liquid) propellants are introduced through injectors into combustion chamber and burnt	Up to ~99% efficient combustion with excellent mixture control, throttleable, can be used with turbopumps which permits incredibly lightweight tanks, can be safe with extreme care	Pumps needed for high performance are expensive to design, huge thermal fluxes across combustion chamber wall can impact reuse, failure modes include major explosions, a lot of plumbing is needed.
Dual mode propulsion rocket	Rocket takes off as a bipropellant rocket, then turns to using just one propellant as a monopropellant	Simplicity and ease of control	Lower performance than bipropellants
Tripropellant rocket	Three different propellants (usually hydrogen, hydrocarbon and liquid oxygen) are introduced into a combustion chamber in variable mixture ratios, or multiple engines are used with fixed propellant mixture ratios and throttled or shut down	Reduces take-off weight, since hydrogen is lighter; combines good thrust to weight with high average I_{sp}, improves payload for launching from Earth by a sizeable percentage	Similar issues to bipropellant, but with more plumbing, more R&D
Air-augmented rocket	Essentially a ramjet where intake air is compressed and burnt with the exhaust from a rocket	Mach 0 to Mach 4.5+ (can also run exoatmospheric), good efficiency at Mach 2 to 4	Similar efficiency to rockets at low speed or exoatmospheric, inlet difficulties, a relatively undeveloped and unexplored type, cooling difficulties, very noisy,

			thrust/weight ratio is similar to ramjets.
Turborocket	A combined cycle turbojet/rocket where an additional oxidizer such as oxygen is added to the airstream to increase maximum altitude	Very close to existing designs, operates in very high altitude, wide range of altitude and airspeed	Atmospheric airspeed limited to same range as turbojet engine, carrying oxidizer like LOX can be dangerous. Much heavier than simple rockets.
Precooled jet engine / LACE (combined cycle with rocket)	Intake air is chilled to very low temperatures at inlet before passing through a ramjet or turbojet engine. Can be combined with a rocket engine for orbital insertion.	Easily tested on ground. High thrust/weight ratios are possible (~14) together with good fuel efficiency over a wide range of airspeeds, mach 0-5.5+; this combination of efficiencies may permit launching to orbit, single stage, or very rapid intercontinental travel.	Exists only at the lab prototyping stage. Examples include RB545, SABRE, ATREX

Electrically powered

Type	Description	Advantages	Disadvantages
Resistojet rocket (electric heating)	A monopropellant is electrically heated by a filament for extra performance	Higher I_{sp} than monopropellant alone, about 40% higher.	Uses a lot of power and hence gives typically low thrust
Arcjet rocket (chemical burning aided by electrical discharge)	Similar to resistojet in concept but with inert propellant, except an arc is used which allows higher temperatures	1600 seconds I_{sp}	Very low thrust and high power, performance is similar to Ion drive.
Pulsed plasma thruster (electric arc heating; emits plasma)	Plasma is used to erode a solid propellant	High I_{sp} , can be pulsed on and off for attitude control	Low energetic efficiency
Variable specific impulse magnetoplasma	Microwave heated plasma with magnetic	Variable I_{sp} from 1000 seconds to 10,000 seconds	similar thrust/weight ratio with ion drives (worse), thermal issues, as with ion

rocket	throat/nozzle		drives very high power requirements for significant thrust, really needs advanced nuclear reactors, never flown, requires low temperatures for superconductors to work

Solar powered

The Solar thermal rocket would make use of solar power to directly heat reaction mass, and therefore does not require an electrical generator as most other forms of solar-powered propulsion do. A solar thermal rocket only has to carry the means of capturing solar energy, such as concentrators and mirrors. The heated propellant is fed through a conventional rocket nozzle to produce thrust. The engine thrust is directly related to the surface area of the solar collector and to the local intensity of the solar radiation and inversely proportional to the I_{sp}.

Type	Description	Advantages	Disadvantages
Solar thermal rocket	Propellant is heated by solar collector	Simple design. Using hydrogen propellant, 900 seconds of I_{sp} is comparable to Nuclear Thermal rocket, without the problems and complexity of controlling a fission reaction. Ability to productively utilize waste gaseous hydrogen—an inevitable byproduct of long-term liquid hydrogen storage in the radiative heat environment of space—for both orbital stationkeeping and attitude control.	Only useful once in space, as thrust is fairly low, but hydrogen has not been traditionally thought to be easily stored in space, otherwise moderate/low I_{sp} if higher–molecular-mass propellants are used. Using higher–molecular-weight propellants, for example water, lowers performance.

Beam powered

Type	Description	Advantages	Disadvantages
light beam powered rocket	Propellant is heated by light beam (often laser) aimed at vehicle from a distance, either directly or	simple in principle, in principle very high exhaust speeds can be achieved	~1 MW of power per kg of payload is needed to achieve orbit, relatively high accelerations, lasers are blocked by clouds, fog, reflected laser light may be dangerous, pretty much needs hydrogen

	indirectly via heat exchanger		monopropellant for good performance which needs heavy tankage, some designs are limited to ~600 seconds due to reemission of light since propellant/heat exchanger gets white hot
microwave beam powered rocket	Propellant is heated by microwave beam aimed at vehicle from a distance	microwaves avoid reemission of energy, so ~900 seconds exhaust speeds might be achieveable	~1 MW of power per kg of payload is needed to achieve orbit, relatively high accelerations, microwaves are absorbed to a degree by rain, reflected microwaves may be dangerous, pretty much needs hydrogen monopropellant for good performance which needs heavy tankage, transmitter diameter is measured in kilometres to achieve a fine enough beam to hit a vehicle at up to 100 km.

Nuclear powered

Nuclear propulsion includes a wide variety of propulsion methods that use some form of nuclear reaction as their primary power source. Various types of nuclear propulsion have been proposed, and some of them tested, for spacecraft applications:

Type	Description	Advantages	Disadvantages
Radioisotope rocket/"Poodle thruster" (radioactive decay energy)	Heat from radioactive decay is used to heat hydrogen	about 700–800 seconds, almost no moving parts	low thrust/weight ratio.
Nuclear thermal rocket (nuclear fission energy)	propellant (typ. hydrogen) is passed through a nuclear reactor to heat to high temperature	I_{sp} can be high, perhaps 900 seconds or more, above unity thrust/weight ratio with some designs	Maximum temperature is limited by materials technology, some radioactive particles can be present in exhaust in some designs, nuclear reactor shielding is heavy, unlikely to be permitted from surface of the Earth, thrust/weight ratio is not high.
Gas core reactor rocket (nuclear fission energy)	Nuclear reaction using a gaseous state fission reactor in	Very hot propellant, not limited by keeping reactor solid, I_{sp}	Difficulties in heating propellant without losing fissionables in exhaust, massive thermal issues

	intimate contact with propellant	between 1500 and 3000 seconds but with very high thrust	particularly for nozzle/throat region, exhaust almost inherently highly radioactive. Nuclear lightbulb variants can contain fissionables, but cut I_{sp} in half.
Fission-fragment rocket (nuclear fission energy)	Fission products are directly exhausted to give thrust		Theoretical only at this point.
Fission sail (nuclear fission energy)	A sail material is coated with fissionable material on one side	No moving parts, works in deep space	Theoretical only at this point.
Nuclear salt-water rocket (nuclear fission energy)	Nuclear salts are held in solution, caused to react at nozzle	Very high I_{sp}, very high thrust	Thermal issues in nozzle, propellant could be unstable, highly radioactive exhaust. Theoretical only at this point.
Nuclear pulse propulsion (exploding fission/fusion bombs)	Shaped nuclear bombs are detonated behind vehicle and blast is caught by a 'pusher plate'	Very high I_{sp}, very high thrust/weight ratio, no show stoppers are known for this technology	Never been tested, pusher plate may throw off fragments due to shock, minimum size for nuclear bombs is still pretty big, expensive at small scales, nuclear treaty issues, fallout when used below Earth's magnetosphere.
Antimatter catalyzed nuclear pulse propulsion (fission and/or fusion energy)	Nuclear pulse propulsion with antimatter assist for smaller bombs	Smaller sized vehicle might be possible	Containment of antimatter, production of antimatter in macroscopic quantities isn't currently feasible. Theoretical only at this point.
Fusion rocket (nuclear fusion energy)	Fusion is used to heat propellant	Very high exhaust velocity	Largely beyond current state of the art.
Antimatter rocket (annihilation energy)	Antimatter annihilation heats propellant	Extremely energetic, very high theoretical exhaust velocity	Problems with antimatter production and handling; energy losses in neutrinos, gamma rays, muons; thermal issues. Theoretical only at this point

History of rocket engines

According to the writings of the Roman Aulus Gellius, in c. 400 BC, a Greek Pythagorean named Archytas, propelled a wooden bird along wires using steam. However, it would not appear to have been powerful enough to take off under its own thrust.

The *aeolipile* described in the first century BC (often known as *Hero's engine*) essentially consists of a steam rocket on a bearing. It was created almost two millennia before the Industrial Revolution but the principles behind it were not well understood, and its full potential was not realized for a millennium.

The availability of black powder to propel projectiles was a precursor to the development of the first solid rocket. Ninth Century Chinese Taoist alchemists discovered black powder in a search for the Elixir of life; this accidental discovery led to fire arrows which were the first rocket engines to leave the ground.

Rocket engines were also brought in use by Tippu Sultan, The king of Mysore. These rockets could be of various sizes, but usually consisted of a tube of soft hammered iron about 8" long and 1½ - 3" diameter, closed at one end and strapped to a shaft of bamboo about 4 ft. long. The iron tube acted as a combustion chamber and contained well packed black powder propellant. A rocket carrying about one pound of powder could travel almost 1,000 yards. These 'rockets', fitted with swords used to travel long distance, several meters above in air before coming down with swords edges facing the enemy. These rockets were used against British empire very effectively.

Slow development of this technology continued up to the later 20th Century, when the writings of Konstantin Tsiolkovsky first talked about liquid fuelled rocket engines.

These independently became a reality thanks to Robert Goddard. Goddard also used a De Laval nozzle for the first time on a rocket, doubling the thrust and multiplying up the efficiency by several times.

During the late 1930s, German scientists, such as Wernher von Braun and Hellmuth Walter, investigated installing liquid-fuelled rockets in military aircraft (Heinkel He 112, He 111, He 176 and Messerschmitt Me 163). The turbopump was first employed by German scientists in WWII. Until then cooling the nozzle was problematic, and the A4 ballistic missile used dilute alcohol for the fuel, which reduced the combustion temperature sufficiently.

Staged combustion (*Замкнутая схема*) was first proposed by Alexey Isaev in 1949. The first staged combustion engine was the S1.5400 used in the Soviet planetary rocket, designed by Melnikov, a former assistant to Isaev. About the same time (1959), Nikolai Kuznetsov began work on the closed cycle engine NK-9 for Korolev's orbital ICBM, GR-1. Kuznetsov later evolved that design into the NK-15 and NK-33 engines for the unsuccessful Lunar N1 rocket.

In the West, the first laboratory staged-combustion test engine was built in Germany in 1963, by Ludwig Boelkow.

Hydrogen peroxide / kerosene fuelled engines such as the British Gamma of the 1950s used a closed-cycle process (arguably not *staged combustion*, but that's mostly a question of semantics) by catalytically decomposing the peroxide to drive turbines *before* combustion with the kerosene in the combustion chamber proper. This gave the efficiency advantages of staged combustion, whilst avoiding the major engineering problems.

Liquid hydrogen engines were first successfully developed in America, the RL-10 engine first flew in 1962. Hydrogen engines were used as part of the Project Apollo; the liquid hydrogen fuel giving a rather lower stage mass and thus reducing the overall size and cost of the vehicle.

Chapter- 3

Reaction Wheel and Control Moment Gyroscope

Reaction wheel

A **reaction wheel** is a type of flywheel used primarily by spacecraft to change their angular momentum without using fuel for rockets or other reaction devices.

Reaction wheels are devices which aim a spacecraft in different directions without firing rockets or jets. They are particularly useful when the spacecraft must be rotated by very small amounts, such as keeping a telescope pointed at a star. They may also reduce the mass fraction needed for fuel. This is accomplished by equipping the spacecraft with an electric motor attached to a flywheel, which when rotated increasingly fast causes the spacecraft to spin the other way in a proportional amount by conservation of angular momentum. Reaction wheels can only rotate the spacecraft around its center of mass, they are not capable of moving the spacecraft from one place to another. Reaction wheels work around a nominal zero rotation speed. However, external torques on the spacecraft may require a gradual buildup of reaction wheel rotation speed to maintain the spacecraft in a fixed orientation.

Momentum wheels (used in the Hubble Space Telescope) are a different type of actuator, mainly used for gyroscopic stabilization of spacecraft: momentum wheels have high rotation speeds (around 6000 rpm) and mass.

Implementation

Reaction wheels are usually implemented as special electric motors. Changes in speed rate (in either direction) are controlled electronically by computer controls. The strength of the materials of a reaction wheel determines the speed at which the wheel would come apart, and therefore how much angular momentum it can store.

Since the reaction wheel is a small fraction of the spacecraft's total mass, easily-measurable changes in its speed provide very precise changes in angle. It therefore permits very precise changes in a spacecraft's attitude. For this reason, reaction wheels are often used to aim spacecraft with cameras or telescopes.

Over time reaction wheels may build up stored momentum that needs to be cancelled. Designers therefore supplement reaction wheel systems with other attitude control mechanisms. In the presence of a magnetic field (as in low Earth orbit), a spacecraft can employ magnetorquers (better known as torque rods) to transfer angular momentum to the Earth through its magnetic field. In the absence of a magnetic field, the most efficient practice is to use high-efficiency attitude jets such as ion thrusters, or small, lightweight solar sails on the ends of projecting masts or solar cell arrays. Most spacecraft, however, also need fast pointing, and cannot afford the extra mass of three attitude control systems. Designers therefore usually use conventional monopropellant vernier engines to cancel reaction wheels, as well as for fast pointing.

Control moment gyroscope

A **control momentum gyroscope** (CMG) is an attitude control device generally used in spacecraft attitude control systems. A CMG consists of a spinning rotor and one or more motorized gimbals that tilt the rotor's angular momentum. As the rotor tilts, the changing angular momentum causes a gyroscopic torque that rotates the spacecraft.

Mechanics

CMGs differ from reaction wheels. The latter applies torque simply by changing rotor spin speed, but the former tilts the rotor's spin axis without necessarily changing its spin speed. CMGs are also far more power efficient. For a few hundred watts and about 100 kg of mass, large CMGs have produced thousands of newton meters of torque. A reaction wheel of similar capability would require megawatts of power.

Design varieties

Single-gimbal

The most effective CMGs include only a single gimbal. When the gimbal of such a CMG rotates, the change in direction of the rotor's angular momentum represents a torque that reacts onto the body to which the CMG is mounted, e.g. a spacecraft. Except for effects due to the motion of the spacecraft, this torque is due to a constraint, so it does no mechanical work (i.e. requires no energy). Single-Gimbal CMGs exchange angular momentum in a way that requires very little power, with the result that they can apply very large torques for minimal electrical input.

Dual-gimbal

Such a CMG includes two gimbals per rotor. As an actuator it is more versatile than a single-gimbal CMG because it is capable of pointing the rotor's momentum vector in any direction. However, the torque caused by one gimbal's motion often must be reacted by the other gimbal on its way to the spacecraft, requiring more power for a given torque than a single-gimbal CMG. If the goal is simply to store momentum in a mass-efficient way, as in the case of the International Space Station, dual-gimbal CMGs are a good design choice. Instead, if a spacecraft requires large output torque per available input power, single-gimbal CMGs are a better choice.

Variable-speed

Most CMGs hold the rotor speed constant. Some academic research has focused on the possibility of spinning up and down the rotor as the CMG gimbals. These so-called variable-speed CMGs (VSCMGs) offer few practical advantages, mostly because the output torque from the rotor is likely orders of magnitude smaller than that caused by the gimbal motion. So, this effect adds nothing of practical value on the time scale of the motion typical of CMGs. However, thanks to the additional degree of freedom, the variable-speed CMG can be used to avoid the geometric singularity that is the most serious drawback of the conventional CMG. The VSCMG also can be used as a mechanical battery to store electric energy as kinetic energy of the flywheels.

Singularities

At least three single-axis CMGs are necessary for control of spacecraft attitude. However, no matter how many CMGs a spacecraft uses, gimbal motion can lead to relative orientations that produce no usable output torque along certain directions. These orientations are known as "singularities" and are related to the kinematics of robotic systems that encounter limits on the end-effector velocities due to certain joint alignments. Avoiding these singularities is naturally of great interest, and several techniques have been proposed. David Bailey and others have argued (in patents and in academic publications) that merely avoiding the "divide by zero" error that is associated with these singularities is sufficient. Two more recent patents summarize competing approaches.

International Space Station

NASA personnel handle a single Control Moment Gyroscope for the International Space Station.

The ISS employs a total of four CMGs as primary actuating devices during normal flight mode operation. The objective of the CMG flight control system is to hold the space station at a fixed attitude relative to the surface of the Earth. In addition, it seeks a Torque Equilibrium Attitude (TEA), in which the combined torque contribution of gravity gradient, atmospheric drag, solar pressure, and geomagnetic interactions are minimized. In the presence of these continual environmental disturbances CMGs absorb momentum in an attempt to maintain the space station at a desired attitude. The CMGs may eventually saturate (absorbing momentum to the point where they can absorb no more), resulting in loss of effectiveness of the CMG array for control. Some kind of momentum management scheme (MMS) is necessary to allow the CMGs to hold a desired attitude and at the same time prevent CMG saturation. Since the CMGs are momentum-exchange devices, external control torques must be used to desaturate the CMGs, that is, bring the momentum back to nominal value. Some methods for unloading CMG momentum include the use of magnetic torques, reaction thrusters, and gravity gradient torque. For the space station, the gravity gradient torque approach is preferred because it requires no consumables or external hardware and because the gravity-gradient torque on the ISS can be very high.

Chapter- 4

Solar Sail
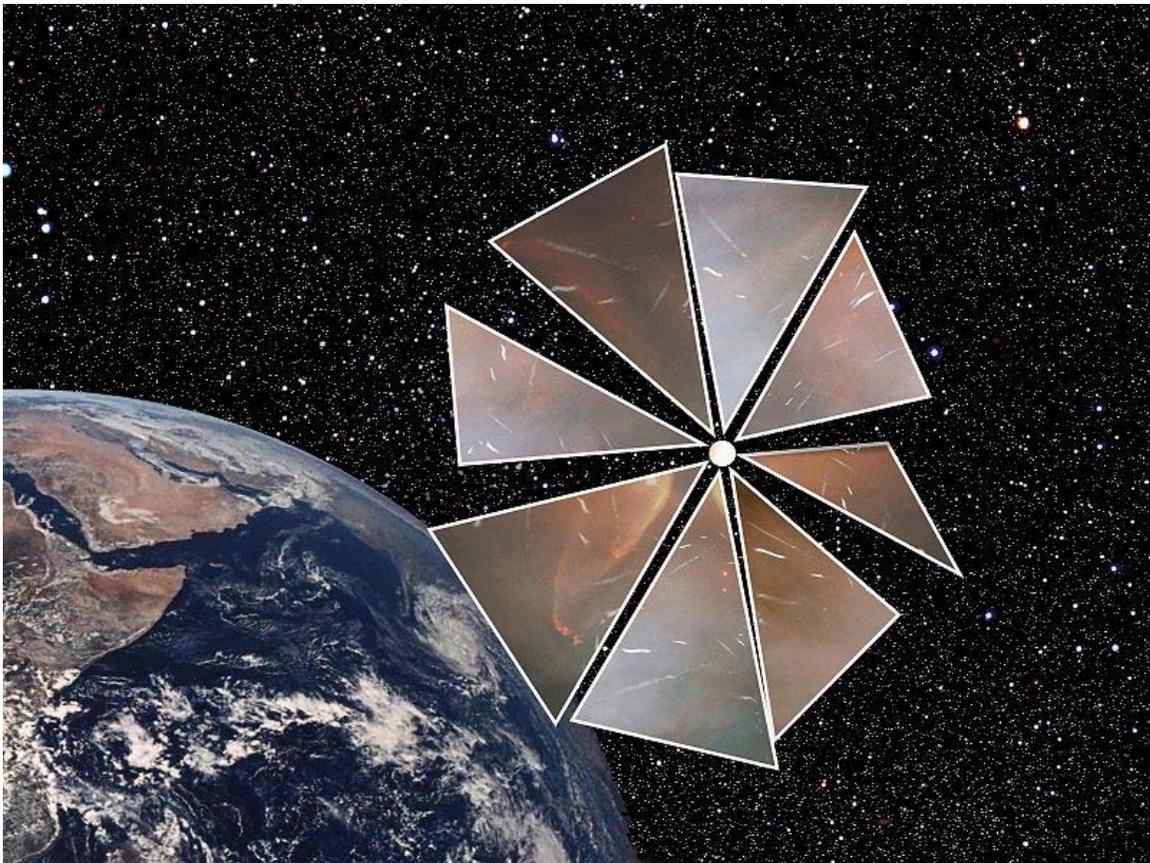
An artist's depiction of a Cosmos 1 type spaceship in orbit

Solar sails (also called **light sails** or **photon sails**) are a form of spacecraft propulsion using the radiation pressure of light from a star or laser to push enormous ultra-thin mirrors to high speeds.

In 2010, IKAROS was the world's first spacecraft designed to use solar sailing propulsion to be successfully launched.

Physics

There are two sources of solar forces. The first is radiation pressure, and the second is due to solar wind. The radiation pressure is much stronger than the wind pressure. In 1924, the Russian space engineer Friedrich Zander proposed that, since light provides a small amount of thrust, this effect could be used as a form of space propulsion requiring no fuel. Einstein proposed – and experiments confirm – that photons have a momentum $p=E/c$, hence each light photon absorbed by or reflecting from a surface exerts a small amount of radiation pressure. This results in forces of about 4.57×10^{-6} N/m^2 for absorbing surfaces perpendicular to the radiation in earth orbit, and twice as much, if the radiation is reflected. This was proven experimentally by Russian physicist Peter Lebedev in 1900, and independently by Nichols and Hull at Dartmouth in 1901 using a Nichols radiometer.

Charged particles from the solar wind are able to knock out power grids on Earth, and point the tails of comets away from the sun. The solar wind averages 6.7 billion tons per hour at 520 km/s with "slow" low energy coronal ejections reaching 400 km/s and "fast" higher energy ejections averaging 750 km/s. At the distance of the earth, this results in average solar wind pressure of 3.4×10^{-9} N/m^2, three orders of magnitude less than the photonic radiation pressure. Still the solar wind dominates many phenomena because its interaction cross section with gases and charged particles is about 10^9 times larger than that of the photons.

Both of these forces are small and decrease with the inverse square distance from the sun. Even large sails produce minute acceleration, but over time, sails can build up considerable speeds. Because the force on the sails and the force of gravity from the sun both vary as inverse square functions, solar sail vessels can be rated by the ratio of the sail's force divided by the gravitational force. Solar sail vessels with the same rating are able to follow the same trajectories.

Changing course trajectories can be accomplished in two ways. First, tilting the sail with respect to the light source changes the direction of acceleration because the force on a sail from reflected radiation and wind acts in a direction perpendicular to its surface. Smaller auxiliary vanes can be used to gently pull the main sail into its new position. Second, gravity from a nearby mass, such as a star or planet, will alter the direction of a spaceship. When orbiting a star or planet, sails can be used to slow down and spiral inward, or to increase the velocity and spiral outward. If the planet has moons or the star has planets, these techniques can be used to achieve slingshots around these bodies.

Fly modes

Escaping planetary orbit

Sails orbit, and therefore do not need to hover or move directly toward or away from the sun. Almost all missions would use the sail to change orbit, rather than thrusting directly away from a planet or the sun. The sail is rotated slowly as the sail orbits around a planet

so the thrust is in the direction of the orbital movement to move to a higher orbit or against it to move to a lower orbit. When an orbit is far enough away from a planet, the sail then begins similar maneuvers in orbit around the sun.

Beam propelled

Most theoretical studies of interstellar missions with a solar sail plan to push the sail with a very large laser beam-powered propulsion direct impulse beam. The thrust vector (spatial vector) would therefore be away from the Sun and toward the target.

In theory a lightsail driven by a laser or other beam from Earth can be used to slow down a spacecraft approaching a distant star or planet, by detaching part of the sail and using it to focus the beam on the forward-facing surface of the rest of the sail. In practice, however, most of the slowing would happen while the two parts are at a great distance from each other, and that means that, to do that focusing, it would be necessary to give the detached part an accurate optical shape and orientation. This solution is also limited because the lasers used to accelerate or decelerate a sail ship could take years, decades, or centuries to reach the craft, depending on the distance.

Limitations of solar sails

Solar sails do not work well, if at all, in low Earth orbit below about 800 km altitude due to erosion or air drag. Above that altitude they give very small accelerations that take months to build up to useful speeds. Solar sails have to be physically large, and payload size is often small. Deploying solar sails is also highly challenging to date.

Investigated sail designs
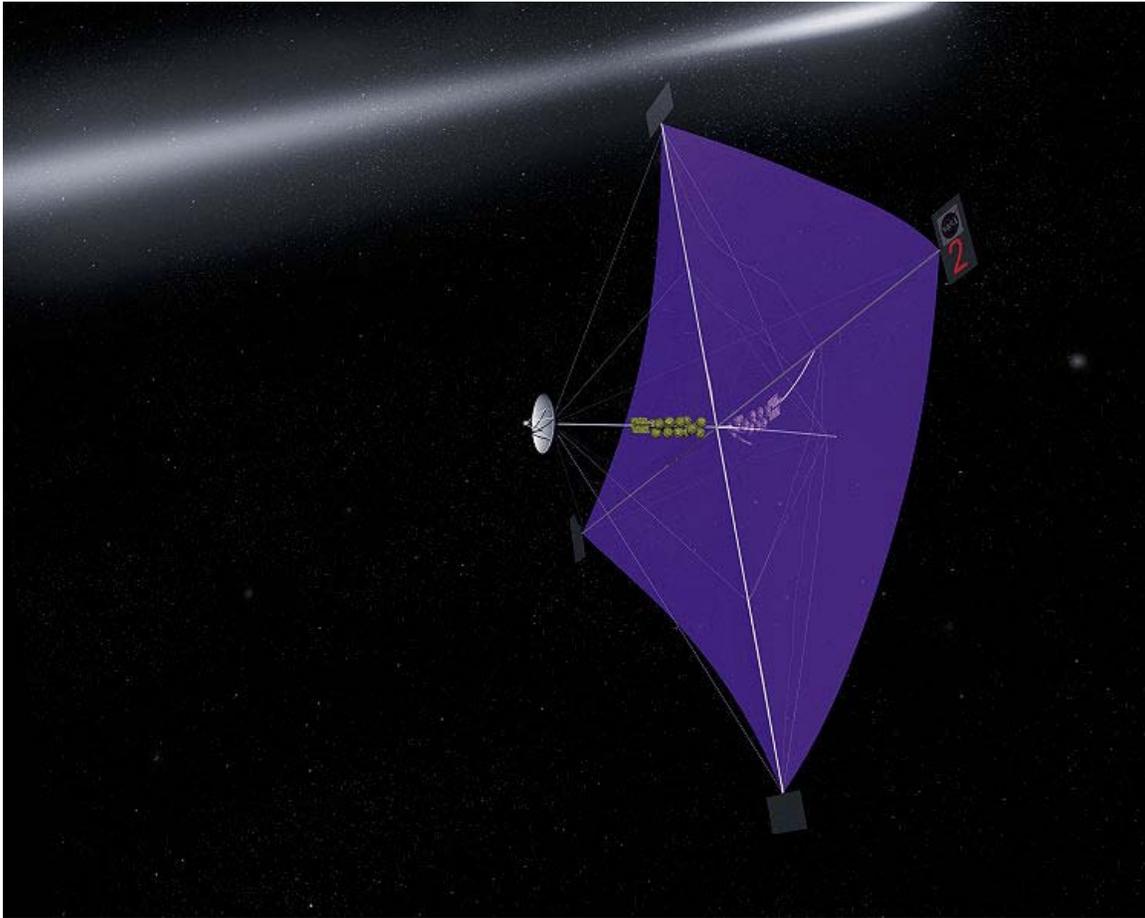
NASA study of a solar sail. The sail would be half a kilometre wide.

"Parachutes" would have very low mass, but theoretical studies show that they will collapse from the forces placed by shrouds. Radiation pressure does not behave like aerodynamic pressure.

The highest thrust-to-mass designs known (2007) were theoretical designs developed by Eric Drexler. He designed a sail using reflective panels of thin aluminium film (30 to 100 nanometres thick) supported by a purely tensile structure. It rotated and would have to be continually under slight thrust. He made and handled samples of the film in the laboratory, but the material is too delicate to survive folding, launch, and deployment, hence the design relied on space-based production of the film panels, joining them to a deployable tension structure. Sails in this class would offer area per unit mass and hence accelerations up to "fifty times higher" than designs based on deployable plastic films.

The highest-thrust to mass designs for ground-assembled deployable structures are square sails with the masts and guy lines on the dark side of the sail. Usually there are four masts that spread the corners of the sail, and a mast in the center to hold guy-wires. One of the largest advantages is that there are no hot spots in the rigging from wrinkling or bagging,

and the sail protects the structure from the sun. This form can therefore go quite close to the sun, where the maximum thrust is present. Control would probably use small sails on the ends of the spars.

Square Sail (not to scale)　　**Heliogyro (not to scale)**　　**Spinning Disk Sail (not to scale)**
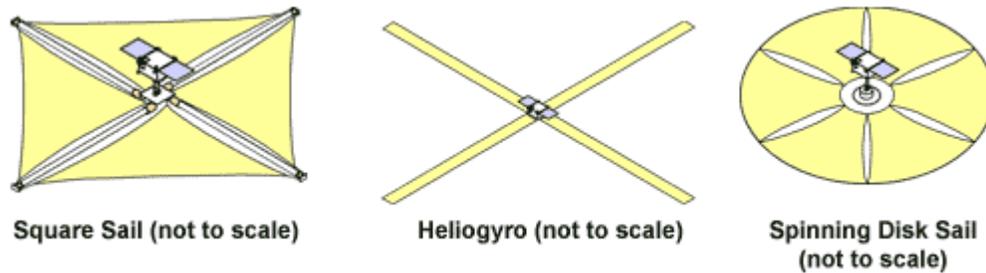
In the 1970s JPL did extensive studies of rotating blade and rotating ring sails for a mission to rendezvous with Halley's Comet. The intention was that such structures would be stiffened by their angular momentum, eliminating the need for struts, and saving mass. In all cases, surprisingly large amounts of tensile strength were needed to cope with dynamic loads. Weaker sails would ripple or oscillate when the sail's attitude changed, and the oscillations would add and cause structural failure. So the difference in the thrust-to-mass ratio was almost nil, and the static designs were much easier to control.

JPL's reference design was called the "heliogyro" and had plastic-film blades deployed from rollers and held out by centrifugal forces as it rotated. The spacecraft's attitude and direction were to be completely controlled by changing the angle of the blades in various ways, similar to the cyclic and collective pitch of a helicopter. Although the design had no mass advantage over a square sail, it remained attractive because the method of deploying the sail was simpler than a strut-based design.

JPL also investigated "ring sails" (Spinning Disk Sail in the above diagram), panels attached to the edge of a rotating spacecraft. The panels would have slight gaps, about one to five percent of the total area. Lines would connect the edge of one sail to the other. Masses in the middles of these lines would pull the sails taut against the coning caused by the radiation pressure. JPL researchers said that this might be an attractive sail design for large manned structures. The inner ring, in particular, might be made to have artificial gravity roughly equal to the gravity on the surface of Mars.

A solar sail can serve a dual function as a high-gain antenna. Designs differ, but most modify the metallization pattern to create a holographic monochromatic lens or mirror in the radio frequencies of interest, including visible light.

Pekka Janhunen from FMI has invented a type of solar sail called the electric solar wind sail. Mechanically it has little in common with the traditional solar sail design, because the sails are substituted with straightened conducting tethers (wires) which are placed radially around the host ship. The wires are electrically charged and thus an electric field is created around the wires. The electric field of the wires extends a few tens of metres into the surrounding solar wind plasma. Because the solar wind electrons react on the

electric field (similarly to the photons on a traditional solar sail), the functional radius of the wires is based on the electric field that is generated around the wire rather than the actual wire itself. This fact also makes it possible to maneuver a ship with an electric solar wind sail by regulating the electric charge of the wires. A full-sized operational electric solar wind sail would have 50-100 straightened wires with a length of about 20 km each.

A quite similar concept is the Magnetic sail, which would also employ the solar wind, but interact with the magnetic charge of the particles in the wind, rather than the electric. Typically it is also constructed with wires as "sails", but in contrast to a electric sail, it uses wire **loops**, and runs a static current through them instead of applying a static voltage.

Both designs have limited ability to direct the thrust, compared to a traditional solar sail, which can thrust sideways by angling the mirror relative to the light source.

Sail testing in space
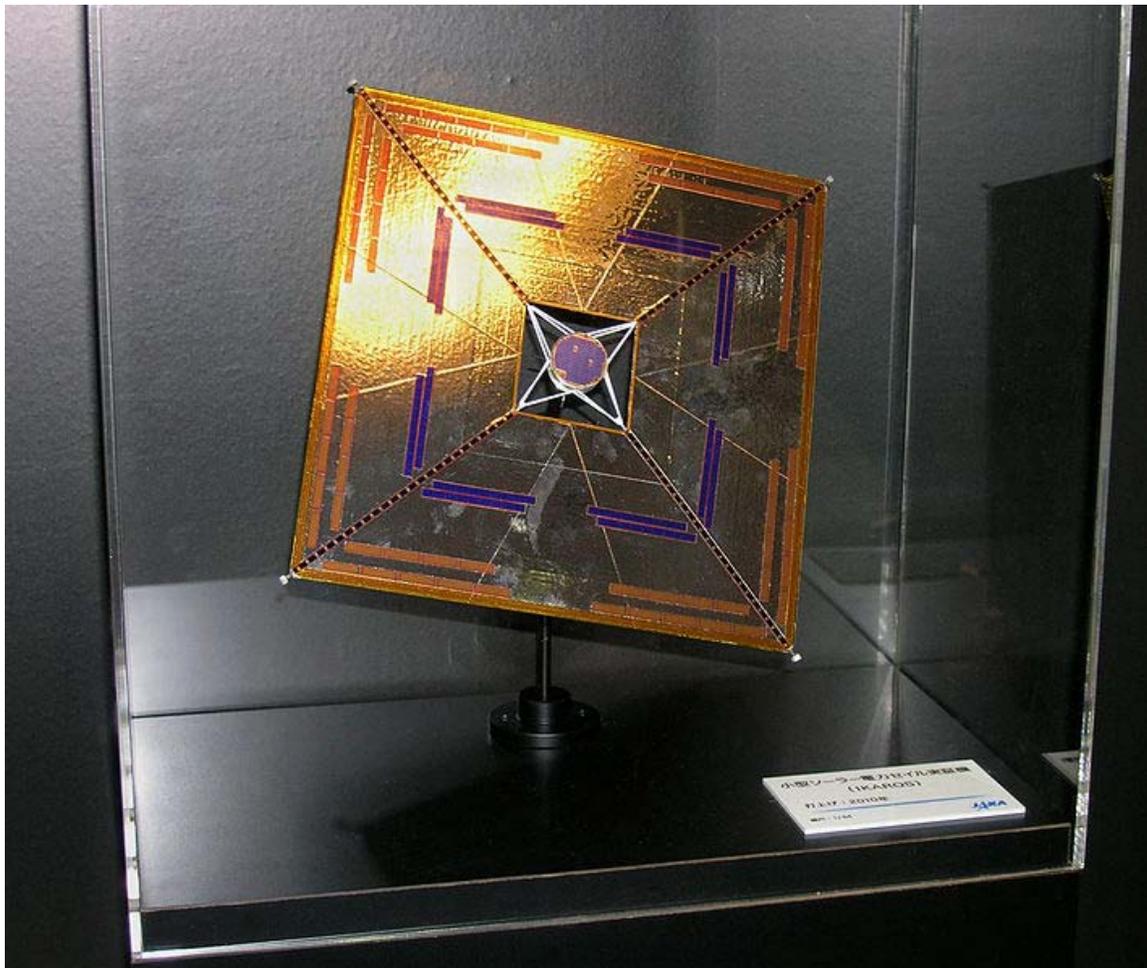
The model of IKAROS at the 61st International Astronautical Congress in 2010

Until 2010, no solar sails had been successfully used in space as primary propulsion systems. On 21 May 2010, the Japan Aerospace Exploration Agency (JAXA) launched

the "IKAROS" (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) spacecraft, which deployed a 200 m^2 polyimide experimental solar sail on June 10. In July, the next phase for the demonstration of acceleration by radiation began. On 9 July, it was verified that IKAROS collected radiation from the sun and began photon acceleration by the orbit determination of IKAROS by range-and-range-rate (RARR) that is newly calculated in addition to the data of the relativization accelerating speed of IKAROS between IKAROS and the Earth that has been taken since before the Doppler effect was utilized. The data showed that IKAROS appears to have been solar-sailing since 3 June when it deployed the sail.

IKAROS has a diagonal spinning square sail 20 m (66 ft) made of a 7.5-micrometre (0.30-mil) thick sheet of polyimide. A thin-film solar array is embedded in the sail. Eight LCD panels are embedded in the sail, whose reflectance can be adjusted for attitude control. IKAROS will spend six months traveling to Venus, and then will begin a three-year journey to the far side of the Sun.

Solar pressure demonstrated for attitude control

Both the Mariner 10 mission, which flew by the planets Mercury and Venus, and the MESSENGER mission to Mercury demonstrated the use of solar pressure as a method of attitude control in order to conserve attitude-control propellant.

Hayabusa also used solar pressure as a method of attitude control to compensate for broken reaction wheels and chemical thruster.

Solar sail deployment tests

Full-scale (20mx20m) deployment test by DLR/ESA in 1999

NASA has successfully tested deployment technologies on small scale sails in vacuum chambers.

On February 4, 1993, Znamya 2, a 20-meter wide aluminized-mylar reflector, was successfully tested from the Russian Mir space station. Although the deployment test was successful, the experiment only demonstrated the deployment, not propulsion. A second test, Znamaya 2.5, failed to deploy properly.

In 1999, a full-scale deployment test of a solar sail has been performed on ground at DLR/ESA in Cologne.

On August 9, 2004, the Japanese ISAS successfully deployed two prototype solar sails from a sounding rocket. A clover type sail was deployed at 122 km altitude and a fan type sail was deployed at 169 km altitude. Both sails used 7.5 micrometer thick film. The experiment was purely a test of the deployment mechanisms, not of propulsion.

Partially successful solar sail propulsion tests
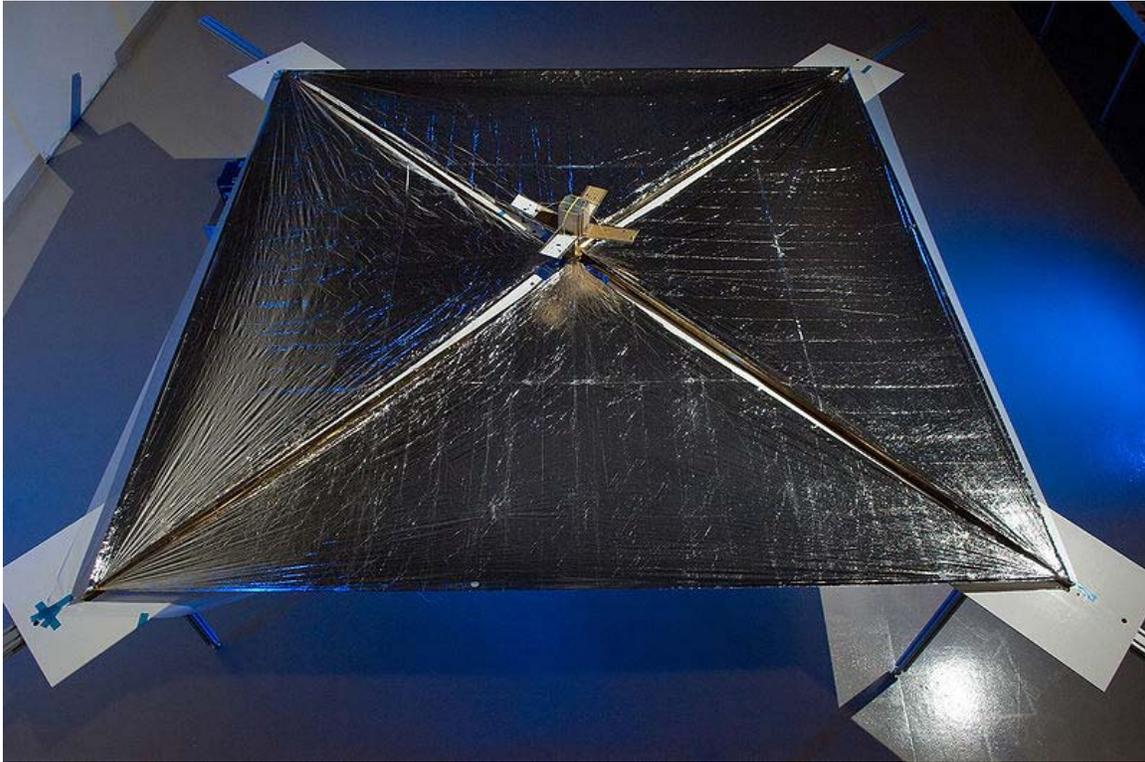
NanoSail-D of LightSail-1 with sail deployed

A joint private project between Planetary Society, Cosmos Studios and Russian Academy of Science launched *Cosmos 1* on June 21, 2005, from a submarine in the Barents Sea, but the Volna rocket failed, and the spacecraft failed to reach orbit. A solar sail would have been used to gradually raise the spacecraft to a higher earth orbit. The mission would have lasted for one month. A suborbital prototype test by the group failed in 2001 as well, also because of rocket failure. The same group announced plans on Carl Sagan's 75th birthday (November 9, 2009) to make three further attempts, dubbed LightSail-1, -2, and -3. The new design will use a 32-square-meter Mylar sail, deployed in four triangular segments like NanoSail-D. The launch configuration is that of three adjacent CubeSats, and is scheduled to launch on a Minotaur IV rocket in Q4 2010.

A 15-meter-diameter solar sail (SSP, solar sail sub payload, *soraseiru sabupeiro-do*) was launched together with ASTRO-F on a M-V rocket on February 21, 2006, and made it to orbit. It deployed from the stage, but opened incompletely.

A team from the NASA Marshall Space Flight Center (Marshall), along with a team from the NASA Ames Research Center, developed a solar sail mission called **NanoSail-D** which was lost in a launch failure aboard a Falcon 1 rocket on 3 August 2008. The second backup version will be launched with FASTSAT on a Minotaur IV on November 19, 2010. The primary objective of the mission is to test sail deployment technologies. The spacecraft might not have returned useful data about solar sail propulsion, according

to Edward E. Montgomery, technology manager of Solar Sail Propulsion at Marshall, "The orbit available to us in this launch opportunity is so low, it may not allow us to stay in orbit long enough for solar pressure effects to accumulate to a measurable degree." The NanoSail-D structure was made of aluminium and plastic, with the spacecraft massing less than 10 pounds (4.5 kg). The sail has about 100 square feet (9.3 m^2) of light-catching surface.

Future solar sail propulsion tests

A team from the Surrey Space Centre at the University of Surrey are developing a solar sail demonstration mission called the "CubeSail". This mission is due to launch in late 2011. The CubeSail is based on the CubeSat standard and when stowed it will occupy a 3U standard volume (3, 100mm x 100mm x 100mm). When in orbit, it will extend four 3.6m booms, deploying a sail of 25m^2. The mission's primary objective is to demonstrate deployment of a solar sail and the concept of solar sailing. Finally and at its end-of-life it will use its sail to change its ballistic coefficient and reenter the Earth's atmosphere. This final phase of the mission has attracted much media attention as it has the potential to be used on board larger spacecraft as a de-orbiting device and potentially to solve the Space debris problem.

Sail materials

NASA engineer Les Johnson views interstellar sail material

The material developed for the Drexler solar sail was a thin aluminum film with a baseline thickness of 0.1 micrometres, to be fabricated by vapor deposition in a space-based system. Drexler used a similar process to prepare films on the ground. As anticipated, these films demonstrated adequate strength and robustness for handling in the laboratory and for use in space, but not for folding, launch, and deployment.

The most common material in current designs is aluminized 2 μm Kapton film. It resists the heat of a pass close to the Sun and still remains reasonably strong. The aluminium reflecting film is on the Sun side. The sails of *Cosmos 1* were made of aluminized PET film (Mylar).

Research by Dr. Geoffrey Landis in 1998-9, funded by the NASA Institute for Advanced Concepts, showed that various materials such as alumina for laser lightsails and carbon fiber for microwave pushed lightsails were superior sail materials to the previously standard aluminium or Kapton films.

In 2000, Energy Science Laboratories developed a new carbon fiber material which might be useful for solar sails. The material is over 200 times thicker than conventional solar sail designs, but it is so porous that it has the same mass. The rigidity and durability of this material could make solar sails that are significantly sturdier than plastic films. The material could self-deploy and should withstand higher temperatures.

There has been some theoretical speculation about using molecular manufacturing techniques to create advanced, strong, hyper-light sail material, based on nanotube mesh weaves, where the weave "spaces" are less than half the wavelength of light impinging on the sail. While such materials have so far only been produced in laboratory conditions, and the means for manufacturing such material on an industrial scale are not yet available, such materials could mass less than 0.1 g/m², making them lighter than any current sail material by a factor of at least 30. For comparison, 5 micrometre thick Mylar sail material mass 7 g/m², aluminized Kapton films have a mass as much as 12 g/m², and Energy Science Laboratories' new carbon fiber material masses 3 g/m².

Applications

Satellites

Robert L. Forward pointed out that a solar sail could be used to modify the orbit of a satellite around the Earth. In the limit, a sail could be used to "hover" a satellite above one pole of the Earth. Spacecraft fitted with solar sails could also be placed in close orbits about the Sun that are stationary with respect to either the Sun or the Earth, a type of satellite named by Forward a statite. This is possible because the propulsion provided by the sail offsets the gravitational potential of the Sun. Such an orbit could be useful for studying the properties of the Sun over long durations.

Such a spacecraft could conceivably be placed directly over a pole of the Sun, and remain at that station for lengthy durations. Likewise a solar sail-equipped spacecraft could also

remain on station nearly above the polar terminator of a planet such as the Earth by tilting the sail at the appropriate angle needed to just counteract the planet's gravity.

In his book, The Case for Mars, Robert Zubrin points out that the reflected sunlight from a large statite placed near the polar terminator of the planet Mars could be focussed on one of the Martian polar ice caps to significantly warm the planet's atmosphere. Such a statite could be made from asteroid material.

Trajectory corrections

The MESSENGER probe en route to Mercury is using light pressure reacting against its solar panels to perform fine trajectory corrections. By changing the angle of the solar panels relative to the sun, the amount of solar radiation pressure can be varied to adjust the spacecraft trajectory more delicately than is possible with thrusters. Minor errors are greatly amplified by gravity assist maneuvers, so very small corrections before lead to large savings in propellant afterward.

Interstellar flight

In the 1980s, Robert Forward proposed two beam-powered propulsion schemes using either lasers or masers to push giant sails to a significant fraction of the speed of light.

In *The Flight of the Dragonfly*, Forward described a light sail propelled by superlasers. As the starship neared its destination, the outer portion of the sail would detach. The outer sail would then refocus and reflect the lasers back onto a smaller, inner sail. This would provide braking thrust to stop the ship in the destination star system.

Both methods pose monumental engineering challenges. The lasers would have to operate for years continuously at gigawatt strength. Second, they would demand more energy than the Earth currently consumes. Third, Forward's own solution to the electrical problem requires enormous solar panel arrays to be built at or near the planet Mercury. Fourth, a planet-sized mirror or fresnel lens would be needed several dozen astronomical units from the Sun to keep the lasers focused on the sail. Fifth, the giant braking sail would have to act as a precision mirror to focus the braking beam onto the inner "deceleration" sail.

A potentially easier approach would be to use a maser to drive a "solar sail" composed of a mesh of wires with the same spacing as the wavelength of the microwaves, since the manipulation of microwave radiation is somewhat easier than the manipulation of visible light. The hypothetical "Starwisp" interstellar probe design would use a maser to drive it. Masers spread out more rapidly than optical lasers owing to their longer wavelength, and so would not have as long an effective range.

Masers could also be used to power a painted solar sail, a conventional sail coated with a layer of chemicals designed to evaporate when struck by microwave radiation. The

momentum generated by this evaporation could significantly increase the thrust generated by solar sails, as a form of lightweight ablative laser propulsion.

To further focus the energy on a distant solar sail, designs have considered the use of a large zone plate. This would be placed at a location between the laser or maser and the spacecraft. The plate could then be propelled outward using the same energy source, thus maintaining its position so as to focus the energy on the solar sail.

Additionally, it has been theorized by da Vinci Project contributor T. Pesando that solar sail-utilizing spacecraft successful in interstellar travel could be used to carry their own zone plates or perhaps even masers to be deployed during flybys at nearby stars. Such an endeavor could allow future solar-sailed craft to effectively utilize focused energy from other stars rather than from the Earth or Sun, thus propelling them more swiftly through space and perhaps even to more distant stars. However, the potential of such a theory remains uncertain if not dubious due to the high-speed precision involved and possible payloads required.

Another more physically realistic approach would be to use the light from the home star to accelerate. The ship would first orbit continuously away around the home star until the appropriate starting velocity is reached, then the ship would begin its trip away from the system using the light from the star to keep accelerating. Beyond some distance, the ship would no longer receive enough light to accelerate it significantly, but would maintain its course due to inertia. When nearing the target star, the ship could turn its sails toward it and begin to orbit inward to decelerate. Additional forward and reverse thrust could be achieved with more conventional means of propulsion such as rockets.

Future approaches

Despite the losses of *Cosmos 1* and NanoSail-D (which were due to failure of their launchers), scientists and engineers around the world remain encouraged and continue to work on solar sails. While most direct applications created so far intend to use the sails as inexpensive modes of cargo transport, some scientists are investigating the possibility of using solar sails as a means of transporting humans. This goal is strongly related to the management of very large (i.e. well above 1 km²) surfaces in space and the sail making advancements. Thus, in the near/medium term, solar sail propulsion is aimed chiefly at accomplishing a very high number of non-crewed missions in any part of the solar system and beyond.

Solar sail launching projects in 2010 and 2011

On 21 May 2010, Japan Aerospace Exploration Agency (Jaxa) launched the world's first interplanetary solar sail spacecraft "IKAROS" (*Interplanetary Kite-craft Accelerated by Radiation Of the Sun*) to Venus. NASA launched the second NanoSail-D unit stowed inside the FASTSAT satellite on the Minotaur IV on November 19, 2010. The ejection date from the FASTSAT microsatellite was planned for December 6, 2010 but

deployment only occurred on January 20, 2011. The Planetary Society of the United States plans to launch an artificial satellite "LightSail-1" onto the Earth's orbit in 2011.

Mathematical survey

The Extended Heliocentric Reference Frame

- In the 1991-92 the classical equations of solar sail motion in the solar gravitational field were written using a different mathematical formalism, namely, *the lightness vector* fully characterizing the sailcraft dynamics. In addition, a solar-sail spacecraft has been supposed to be able to reverse its motion (in the solar system) provided that its sail is sufficiently light that *sailcraft sail loading* (σ) is not higher than 2.1 g/m². This value entails a very high-performance technology, but probably within the capabilities of emerging technologies.
- For describing the concept of fast sailing and some related items, we need to define two frames of reference. The first is an inertial Cartesian coordinate system centred on the Sun or a heliocentric inertial frame (HIF, for short). For instance, the plane of reference, or the XY plane, of HIF can be the mean ecliptic at some standard epoch such as J2000. The second Cartesian reference frame is the so-called heliocentric orbital frame (HOF, for short) with the origin in the sailcraft barycenter. The x-axis of HOF is the direction of the Sun-to-sailcraft vector, or position vector, the z-axis is along the sailcraft orbital angular momentum, whereas the y-axis completes the counterclockwise triad. Such a definition can be extended to sailcraft trajectories, including both counterclockwise and clockwise arcs of motion, in such a way that HOF is always a continuous positively-oriented triad. The sail orientation unit vector (defined in sailcraft), say, **n** can be specified in HOF by a pair of angles, e.g. the azimuth α and the elevation δ. Elevation is the angle that **n** forms with the xy-plane of HOF (-90° $\leq \delta \leq$ 90°). Azimuth is the angle that the projection of **n** onto the HOF xy-plane forms with the HOF x-axis (0 $\leq \alpha <$ 360 °). In HOF, azimuth and elevation are equivalent to longitude and latitude, respectively.

- The sailcraft lightness vector $\mathbf{L} = [\lambda_r , \lambda_t , \lambda_n]$ depends on α and δ (non-linearly) and the thermo-optical parameters of the sail materials (linearly). Neglecting a small contribution coming from the aberration of light, one has the following particular cases (irrespective of the sail material):

1. $\alpha = 0$, $\delta = 0 \Leftrightarrow [\lambda_r , 0 , 0] \Leftrightarrow \lambda=|\mathbf{L}|=\lambda_r$
2. $\alpha \neq 0$, $\delta = 0 \Leftrightarrow [\lambda_r , \lambda_t , 0]$
3. $\alpha = 0$, $\delta \neq 0 \Leftrightarrow [\lambda_r , 0 , \lambda_n]$

A flight example

Conventional strategy

- Suppose a sailcraft is built with an all-metal sail of aluminium and chromium such that σ = 2 g/m². A launcher delivers the (packed) sailcraft at some million kilometers from the Earth. There, the whole sailcraft is deployed and begins its flight in the solar system (here, for the sake of simplicity, any gravitational perturbation from planets is neglected). A conventional spacecraft would move approximately in a circular orbit at about 1 AU from the Sun. In contrast, a sailcraft like this one is sufficiently light to be able to escape the solar system or to point to some distant object in the heliosphere. If the direction that sail's surface faces, represented by surface normal vector **n**, is parallel to the local sun-light direction (i.e. the sail faces toward the sun), then $\lambda_r = \lambda = 0.725$ (i.e. $1/2 < \lambda < 1$); as a result, this sailcraft moves on a hyperbolic orbit. Its speed *at infinity* is equal to 20 km/s. Strictly speaking, this potential solar sail mission would be faster than the current record speed for missions beyond the planetary range, that of Voyager 1, which is 17 km/s or about 3.6 AU/yr (1 AU/yr = 4.7404 km/s). However, three kilometers per second are not meaningful in the context of very deep space missions.
- As a consequence, one has to resort to some **L** having more than one component different from zero. The classical way to gain speed is to tilt the sail at some suitable *positive* α. If α= +21°, then the sailcraft begins by accelerating; after about two months, it achieves 32 km/s. However, this is a speed peak inasmuch as its subsequent motion is characterized by a monotonic speed decrease towards an asymptotic value, or the cruise speed, of 26 km/s. After 18 years, the sailcraft is 100 AU away from the Sun. This would mean a pretty fast mission. However, considering that a sailcraft with 2 g/m² is technologically advanced, is there any other way to increase its speed significantly? Yes, there is. Let us try to explain this effect of non-linear dynamics.

Optimal strategy

- The above figures show that spiralling out from a circular orbit is not a convenient mode for a sailcraft to be sent away from the Sun since it would not have a high enough excess speed. On the other hand, it is known from astrodynamics that a conventional Earth satellite has to perform a rocket maneuver at/around its perigee for maximizing its speed at "infinity". Similarly, one can think of delivering a sailcraft close to the Sun to get much more energy from the solar photon pressure (that scales as $1/R^2$). For instance, suppose one starts from a point at 1 AU on the ecliptic and achieves a perihelion distance of 0.2 AU in the same plane by a two-dimensional trajectory. In general, there are three ways to deliver a sailcraft, initially at R_0 from the Sun, to some distance $R < R_0$:
    - using an additional propulsion system to send the folded-sail sailcraft to the perihelion of an elliptical orbit; there, the sail is deployed with its axis

parallel to the sun-light for getting the maximum solar flux at the chosen distance;
- o spiralling in by α slightly negative, namely, via a slow deceleration;
- o strongly decelerating by a "sufficiently large" sail-axis angle negative in HOF.

The first way - although usable as a good reference mode - requires another high-performance propulsion system.

The second way is ruled out in the present case of $\sigma = 2$ g/m²; as a matter of fact, a small $\alpha < 0$ entails a λ_r too high and a negative λ_t too low in absolute value: the sailcraft would go far from the Sun with a decreasing speed (as discussed above). In the third way, there is a *critical negative* sail-axis angle in HOF, say, α_{cr} such that for sail orientation angles $\alpha < \alpha_{cr}$ the sailcraft trajectory is characterized as follows:

1. the distance (from the Sun) first increases, achieves a local maximum at some point M, then decreases. The orbital angular momentum (per unit mass), say, **H** of the sailcraft decreases in magnitude. It is suitable to define the scalar $H = \mathbf{H} \cdot \mathbf{k}$, where **k** is the unit vector of the HIF Z-axis;
2. after a short time (few weeks or less, in general), the sailcraft speed $V = |\mathbf{V}|$ achieves a local minimum at a point P. H continues to decrease;
3. past P, the sailcraft speed increases because the **total** vector acceleration, say, **A** begins by forming an acute angle with the vector velocity **V**; in mathematical terms, $dV / dt = \mathbf{A} \cdot \mathbf{V} / V > 0$. *This is the first key-point to realize*;
4. eventually, the sailcraft achieves a point Q where $H = 0$; here, the sailcraft's total energy (per unit mass), say, E (including the contribution of the solar pressure on the sail) shows a (negative) local minimum. *This is the second key-point*;
5. past Q, the sailcraft - keeping the negative value of the sail orientation - regains angular momentum by **reversing** its motion (that is **H** is oriented down and $H < 0$). R keeps on decreasing while dV/dt augments. *This is the third key-point*;
6. the sailcraft energy continues to increase and a point S is reached where $E=0$, namely, the escape condition is satisfied; the sailcraft keeps on accelerating. *S is located before the perihelion*. The (negative) H continues to decrease;
7. if the sail attitude α has been chosen appropriately (about -25.9 deg in this example), the sailcraft flies-by the Sun at the desired (0.2 AU) perihelion, say, U; however, differently from a Keplerian orbit (for which the perihelion is the point of maximum speed), past the perihelion, V increases further while the sailcraft recedes from the Sun.
8. past U, the sailcraft is very fast and pass through a point, say, W of local maximum for the speed, since $\lambda < 1$. Thus, speed decreases but, at a few AU from the Sun (about 2.7 AU in this example), both the (positive) E and the (negative) H begin a plateau or cruise phase; V becomes practically

constant and, the most important thing, takes on a cruise value considerably higher than the speed of the circular orbit of the departure planet (the Earth, in this case). This example shows a cruise speed of 14.75 AU/yr or 69.9 km/s. At 100 AU, the sailcraft speed is 69.6 km/s.

H-reversal sun flyby trajectory

The figure below shows the mentioned sailcraft trajectory. Only the initial arc around the Sun has been plotted. The remaining part is rectilinear, in practice, and represents the cruise phase of the spacecraft. The sail is represented by a short segment with a central arrow that indicates its orientation. Note that the complicate change of sail direction in HIF is very simply achieved by a **constant** attitude in HOF. That brings about a net non-Keplerian feature to the whole trajectory.

Fast Solar Sailing: Sun Flyby via 2D Motion–Reversal Mode of a Sailcraft with Sail Loading = 2 g / m²
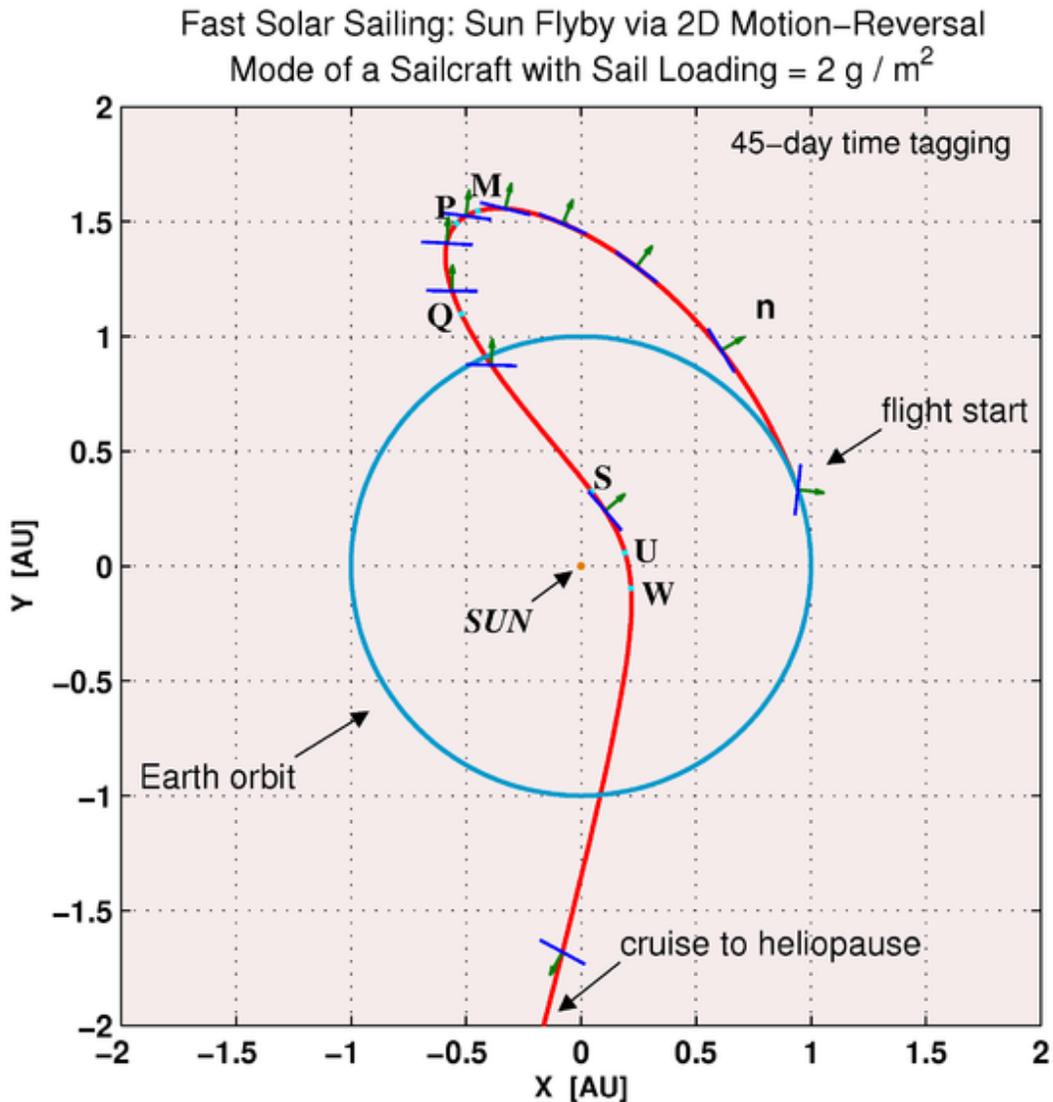
- As mentioned in point-3, the strong sailcraft speed increase is due to **both** the solar-light thrust and gravity acceleration vectors. In particular, dV / dt, or the along-track component of the total acceleration, is positive and particularly high from the point-Q to the point-U. This suggests that if a quick sail attitude maneuver is performed just before H vanishes, α → -α, the sailcraft motion continues to be a **direct** motion with a final cruise velocity equal in magnitude to the reversal one (because the above maneuver keeps the perihelion value unchanged). The basic principle both sailing modes *share* may be summarised as follows: *a sufficiently light sailcraft needs to lose most of its initial energy for subsequently achieving the absolute maximum of energy compliant with its given technology*.

- The above 2D class of new trajectories represents an ideal case. The realistic 3D fast sailcraft trajectories are considerably more complicated than the 2D cases. However, the general feature of producing a fast cruise speed can be further enhanced. Some of the enclosed references contain strict mathematical algorithms for dealing with this topic. Recently (July 2005), in an international symposium an evolution of the above concept of fast solar sailing has been discussed. A sailcraft with σ = 1 g/m² could achieve over 30 AU/yr (0.000474 c) in cruise (by keeping the perihelion at 0.2 AU), namely, well beyond the cruise speed of any nuclear-electric spacecraft (at least as conceived today). Such paper has been published on the Journal of the British Interplanetary Society (JBIS) in 2006.

Chapter- 5

Reaction Control System

A **reaction control system** (**RCS**) is a subsystem of a spacecraft whose purpose is attitude control and steering by the use of thrusters. An RCS system is capable of providing small amounts of thrust in any desired direction or combination of directions. An RCS is also capable of providing torque to allow control of rotation (pitch, yaw, and roll). This is in contrast to a spacecraft's main engine, which is only capable of providing thrust in one direction, but is much more powerful.

RCS systems often use combinations of large and smaller (vernier) thrusters, to allow different levels of response from the combination.

Reaction control systems are used:

- for attitude control during re-entry;
- for stationkeeping in orbit;
- for close maneuvering during docking procedures;
- for control of orientation, or 'pointing the nose' of the craft;
- as a backup means of deorbiting;
- for Harrier "jump jet" stabilisation during operations below stall speed.

Because spacecraft only contain a finite amount of fuel and there is little chance to refill them, some alternative reaction control systems have been developed so that fuel can be conserved. For stationkeeping, some spacecraft (particularly those in geosynchronous orbit) use high-specific impulse engines such as arcjets, ion thrusters, or Hall effect thrusters. To control orientation, a few spacecraft use momentum wheels which spin to control rotational rates on the vehicle.

Location of thrusters on space capsules
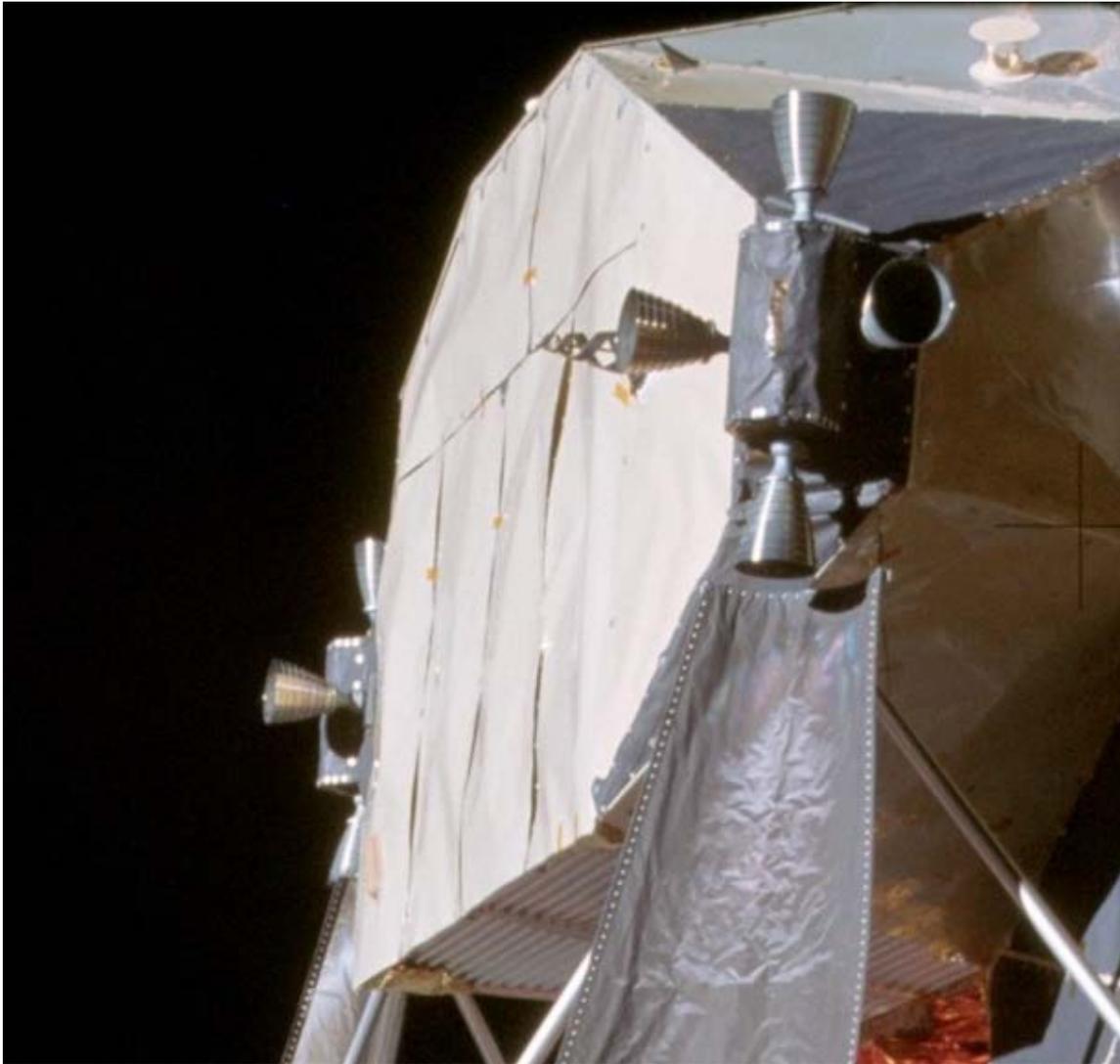
RCS blocks on the Apollo Lunar Module

Two Apollo spacecraft (the Service Module and the Lunar Module) had translation thrusters grouped into external blocks of four, which served to translate and orient the spacecraft. Other designs used separate sets of thrusters for these two tasks. The Apollo thrusters were configured to allow "coupled" RCS firings (where thrusters on opposite sides of the spacecraft fired together), which allowed adjusting the vehicle attitude without affecting the critical accuracy of their orbital, trans-lunar and trans-earth trajectories.

The Mercury and Gemini spacecraft each had groupings of two nozzles inserted into their forward compartments, with slots cut out from which the exhaust could escape. These thrusters were used for orientation, not translation. (Indeed, the Mercury spacecraft had

no separate capacity for translation at all.) Similarly, the command modules of both the Apollo and Soyuz spacecraft have their re-entry RCS thrusters ungrouped.

Gemini, due to its relatively low mass, was able to change its orbit using its thrusters, and did not require an engine (unlike its heavier descendants).

A pair of translation thrusters are located at the rear of both the Gemini and Soyuz spacecraft; the counter-acting thrusters are similarly paired in the middle of each spacecraft (near the center of mass) pointing outwards and forward. These act in pairs to prevent the spacecraft from rotating. The thrusters for the lateral directions are mounted close to the center of mass of each of these spacecraft as well, but Gemini has only one engine for each of the directions while Soyuz again uses a pair.

None of these engines is intended for orientation. For that purpose, both Gemini and Soyuz have engines at the extreme rear of the spacecraft. Here Soyuz uses engines only one-tenth the power of the others.

The placement of the translation thrusters (which are used to alter the spacecraft's velocity) has one important requirement that the placement of the orientation thrusters (which are used to rotate and orient the spacecraft) does not: if the direction of thrust of the translation thrusters does not pass through the center of mass of the spacecraft (when tracked backward from the nozzle) the spacecraft will rotate — an unwanted side effect. Current and past spacecraft are not operated by automatically firing the orientation thrusters to counteract this rotation because such a system might fail, so manual re-orientation is required afterward. Because of these constraints, translation thrusters can generally be placed in fewer locations than orientation thrusters.

Finally, Soyuz has a thruster at the rear of the spacecraft that points parallel to each solar panel. This thruster is used for orientation, but has the unique application of keeping the spacecraft's solar panels pointing towards the sun. Without this thruster, a computer system would have to keep the panels properly aligned, wasting electricity. The spin is dampened by a counterpart thruster on the other side.

Location of thrusters on spaceplanes

RCS thrusters on the nose of the Space Shuttle

The suborbital X-15 and a companion training aero-spacecraft, the NF-104 AST, both intended to travel to an altitude that rendered their aerodynamic control surfaces unusable, established a convention for locations for thrusters on winged vehicles not intended to dock in space; that is, those that only have attitude control thrusters. Those for pitch and yaw are located in the nose, forward of the cockpit, and replace a standard radar system. Those for roll are located at the wingtips. The X-20, which would have gone into orbit, continued this pattern.

Unlike these, the Space Shuttle has many more thrusters, as it is required to carry out docking manoeuvres in orbit. Shuttle thrusters are grouped in the nose of the vehicle and on each of the two aft Orbital Maneuvering System pods. No nozzles interrupt the heat shield on the underside of the craft, instead, the nose RCS nozzles which control positive pitch are mounted on the side of the vehicle, and are canted downward. The downward-facing negative pitch thrusters are located in the OMS pods mounted in the tail/afterbody.

Chapter- 6

Gyroscope
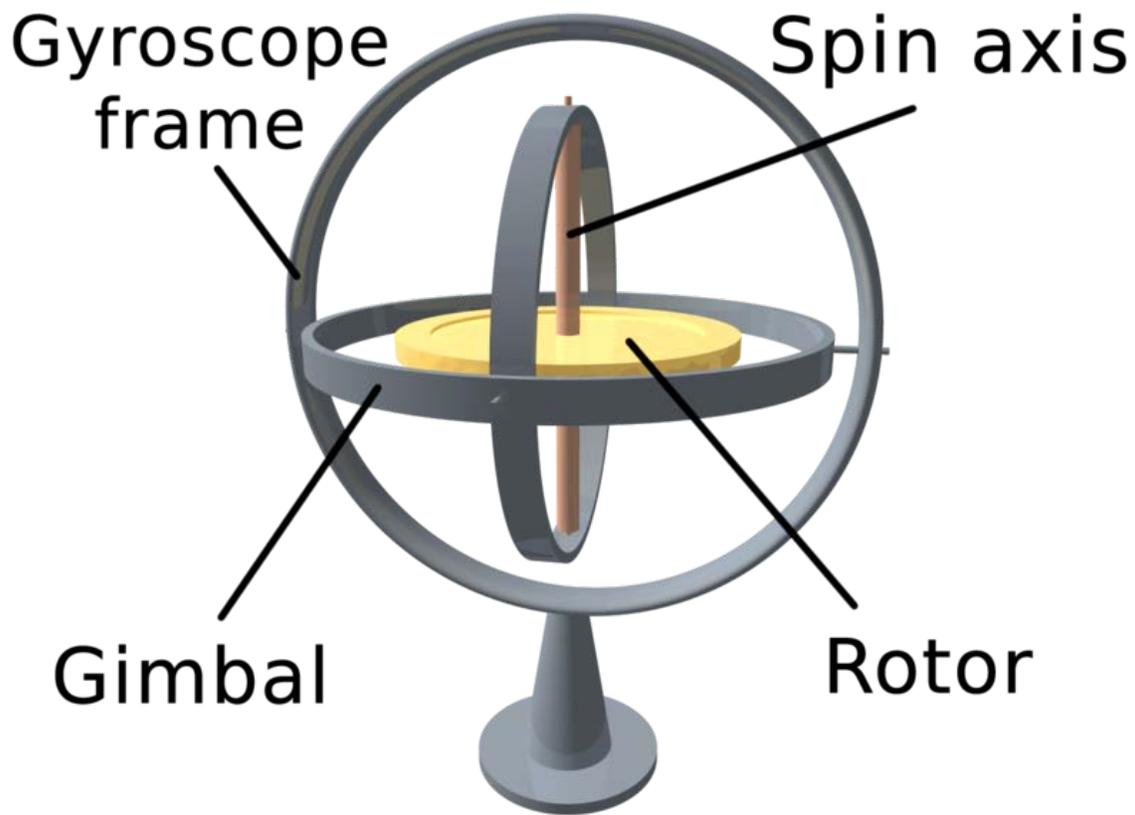
A gyroscope

A **gyroscope** is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum. A mechanical gyroscope is essentially a spinning wheel or disk whose axle is free to take any orientation. This orientation changes much less in response to a given external torque than it would without the large angular momentum associated with the gyroscope's high rate of spin. Since external torque is

minimized by mounting the device in gimbals, its orientation remains nearly fixed, regardless of any motion of the platform on which it is mounted.

Gyroscopes based on other operating principles also exist, such as the electronic, microchip-packaged MEMS gyroscope devices found in consumer electronic devices, solid state ring lasers, fibre optic gyroscopes and the extremely sensitive quantum gyroscope.

Applications of gyroscopes include navigation (INS) when magnetic compasses do not work (as in the Hubble telescope) or are not precise enough (as in ICBMs) or for the stabilization of flying vehicles like radio-controlled helicopters or UAVs. Due to their high precision, gyroscopes are also used to maintain direction in tunnel mining.
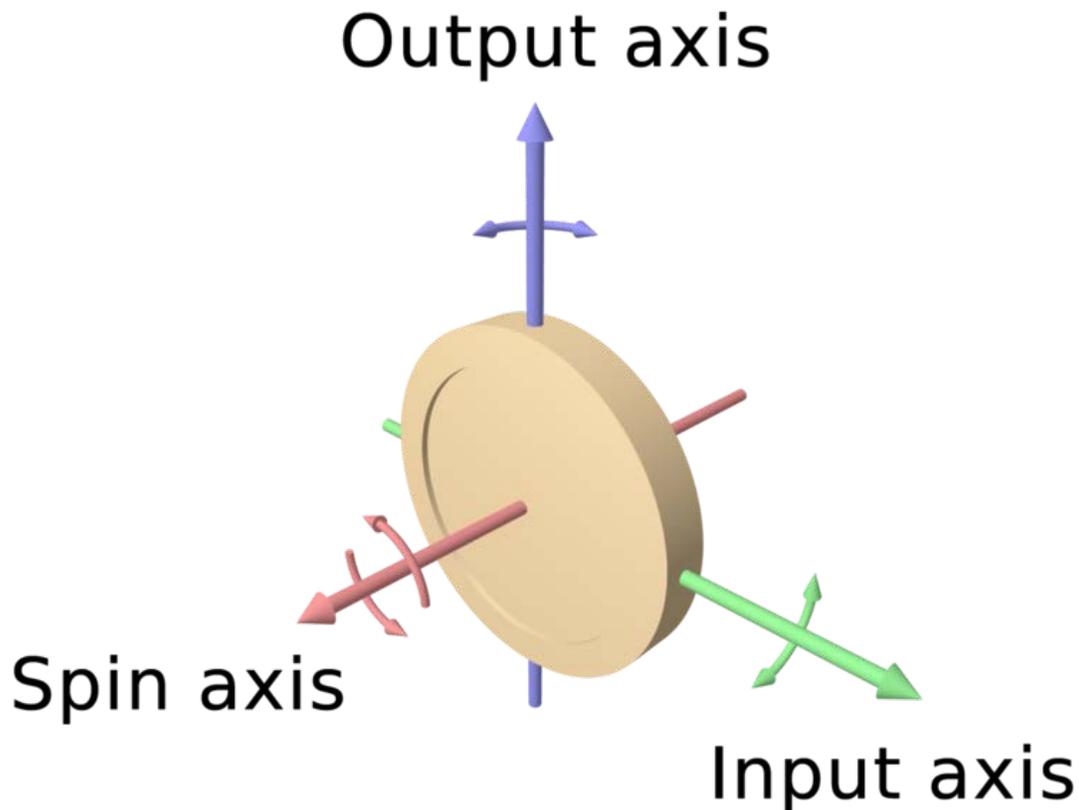
Description and diagram

Diagram of a gyro wheel. Reaction arrows about the output axis (blue) correspond to forces applied about the input axis (green), and vice versa.

Within mechanical systems or devices, a conventional *gyroscope* is a mechanism comprising a rotor journalled to spin about one axis, the journals of the rotor being mounted in an inner gimbal or ring, the inner gimbal is journalled for oscillation in an outer gimbal which is journalled in another gimbal for a total of three gimbals.

The **outer gimbal** or ring which is the gyroscope frame is mounted so as to pivot about an axis in its own plane determined by the support. This outer gimbal possesses one degree of rotational freedom and its axis possesses none. The next **inner gimbal** is mounted in the gyroscope frame (outer gimbal) so as to pivot about an axis in its own plane that is always perpendicular to the pivotal axis of the gyroscope frame (outer gimbal). This inner gimbal has two degrees of rotational freedom. Similarly, next **innermost gimbal** is attached to the inner gimbal which has three degrees of rotational freedom and its axis possesses two.

The axle of the spinning wheel defines the spin axis. The rotor is journaled to spin about an axis which is always perpendicular to the axis of the innermost gimbal. So, the rotor possesses four degrees of rotational freedom and its axis possesses three. The wheel responds to a force applied about the input axis by a reaction force about the output axis.

The behaviour of a gyroscope can be most easily appreciated by consideration of the front wheel of a bicycle. If the wheel is leaned away from the vertical so that the top of the wheel moves to the left, the forward rim of the wheel also turns to the left. In other words, rotation on one axis of the turning wheel produces rotation of the third axis.

A **gyroscope flywheel** will roll or resist about the output axis depending upon whether the output gimbals are of a free- or fixed- configuration. Examples of some free-output-gimbal devices would be the attitude reference gyroscopes used to sense or measure the pitch, roll and yaw attitude angles in a spacecraft or aircraft.

A gyro wheel in action

The centre of gravity of the rotor can be in a fixed position. The rotor simultaneously spins about one axis and is capable of oscillating about the two other axes, and thus, except for its inherent resistance due to rotor spin, it is free to turn in any direction about the fixed point. Some gyroscopes have mechanical equivalents substituted for one or more of the elements, e.g., the spinning rotor may be suspended in a fluid, instead of being pivotally mounted in gimbals. A control moment gyroscope (CMG) is an example

of a fixed-output-gimbal device that is used on spacecraft to hold or maintain a desired attitude angle or pointing direction using the gyroscopic resistance force.

In some special cases, the outer gimbal (or its equivalent) may be omitted so that the rotor has only two degrees of freedom. In other cases, the centre of gravity of the rotor may be offset from the axis of oscillation and thus the centre of gravity of the rotor and the centre of suspension of the rotor may not coincide.

History

Gyroscope invented by Léon Foucault in 1852. Replica built by Dumoulin-Froment for the Exposition universelle in 1867. National Conservatory of Arts and Crafts museum, Paris.

The earliest known gyroscope-like instrument was made by German Johann Bohnenberger, who first wrote about it in 1817. At first he called it the "Machine". Bohnenberger's machine was based on a rotating massive sphere. In 1832, American Walter R. Johnson developed a similar device that was based on a rotating disk. The French mathematician Pierre-Simon Laplace, working at the École Polytechnique in Paris, recommended the machine for use as a teaching aid, and thus it came to the attention of Léon Foucault. In 1852, Foucault used it in an experiment involving the rotation of the Earth. It was Foucault who gave the device its modern name, in an experiment to see the Earth's rotation (Greek *gyros*, circle or rotation), which was visible in the 8 to 10 minutes before friction slowed the spinning rotor.

In the 1860s, the advent of electric motors made it possible for a gyroscope to spin indefinitely; this led to the first prototype gyrocompasses. The first functional marine gyrocompass was patented in 1907 by German inventor Hermann Anschütz-Kaempfe. The American Elmer Sperry followed with his own design later that year, and other nations soon realized the military importance of the invention—in an age in which naval prowess was the most significant measure of military power—and created their own gyroscope industries. The Sperry Gyroscope Company quickly expanded to provide aircraft and naval stabilizers as well, and other gyroscope developers followed suit.

In 1917, the Chandler Company of Indianapolis, Indiana, created the "Chandler gyroscope", a toy gyroscope with a pull string and pedestal. Chandler continued to produce the toy until the company was purchased by TEDCO inc. in 1982. The chandler toy is still produced by TEDCO today.

In the first several decades of the 20th century, other inventors attempted (unsuccessfully) to use gyroscopes as the basis for early black box navigational systems by creating a stable platform from which accurate acceleration measurements could be performed (in order to bypass the need for star sightings to calculate position). Similar principles were later employed in the development of inertial guidance systems for ballistic missiles.

During World War Two, the gyroscope became the prime component for aircraft and anti-aircraft gun sights.

Properties

A gyroscope in operation with freedom in all three axes. The rotor will maintain its spin axis direction regardless of the orientation of the outer frame.

A gyroscope exhibits a number of behaviours including precession and nutation. Gyroscopes can be used to construct gyrocompasses which complement or replace magnetic compasses (in ships, aircraft and spacecraft, vehicles in general), to assist in stability (Hubble Space Telescope, bicycles, motorcycles, and ships) or be used as part of an inertial guidance system. Gyroscopic effects are used in tops, boomerangs, yo-yos, and Powerballs. Many other rotating devices, such as flywheels, behave gyroscopically although the gyroscopic effect is not being used.

The fundamental equation describing the behavior of the gyroscope is:

$$\boldsymbol{\tau} = \frac{d\mathbf{L}}{dt} = \frac{d(I\boldsymbol{\omega})}{dt} = I\boldsymbol{\alpha}$$

where the vectors $\boldsymbol{\tau}$ and $\mathbf{L}$ are, respectively, the torque on the gyroscope and its angular momentum, the scalar I is its moment of inertia, the vector $\boldsymbol{\omega}$ is its angular velocity, and the vector $\boldsymbol{\alpha}$ is its angular acceleration.

It follows from this that a torque $\boldsymbol{\tau}$ applied perpendicular to the axis of rotation, and therefore perpendicular to $\mathbf{L}$, results in a rotation about an axis perpendicular to both $\boldsymbol{\tau}$ and $\mathbf{L}$. This motion is called *precession*. The angular velocity of precession $\boldsymbol{\Omega}_{\mathrm{P}}$ is given by the cross product:

$$\boldsymbol{\tau} = \boldsymbol{\Omega}_{\mathrm{P}} \times \mathbf{L}.$$
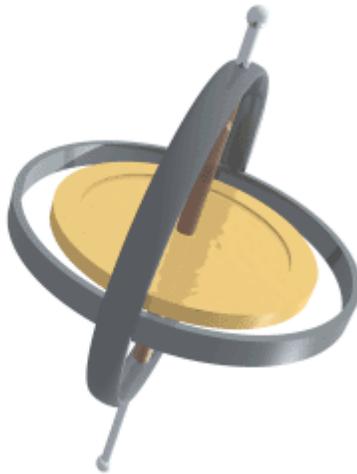
Precession on a gyroscope

Precession can be demonstrated by placing a spinning gyroscope with its axis horizontal and supported loosely (frictionless toward precession) at one end. Instead of falling, as might be expected, the gyroscope appears to defy gravity by remaining with its axis horizontal, when the other end of the axis is left unsupported and the free end of the axis slowly describes a circle in a horizontal plane, the resulting precession turning. This effect is explained by the above equations. The torque on the gyroscope is supplied by a couple of forces: gravity acting downwards on the device's centre of mass, and an equal force acting upwards to support one end of the device. The rotation resulting from this torque is not downwards, as might be intuitively expected, causing the device to fall, but perpendicular to both the gravitational torque (horizontal and perpendicular to the axis of rotation) and the axis of rotation (horizontal and outwards from the point of support), i.e. about a vertical axis, causing the device to rotate slowly about the supporting point.

Under a constant torque of magnitude τ, the gyroscope's speed of precession Ω_P is inversely proportional to L, the magnitude of its angular momentum:

$$\tau = \Omega_\mathrm{P} L \sin \theta,$$

where θ is the angle between the vectors $\boldsymbol{\Omega}_\mathrm{P}$ and $\mathbf{L}$. Thus if the gyroscope's spin slows down (for example, due to friction), its angular momentum decreases and so the rate of precession increases. This continues until the device is unable to rotate fast enough to support its own weight, when it stops precessing and falls off its support, mostly because friction against precession cause another precession that goes to cause the fall.

By convention, these three vectors, torque, spin, and precession, are all oriented with respect to each other according to the right-hand rule.

To easily ascertain the direction of gyro effect, simply remember that a rolling wheel tends, when it leans to the side, to turn in the direction of the lean.

Variations

Gyrostat

A **gyrostat** is a variant of the gyroscope. It consists of a massive flywheel concealed in a solid casing. Its behaviour on a table, or with various modes of suspension or support, serves to illustrate the curious reversal of the ordinary laws of static equilibrium due to the gyrostatic behaviour of the interior invisible flywheel when rotated rapidly. The first gyrostat was designed by Lord Kelvin to illustrate the more complicated state of motion of a spinning body when free to wander about on a horizontal plane, like a top spun on the pavement, or a hoop or bicycle on the road.

MEMS

A MEMS gyroscope takes the idea of the Foucault pendulum and uses a vibrating element, known as a MEMS (Micro Electro-Mechanical System). The MEMS-based gyro was initially made practical and producible by Systron Donner Inertial (SDI). Today, SDI is a large manufacturer of MEMS gyroscopes.

FOG

A fiber optic gyroscope (FOG) is a gyroscope that uses the interference of light to detect mechanical rotation. The sensor is a coil of as much as 5 km of optical fiber. The development of low loss single mode optical fiber in the early 1970s for the telecommunications industry enabled the development of Sagnac effect fiber optic gyros.

VSG or CVG

A vibrating structure gyroscope (VSG), also called a **coriolis vibratory gyroscope** (CVG), uses a resonator made of different metallic alloys. It takes a position between the low accuracy, low cost MEMS gyroscope and the higher accuracy and higher cost fiber optic gyroscope (FOG). Accuracy parameters are increased by using low intrinsic damping materials, resonator vacuumization, and digital electronics to reduce temperature dependent drift and instability of control signals.

High-Q Wine-Glass Resonators for precise sensors like HRG or CRG are based on Bryan's "wave inertia effect". They are made from high-purity quartz glass or from single-crystalline sapphire.

DTG

A dynamically tuned gyroscope (DTG) is a rotor suspended by a universal joint with flexure pivots. The flexure spring stiffness is independent of spin rate. However, the

dynamic inertia (from the gyroscopic reaction effect) from the gimbal provides negative spring stiffness proportional to the square of the spin speed (Howe and Savet, 1964; Lawrence, 1998). Therefore, at a particular speed, called the tuning speed, the two moments cancel each other, freeing the rotor from torque, a necessary condition for an ideal gyroscope.

London moment

A London moment gyroscope relies on the quantum-mechanical phenomenon whereby a spinning superconductor generates a magnetic field whose axis lines up exactly with the spin axis of the gyroscopic rotor. A magnetometer determines the orientation of the generated field, which is interpolated to determine the axis of rotation. Gyroscopes of this type can be extremely accurate and stable, for example those used in the Gravity Probe B experiment measured changes in gyroscope spin axis orientation to better than 0.5 milliarcseconds (1.4×10^{-7} degrees) over a one-year period. This is equivalent to an angular separation the width of a human hair viewed from 32 kilometers (20 miles) away.

The GP-B gyro consists of a nearly-perfect spherical rotating mass made of fused quartz which provides a dielectric support for a thin layer of niobium superconducting material. To eliminate friction found in conventional mechanical bearings, the rotor assembly is suspended by six electromagnets that form a magnetic bearing. After the initial spin-up by a jet of helium brings the rotor to 4,000 RPM, the polished gyroscope housing is evacuated to a ultra-high vacuum to further reduce drag on the rotor. Provided the suspension electronics remain powered, the extreme rotational symmetry, lack of friction, and low drag will allow the angular momentum of the rotor to keep it spinning for about 15,000 years.

A sensitive DC SQUID magnetometer able to discriminate changes as small as one quantum, or about 2×10^{-15} Wb, is used to monitor the gyroscope. A precesses, or tilt, in the orientation of the rotor causes the London moment magnetic field to shift relative to the housing. The moving field passes through a superconducting pickup loop fixed to the housing, inducing a small electric current. The current produces a voltage across a shunt resistance, which is resolved to spherical coordinates by a microprocessor. The system is designed to minimize Lorentz torque on the rotor.

Modern uses

In addition to being used in compasses, aircraft, computer pointing devices, etc., gyroscopes have been introduced into consumer electronics. Since the gyroscope allows the calculation of orientation and rotation, designers have incorporated them into modern technology. The integration of the gyroscope has allowed for more accurate recognition of movement within a 3D space than the previous lone accelerometer within a number of smartphones. Scott Steinberg, known for his critiques on newly released technology, says that the new addition of the gyroscope in the iPhone 4 may "completely redefine the way we interact with downloadable apps".

Nintendo has integrated a gyroscope into the Wii console's Wii Remote controller by an additional piece of hardware called "Wii MotionPlus".

Chapter- 7

Spacecraft Propulsion
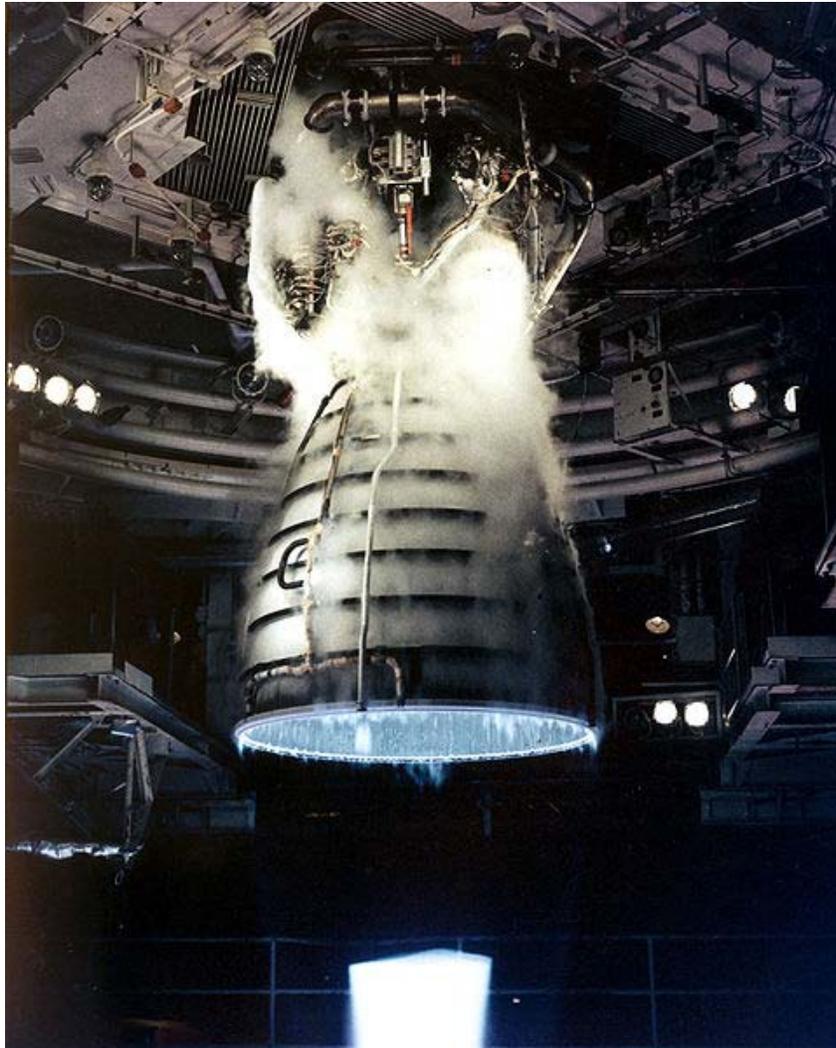
A remote camera captures a close-up view of a Space Shuttle Main Engine during a test firing at the John C. Stennis Space Center in Hancock County, Mississippi

Spacecraft propulsion is any method used to accelerate spacecraft and artificial satellites. There are many different methods. Each method has drawbacks and advantages, and spacecraft propulsion is an active area of research. However, most spacecraft today are propelled by forcing a gas from the back/rear of the vehicle at very high speed through a supersonic de Laval nozzle. This sort of engine is called a rocket engine.

All current spacecraft use chemical rockets (bipropellant or solid-fuel) for launch, though some (such as the Pegasus rocket and SpaceShipOne) have used air-breathing engines on their first stage. Most satellites have simple reliable chemical thrusters (often monopropellant rockets) or resistojet rockets for orbital station-keeping and some use momentum wheels for attitude control. Soviet bloc satellites have used electric propulsion for decades, and newer Western geo-orbiting spacecraft are starting to use them for north-south stationkeeping. Interplanetary vehicles mostly use chemical rockets as well, although a few have used ion thrusters and Hall effect thrusters (two different types of electric propulsion) to great success.

Requirements

Artificial satellites must be launched into orbit, and once there they must be placed in their nominal orbit. 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 stationkeeping). 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 over once it has exhausted its ability to adjust its orbit.

Spacecraft designed to travel further also need propulsion methods. They need to be launched out of the Earth's atmosphere just as satellites do. Once there, they need to leave orbit and move around.

For interplanetary travel, a spacecraft must use its engines to leave Earth orbit. Once it has done so, it must somehow 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 simply falls freely along its trajectory. 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 are sometimes used for this final orbital adjustment.
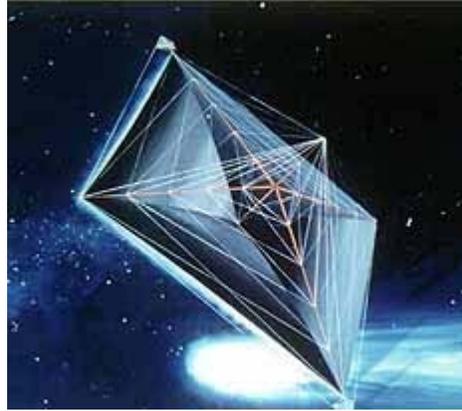
Artist's concept of a solar sail

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.

Spacecraft for interstellar travel also need propulsion methods. No such spacecraft has yet been built, but many designs have been discussed. Since interstellar distances are very 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 will be a formidable challenge for spacecraft designers.

Effectiveness

When in space, the purpose of a propulsion system is to change the velocity, or *v*, of a spacecraft. Since this is more difficult for more massive spacecraft, designers generally discuss momentum, *mv*. The amount of change in momentum is called impulse. So the goal of a propulsion method in space is to create an impulse.

When launching a spacecraft from the Earth, a propulsion method must overcome a higher gravitational pull to provide a positive net acceleration. In orbit, any additional impulse, even very tiny, will result in a change in the orbit path.

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 one can apply 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 but runs for a long time can produce the same impulse as a propulsion method that produces large accelerations for a short time. When launching from a planet, tiny accelerations cannot overcome the planet's gravitational pull and so cannot be used.

The Earth's surface is situated fairly deep in a gravity well. The escape velocity required to get out of it is 11.2 kilometers/second. As human beings evolved in a gravitational field of 1g (9.8 m/s²), an ideal propulsion system would be one that provides a continuous acceleration of **1g** (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 all the ill effects of free fall, such as nausea, muscular weakness, reduced sense of taste, or leaching of calcium from their bones.

The law of conservation of momentum means that in order for a propulsion method to change the momentum of a space craft it must change the momentum of something else as well. A few designs take advantage of things like magnetic fields or light pressure in order to change the spacecraft's momentum, but in free space the rocket must bring along some mass to accelerate away in order to push itself forward. Such mass is called reaction mass.

In order for a rocket to work, it needs two things: reaction mass and energy. The impulse provided by launching a particle of reaction mass having mass m at velocity v is mv. But this particle has kinetic energy $mv^2/2$, which must come from somewhere. In a conventional solid, liquid, or hybrid rocket, the fuel is burned, providing the energy, and the reaction products are allowed to flow out the back, providing the reaction mass. In an ion thruster, electricity is used to accelerate ions out the back. Here some other source must provide the electrical energy (perhaps a solar panel or a nuclear reactor), while the ions provide the reaction mass.

When discussing the efficiency of a propulsion system, designers often focus on effectively using the reaction mass. Reaction mass must be carried along with the rocket and is irretrievably consumed when used. One way of measuring the amount of impulse that can be obtained from a fixed amount of reaction mass is the specific impulse, the impulse per unit weight-on-Earth (typically designated by I_{sp}). The unit for this value is seconds. Since 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. This alternate form of specific impulse uses the same units as velocity (e.g. m/s), and in fact it is equal to the effective exhaust velocity of the engine (typically designated v_e). Confusingly, both values are sometimes called specific impulse. The two values differ by a factor of g_n, the standard acceleration due to gravity 9.80665 m/s² ($I_{sp}g_n = v_e$).

A rocket with a high exhaust velocity can achieve the same impulse with less reaction mass. However, the energy required for that impulse is proportional to the exhaust velocity, so that more mass-efficient engines require much more energy, and are typically less energy efficient. This is a problem if the engine is to provide a large amount of thrust. To generate a large amount of impulse per second, it must use a large amount of energy per second. So high-mass-efficient engines require enormous amounts of energy per second to produce high thrusts. As a result, most high-mass-efficient engine designs also provide lower thrust due to the unavailability of high amounts of energy.

Methods

Propulsion methods can be classified based on their means of accelerating the reaction mass. There are also some special methods for launches, planetary arrivals, and landings.

Reaction engines

A **reaction engine** is an engine which provides propulsion by expelling reaction mass, in accordance with Newton's third law of motion. This law of motion is most commonly paraphrased as: "For every action force there is an equal, but opposite, reaction force".

Examples include both duct engines and rocket engines, and more uncommon variations such as Hall effect thrusters, ion drives and mass drivers. Duct engines are obviously not used for space propulsion due to the lack of air; however some proposed spacecraft have these kinds of engines to assist takeoff and landing.

Delta-v and propellant

Rocket Mass ratio versus Delta-V
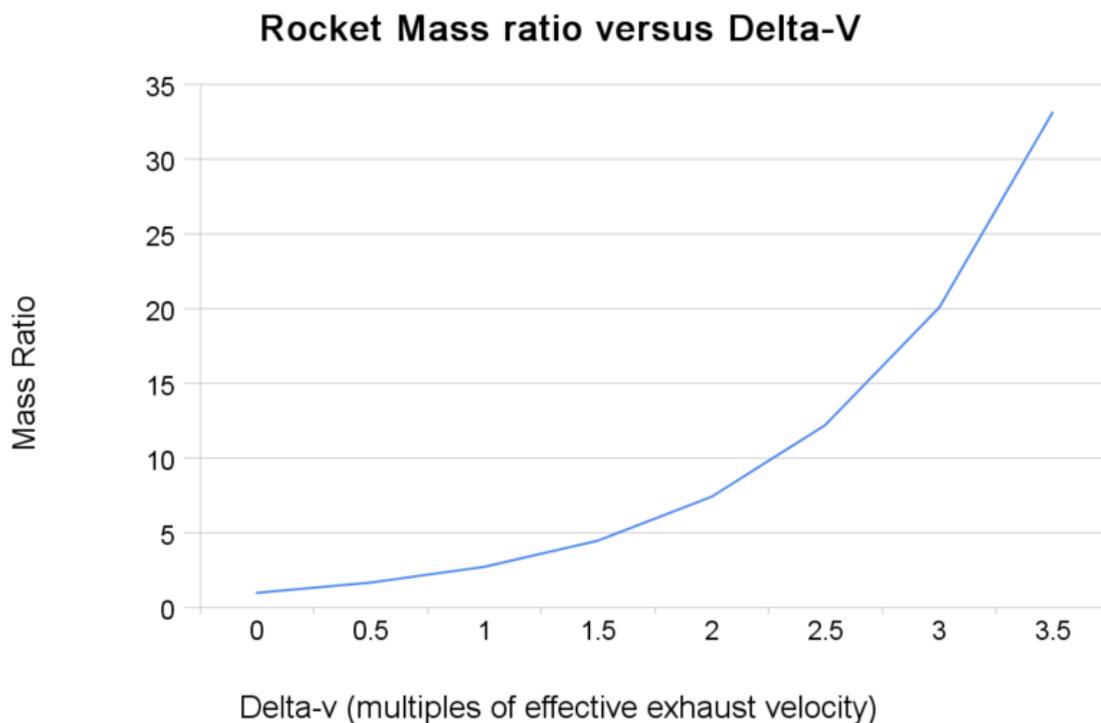
Rocket mass ratios versus final velocity, as calculated from the rocket equation

Exhausting the entire usable propellant of a spacecraft through the engines in a straight line in free space would produce a net velocity change to the vehicle; this number is termed 'delta-v' (Δv).

If the exhaust velocity is constant then the total Δv of a vehicle can be calculated using the rocket equation, where M is the mass of propellant, P is the mass of the payload (including the rocket structure), and v_e is the velocity of the rocket exhaust. This is known as the Tsiolkovsky rocket equation:

$$\Delta v = v_e \ln \left(\frac{M + P}{P} \right).$$

For historical reasons, as discussed above, v_e is sometimes written as

$$v_e = I_{sp} g_o$$

where I_{sp} is the specific impulse of the rocket, measured in seconds, and g_o is the gravitational acceleration at sea level.

For a high delta-v mission, the majority of the spacecraft's mass needs to be reaction mass. Since a rocket must carry all of its reaction mass, most of the initially-expended reaction mass goes towards accelerating reaction mass rather than payload. If the rocket has a payload of mass P, the spacecraft needs to change its velocity by Δv, and the rocket engine has exhaust velocity v_e, then the mass M of reaction mass which is needed can be calculated using the rocket equation and the formula for I_{sp}:

$$M = P \left(e^{\Delta v / v_e} - 1 \right).$$

For Δv much smaller than v_e, this equation is roughly linear, and little reaction mass is needed. If Δv is comparable to v_e, then there needs to be about twice as much fuel as combined payload and structure (which includes engines, fuel tanks, and so on). Beyond this, the growth is exponential; speeds much higher than the exhaust velocity require very high ratios of fuel mass to payload and structural mass.

For a mission, for example, when launching from or landing on a planet, the effects of gravitational attraction and any atmospheric drag must be overcome by using fuel. It is typical to combine the effects of these and other effects into an effective mission delta-v. For example a launch mission to low Earth orbit requires about 9.3–10 km/s delta-v. These mission delta-vs are typically numerically integrated on a computer.

Some effects such as Oberth effect can only be significantly utilised by high thrust engines such as rockets, i.e. engines that can produce a high g-force (thrust per unit mass, equal to delta-v per unit time).
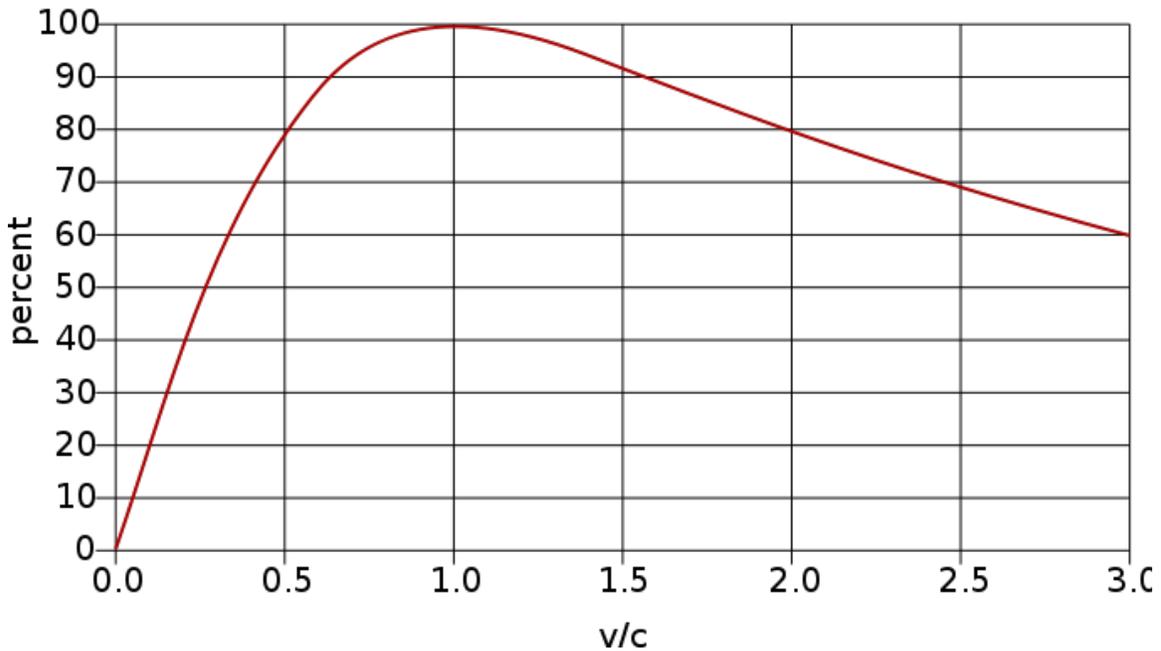
Power use and propulsive efficiency

For all reaction engines (such as rockets and ion drives) some energy must go into accelerating the reaction mass. Every engine will waste some energy, but even assuming 100% efficiency, to accelerate an exhaust the engine will need energy amounting to

$$\frac{1}{2}\dot{m}v_e^2$$

This energy is not necessarily lost- some of it usually ends up as kinetic energy of the vehicle, and the rest is wasted in residual motion of the exhaust.

Propulsive efficiency

Due to energy carried away in the exhaust the energy efficiency of a reaction engine varies with the speed of the exhaust relative to the speed of the vehicle, this is called propulsive efficiency

Comparing the rocket equation (which shows how much energy ends up in the final vehicle) and the above equation (which shows the total energy required) shows that even with 100% engine efficiency, certainly not all energy supplied ends up in the vehicle - some of it, indeed usually most of it, ends up as kinetic energy of the exhaust.

The exact amount depends on the design of the vehicle, and the mission. However there are some useful fixed points:

- if the I_{sp} is fixed, for a mission delta-v, there is a particular I_{sp} that minimises the overall energy used by the rocket. This comes to an exhaust velocity of about ⅔ of the mission delta-v. Drives with a specific impulse that is both high and fixed such as Ion thrusters have exhaust velocities that can be enormously higher than this ideal for many missions.

- if the exhaust velocity can be made to vary so that at each instant it is equal and opposite to the vehicle velocity then the absolute minimum energy usage is

achieved. When this is achieved, the exhaust stops in space and has no kinetic energy; and the propulsive efficiency is 100%- all the energy ends up in the vehicle (in principle such a drive would be 100% efficient, in practice there would be thermal losses from within the drive system and residual heat in the exhaust). However in most cases this uses an impractical quantity of propellant, but is a useful theoretical consideration. Anyway the vehicle has to move before the method can be applied.

Some drives (such as VASIMR or Electrodeless plasma thruster) actually can significantly vary their exhaust velocity. This can help reduce propellant usage or improve acceleration at different stages of the flight. However the best energetic performance and acceleration is still obtained when the exhaust velocity is close to the vehicle speed. Proposed ion and plasma drives usually have exhaust velocities enormously higher than that ideal (in the case of VASIMR the lowest quoted speed is around 15000 m/s compared to a mission delta-v from high Earth orbit to Mars of about 4000m/s).

It might be thought that adding power generation capacity is helpful, and while initially this can improve performance, this inevitably increases the weight of the power source, and eventually the mass of the power source and the associated engines and propellant dominates the weight of the vehicle, and then adding more power gives no significant improvement.

For, although solar power and nuclear power are virtually unlimited sources of *energy*, the maximum *power* they can supply is substantially proportional to the mass of the powerplant (i.e. specific power takes a largely constant value which is dependent on the particular powerplant technology). For any given specific power, with a large v_e which is desirable to save propellant mass, it turns out that the maximum acceleration is inversely proportional to v_e. Hence the time to reach a required delta-v is proportional to v_e. Thus the latter should not be too large.

Power to thrust ratio

The power to thrust ratio is simply:

$$\frac{P}{F} = \frac{\frac{1}{2}\dot{m}v^2}{\dot{m}v} = \frac{1}{2}v$$

Thus for any vehicle power P, the thrust that may be provided is:

$$F = \frac{P}{\frac{1}{2}v} = \frac{2P}{v}$$

Example

Suppose we want to send a 10,000 kg space probe to Mars. The required Δ*v* from LEO is approximately 3000 m/s, using a Hohmann transfer orbit. (A manned craft would need to take a faster route and use more fuel). For the sake of argument, let us say that the following thrusters may be used:

Engine	Effective Exhaust Velocity (km/s)	Specific impulse (s)	Fuel mass (kg)	Energy required (GJ)	Energy per kg of propellant	minimum power/thrust	Power generator mass/thrust*
Solid rocket	1	100	190,000	95	500 kJ	0.5 kW/N	N/A
Bipropellant rocket	5	500	8,200	103	12.6 MJ	2.5 kW/N	N/A
Ion thruster	50	5,000	620	775	1.25 GJ	25 kW/N	25 kg/N
Advance electrically powered drive	1,000	100,000	30	15,000	500 GJ	500 kW/N	500 kg/N

* - assumes a specific power of 1kW/kg

Observe that the more fuel-efficient engines can use far less fuel; its mass is almost negligible (relative to the mass of the payload and the engine itself) for some of the engines. However, note also that these require a large total amount of energy. For Earth launch, engines require a thrust to weight ratio of more than one. To do this with the ion or more theoretical electrical drives, the engine would have to be supplied with one to several gigawatts of power — equivalent to a major metropolitan generating station. From the table it can be seen that this is clearly impractical with current power sources.

Instead, a much smaller, less powerful generator may be included which will take much longer to generate the total energy needed. This lower power is only sufficient to accelerate a tiny amount of fuel per second, and would be insufficient for launching from the Earth. However, over long periods in orbit where there is no friction, the velocity will be finally achieved. For example. it took the SMART-1 more than a year to reach the Moon, while with a chemical rocket it takes a few days. Because the ion drive needs much less fuel, the total launched mass is usually lower, which typically results in a lower overall cost, but takes longer.

Mission planning therefore frequently involves adjusting and choosing the propulsion system so as to minimise the total cost of the project, and can involve trading off launch costs and mission duration against payload fraction.

Rocket engines

SpaceX's Kestrel engine is tested

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. This 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 nozzle. This bell-shaped nozzle is what gives a rocket engine its characteristic shape. The effect of the nozzle is to dramatically accelerate the mass, converting most of the thermal energy into kinetic energy. Exhaust speed reaching as high as 10 times the speed of sound at sea level are common.

Rocket engines provide essentially the highest specific powers and high specific thrusts of any engine used for spacecraft propulsion.

Ion propulsion rockets can heat a plasma or charged gas inside a magnetic bottle and release it via a magnetic nozzle, so that no solid matter need come in contact with the plasma. Of course, the machinery to do this is complex, but research into nuclear fusion has developed methods, some of which have been proposed to be used in propulsion systems, and some have been tested in a lab.

Electromagnetic propulsion
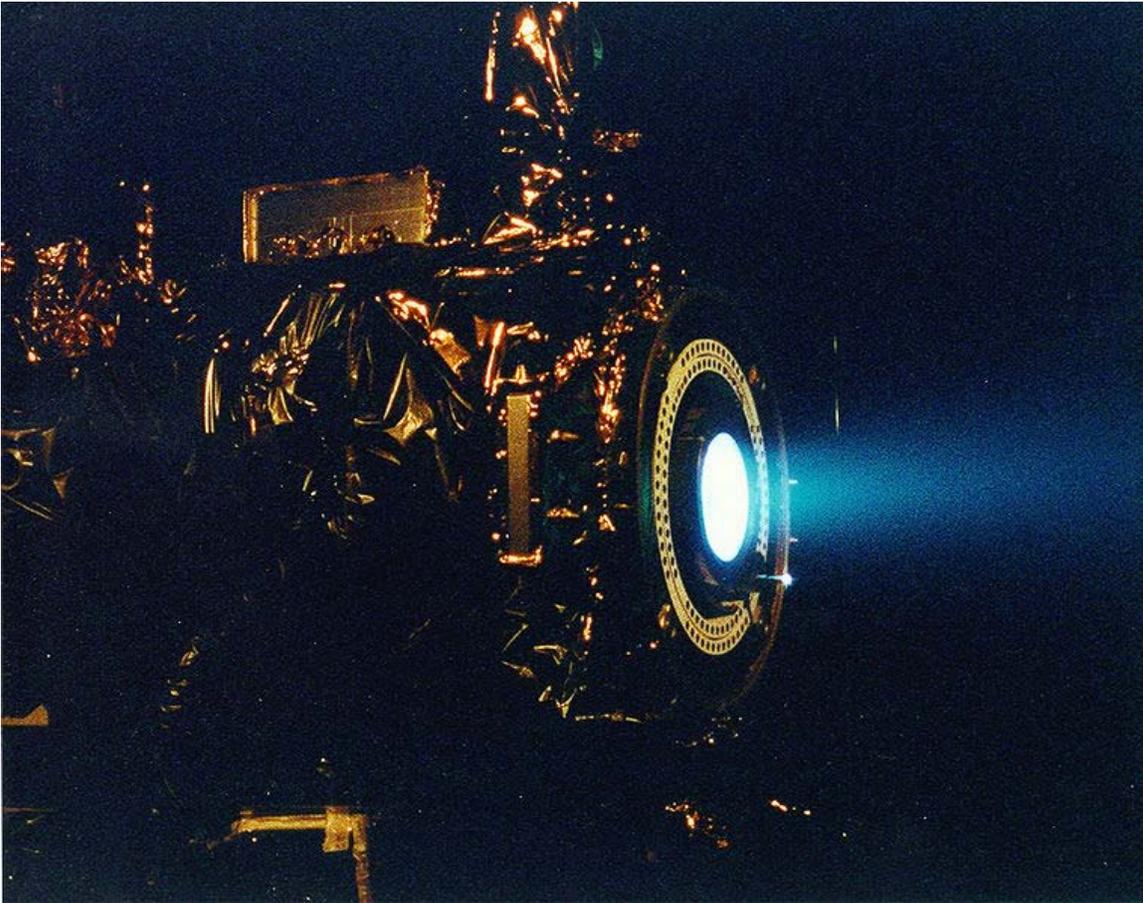
This test engine accelerates ions using electrostatic forces

Rather than relying on high temperature and fluid dynamics to accelerate the reaction mass to high speeds, there are a variety of methods that use electrostatic or electromagnetic forces to accelerate the reaction mass directly. Usually the reaction mass is a stream of ions. Such an engine typically uses electric power, first to ionize atoms, and then to create a voltage gradient to accelerate the ions to high exhaust velocities.

The idea of electric propulsion dates back to 1906, when Robert Goddard considered the possibility in his personal notebook. Konstantin Tsiolkovsky published the idea in 1911.

For these drives, at the highest exhaust speeds, energetic efficiency and thrust are all inversely proportional to exhaust velocity. Their very high exhaust velocity means they require huge amounts of energy and thus with practical power sources provide low thrust, but use hardly any fuel.

For some missions, particularly reasonably close to the Sun, solar energy may be sufficient, and has very often been used, but for others further out or at higher power,

nuclear energy is necessary; engines drawing their power from a nuclear source are called nuclear electric rockets.

With any current source of electrical power, chemical, nuclear or solar, the maximum amount of power that can be generated limits the amount of thrust that can be produced to a small value. Power generation adds significant mass to the spacecraft, and ultimately the weight of the power source limits the performance of the vehicle.

Current nuclear power generators are approximately half the weight of solar panels per watt of energy supplied, at terrestrial distances from the Sun. Chemical power generators are not used due to the far lower total available energy. Beamed power to the spacecraft shows some potential. However, the dissipation of waste heat from any power plant may make any propulsion system requiring a separate power source infeasible for interstellar travel.
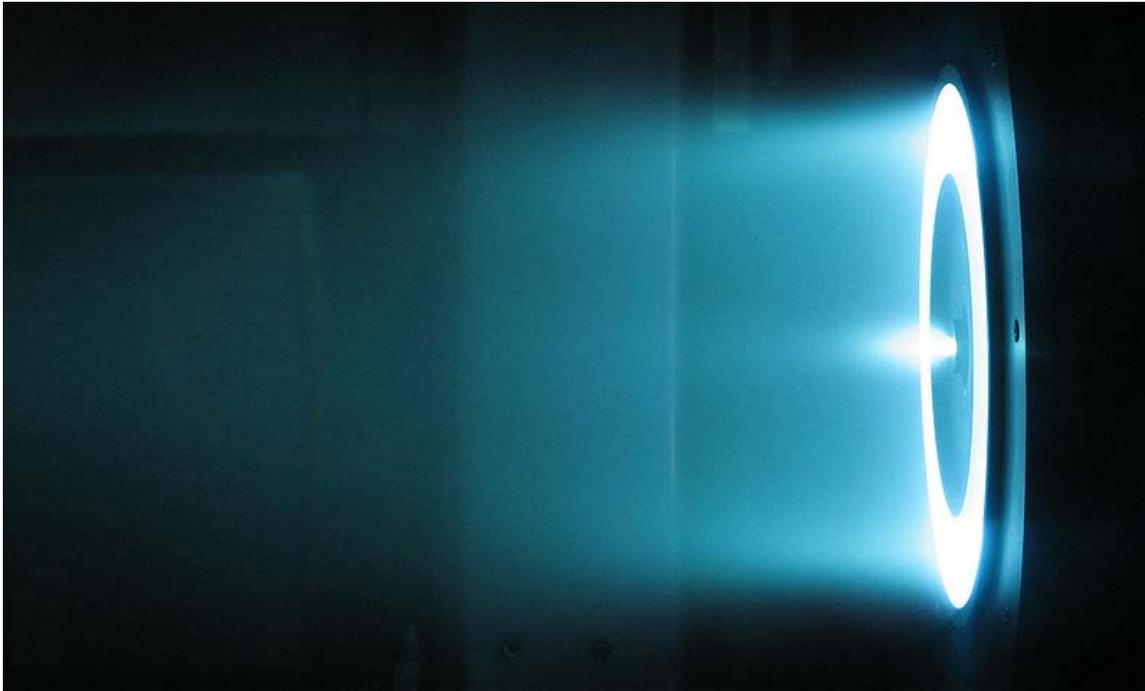
6 kW Hall thruster in operation at the NASA Jet Propulsion Laboratory.

Some electromagnetic methods:

- Ion thrusters (accelerate ions first and later neutralize the ion beam with an electron stream emitted from a cathode called a neutralizer)
    - Electrostatic ion thruster
    - Field Emission Electric Propulsion
    - Hall effect thruster
    - Colloid thruster
- Electrothermal thrusters (electromagnetic fields are used to generate a plasma to increase the heat of the bulk propellant, the thermal energy imparted to the

propellant gas is then converted into kinetic energy by a nozzle of either physical material construction or by magnetic means)

- o DC arcjet
- o microwave arcjet
- o Pulsed plasma thruster
- o Helicon Double Layer Thruster
- Electromagnetic thrusters (ions are accelerated either by the Lorentz Force or by the effect of electromagnetic fields where the electric field is not in the direction of the acceleration)
    - o Magnetoplasmadynamic thruster
    - o Electrodeless plasma thruster
    - o Pulsed inductive thruster
    - o Variable specific impulse magnetoplasma rocket (VASIMR)
- Mass drivers (for propulsion)

In electrothermal and electromagnetic thrusters, both ions and electrons are accelerated simultaneously, no neutralizer is required.

Without internal reaction mass
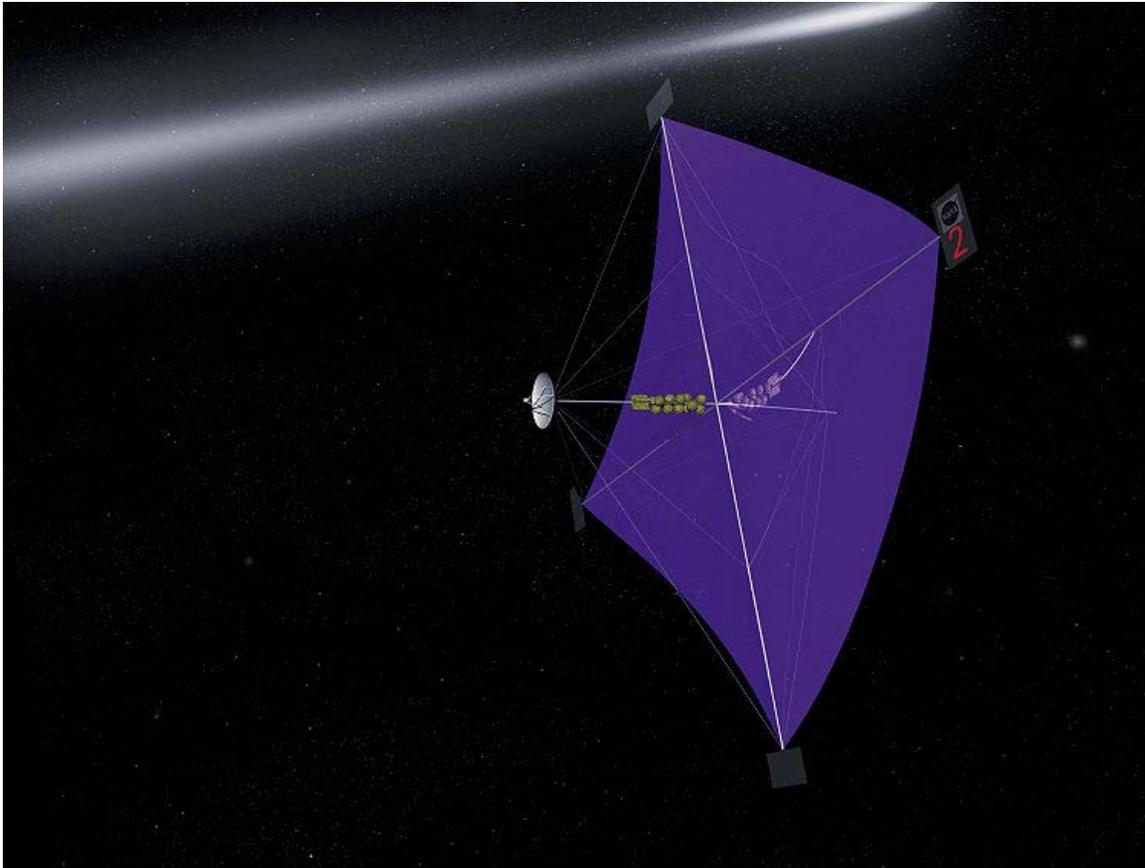
NASA study of a solar sail. The sail would be half a kilometer wide.

The law of conservation of momentum states that any engine which uses no reaction mass cannot accelerate the center of mass of a spaceship (changing orientation, on the other hand, is possible). But space is not empty, especially space inside the Solar System; there are gravitation fields, magnetic fields, solar wind and solar radiation. Various propulsion methods try to take advantage of these. However, since these phenomena are diffuse in nature, corresponding propulsion structures need to be proportionately large.

There are several different space drives that need little or no reaction mass to function. A tether propulsion system employs a long cable with a high tensile strength to change a spacecraft's orbit, such as by interaction with a planet's magnetic field or through momentum exchange with another object. Solar sails rely on radiation pressure from electromagnetic energy, but they require a large collection surface to function effectively. The magnetic sail deflects charged particles from the solar wind with a magnetic field, thereby imparting momentum to the spacecraft. A variant is the mini-magnetospheric plasma propulsion system, which uses a small cloud of plasma held in a magnetic field to deflect the Sun's charged particles. An E-sail would use very thin and lightweight wires holding an electric charge to deflect these particles, and may have more controllable directionality.

Proof of concept - Nanosail-D becomes first nanosatellite to orbit the Earth. Plans to add them to future Earth orbit satellites, enabling them to de-orbit and burn up once they are no longer needed. Cube sail aims to tackle Space Junk

A satellite or other space vehicle is subject to the law of conservation of angular momentum, which constrains a body from a net change in angular velocity. Thus, for a vehicle to change its relative orientation without expending reaction mass, another part of the vehicle may rotate in the opposite direction. Non-conservative external forces, primarily gravitational and atmospheric, can contribute up to several degrees per day to angular momentum, so secondary systems are designed to "bleed off" undesired rotational energies built up over time. Accordingly, many spacecraft utilize reaction wheels or control moment gyroscopes to control orientation in space.

A gravitational slingshot can carry a space probe onward to other destinations without the expense of reaction mass. By harnessing the gravitational energy of other celestial objects, the spacecraft can pick up kinetic energy. However, even more energy can be obtained from the gravity assist if rockets are used.

Planetary and atmospheric propulsion

Launch mechanisms

An artist's concept of an electromagnetic catapult on the Moon

High thrust is of vital importance for Earth launch, thrust has to be greater than weight. Many of the propulsion methods above give a thrust/weight ratio of much less than 1, and so cannot be used for launch.

All current spacecraft use chemical rocket engines (bipropellant or solid-fuel) for launch. Other power sources such as nuclear have been proposed and tested, but safety, environmental and political considerations have so far curtailed their use.

One advantage that spacecraft have in launch is the availability of infrastructure on the ground to assist them. Proposed non-rocket spacelaunch ground-assisted launch mechanisms include:

- Space elevator (a geostationary tether to orbit)
- Launch loop (a very fast enclosed rotating loop about 80 km tall)
- Space fountain (a very tall building held up by a stream of masses fired from base)
- Orbital ring (a ring around the Earth with spokes hanging down off bearings)
- Hypersonic skyhook (a fast spinning orbital tether)
- Electromagnetic catapult (railgun, coilgun) (an electric gun)

- Rocket sled launch
- Space gun (Project HARP, ram accelerator) (a chemically powered gun)
- Beam-powered propulsion rockets and jets powered from ground via a beam
- High Altitude Platforms to assist initial stage

Airbreathing engines

Studies generally show that conventional air-breathing engines, such as ramjets or turbojets are basically too heavy (have too low a thrust/weight ratio) to give any significant performance improvement when installed on a launch vehicle itself. However, launch vehicles can be air launched from separate lift vehicles (e.g. B-29, Pegasus Rocket and White Knight) which do use such propulsion systems. Jet engines mounted on a launch rail could also be so used.

On the other hand, very lightweight or very high speed engines have been proposed that take advantage of the air during ascent:

- SABRE - a lightweight hydrogen fuelled turbojet with precooler
- ATREX - a lightweight hydrogen fuelled turbojet with precooler
- Liquid air cycle engine - a hydrogen fuelled jet engine that liquifies the air before burning it in a rocket engine
- Scramjet - jet engines that use supersonic combustion

Normal rocket launch vehicles fly almost vertically before rolling over at an altitude of some tens of kilometers before burning sideways for orbit; this initial vertical climb wastes propellant but is optimal as it greatly reduces airdrag. Airbreathing engines burn propellant much more efficiently and this would permit a far flatter launch trajectory, the vehicles would typically fly approximately tangentially to the earth surface until leaving the atmosphere then perform a rocket burn to bridge the final delta-v to orbital velocity.

Planetary arrival and landing

A test version of the MARS Pathfinder airbag system

When a vehicle is to enter orbit around its destination planet, or when it is to land, it must adjust its velocity. This can be done using all the methods listed above (provided they can generate a high enough thrust), but there are a few methods that can take advantage of planetary atmospheres and/or surfaces.

- Aerobraking allows a spacecraft to reduce the high point of an elliptical orbit by repeated brushes with the atmosphere at the low point of the orbit. This can save a considerable amount of fuel since it takes much less delta-V to enter an elliptical orbit compared to a low circular orbit. Since the braking is done over the course of many orbits, heating is comparatively minor, and a heat shield is not required. This has been done on several Mars missions such as Mars Global Surveyor, Mars Odyssey and Mars Reconnaissance Orbiter, and at least one Venus mission, Magellan.
- Aerocapture is a much more aggressive manoeuver, converting an incoming hyperbolic orbit to an elliptical orbit in one pass. This requires a heat shield and much trickier navigation, since it must be completed in one pass through the atmosphere, and unlike aerobraking no preview of the atmosphere is possible. If the intent is to remain in orbit, then at least one more propulsive maneuver is required after aerocapture—otherwise the low point of the resulting orbit will remain in the atmosphere, resulting in eventual re-entry. Aerocapture has not yet been tried on a planetary mission, but the re-entry skip by Zond 6 and Zond 7

upon lunar return were aerocapture maneuvers, since they turned a hyperbolic orbit into an elliptical orbit. On these missions, since there was no attempt to raise the perigee after the aerocapture, the resulting orbit still intersected the atmosphere, and re-entry occurred at the next perigee.

- a Ballute is an inflatable drag device
- Parachutes can land a probe on a planet with an atmosphere, usually after the atmosphere has scrubbed off most of the velocity, using a heat shield.
- Airbags can soften the final landing.
- Lithobraking, or stopping by simply smashing into the target, is usually done by accident. However, it may be done deliberately with the probe expected to survive, in which case very sturdy probes and low approach velocities are required.

Hypothetical methods
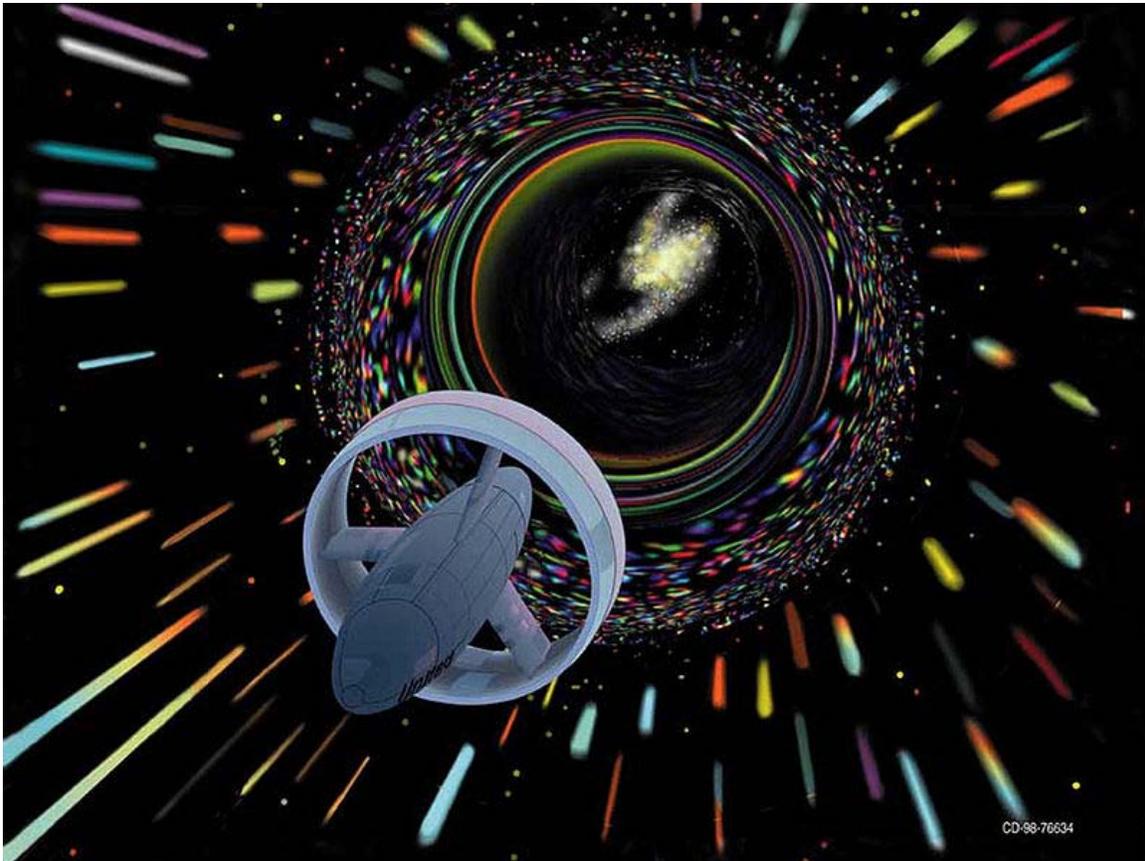
Artist's conception of a warp drive design

A variety of hypothetical propulsion techniques have been considered that would require entirely new principles of physics to realize and that may not actually be possible. To date, such methods are highly speculative and include:

- Diametric drive
- Pitch drive

- Bias drive
- Disjunction drive
- Alcubierre drive (a form of Warp drive)
- Differential sail
- Wormholes - theoretically possible, but unachieveable in practice with current technology
- Reactionless drives - breaks the law of conservation of momentum; theoretically impossible
- EmDrive - tries to circumvent the law of conservation of momentum; may be theoretically impossible
- A "hyperspace" drive based upon Heim theory

A NASA assessment is found at Marc G Millis *Assessing potential propulsion breakthroughs* (2005)

Table of methods

Below is a summary of some of the more popular, proven technologies, followed by increasingly speculative methods.

Four numbers are shown. The first is the effective exhaust velocity: the equivalent speed that the propellant leaves the vehicle. This is not necessarily the most important characteristic of the propulsion method, thrust and power consumption and other factors can be, however:

- if the delta-v is much more than the exhaust velocity, then exorbitant amounts of fuel are necessary
- if it is much more than the delta-v, then, proportionally more energy is needed; if the power is limited, as with solar energy, this means that the journey takes a proportionally longer time

The second and third are the typical amounts of thrust and the typical burn times of the method. Outside a gravitational potential small amounts of thrust applied over a long period will give the same effect as large amounts of thrust over a short period. (This result does not apply when the object is significantly influenced by gravity.)

The fourth is the maximum delta-v this technique can give (without staging). For rocket-like propulsion systems this is a function of mass fraction and exhaust velocity. Mass fraction for rocket-like systems is usually limited by propulsion system weight and tankage weight. For a system to achieve this limit, typically the payload may need to be a negligible percentage of the vehicle, and so the practical limit on some systems can be much lower.

Propulsion methods

Method	Effective Exhaust Velocity (km/s)	Thrust (N)	Firing Duration	Maximum Delta-v (km/s)	Technology readiness level
Solid-fuel rocket	1 - 4	10^3 - 10^7	minutes	~ 7	9:Flight proven
Hybrid rocket	1.5 - 4.2	<0.1 - 10^7	minutes	> 3	9:Flight proven
Monopropellant rocket	1 - 3	0.1 - 100	milliseconds-minutes	~ 3	9:Flight proven
Liquid-fuel rocket	1 - 4.7	0.1 - 10^7	minutes	~ 9	9:Flight proven
Electrostatic ion thruster	15 - 210	10^{-3} - 10	months/years	> 100	9:Flight proven
Hall effect thruster (HET)	8 - 50	10^{-3} - 10	months/years	> 100	9:Flight proven
Resistojet rocket	2 - 6	10^{-2} - 10	minutes	*?*	8:Flight qualified
Arcjet rocket	4 - 16	10^{-2} - 10	minutes	*?*	8:Flight qualified
Field Emission Electric Propulsion (FEEP)	100-130	10^{-6}-10^{-3}	months/years	*?*	8:Flight qualified
Pulsed plasma thruster (PPT)	~ 20	~ 0.1	~2,000-10,000 hours	*?*	7:Prototype demoed in space
Dual mode propulsion rocket	1 - 4.7	0.1 - 10^7	milliseconds-minutes	~ 3 - 9	7:Prototype demoed in space
Solar sails	300,000:Light 145-750:Wind	9/km^2 @ 1 AU 230/km^2@0.2 AU 10^{-10}/km^2@4 ly	indefinite	> 40	9:Light pressure attitude-control flight proven 6:Deploy-only demoed in space 5:Light-sail validated in lit vacuum

Tripropellant rocket	2.5 - 5.3	$0.1 - 10^7$	minutes	~ 9	6:Prototype demoed on ground
Magnetoplasmadynamic thruster (MPD)	20 - 100	100	weeks	*?*	6:Model-1 kW demoed in space
Nuclear thermal rocket	9	10^7	minutes	> ~ 20	6:Prototype demoed on ground
Mass drivers (for propulsion)	0 - ~30	$10^4 - 10^8$	months	*?*	6:Model-32MJ demoed on ground
Tether propulsion	N/A	$1 - 10^{12}$	minutes	~ 7	6:Model-31.7 km demoed in space
Air-augmented rocket	5 - 6	$0.1 - 10^7$	seconds-minutes	> 7?	6:Prototype demoed on ground
Liquid air cycle engine	4.5	$10^3 - 10^7$	seconds-minutes	*?*	6:Prototype demoed on ground
Pulsed inductive thruster (PIT)	10-80	20	months	*?*	5:Component validated in vacuum
Variable Specific Impulse Magnetoplasma Rocket (VASIMR)	10 - 300	40 - 1,200	days - months	> 100	5:Component-200 kW validated in vacuum
Magnetic field oscillating amplified thruster	10 - 130	0.1 - 1	days - months	> 100	5:Component validated in vacuum
Solar thermal rocket	7 - 12	1 - 100	weeks	> ~ 20	4:Component validated in lab
Radioisotope rocket	7 - 8	1.3 - 1.5	months	*?*	4:Component validated in lab

Nuclear electric rocket(As electric prop. method used)	Variable	Variable	Variable	*?*	4:Component-400kW validated in lab
Orion Project (Near term nuclear pulse propulsion)	20 - 100	10^9 - 10^{12}	several days	~30-60	3:Validated-900 kg proof-of-concept
Space elevator	N/A	N/A	indefinite	> 12	3:Validated proof-of-concept
Reaction Engines SABRE	30/4.5	0.1 - 10^7	minutes	9.4	3:Validated proof-of-concept
Magnetic sails	145-750:Wind	70/40Mg	indefinite	*?*	3:Validated proof-of-concept
Magnetic sail#Mini-magnetospheric plasma propulsion	200	~1 N/kW	months	*?*	3:Validated proof-of-concept
Beam-powered/Laser(As prop. method powered by beam)	Variable	Variable	Variable	*?*	3:Validated-71m proof-of-concept
Launch loop/Orbital ring	N/A	~10^4	minutes	>>11-30	2:Technology concept formulated
Nuclear pulse propulsion (Project Daedalus' drive)	20 - 1,000	10^9 - 10^{12}	years	~15,000	2:Technology concept formulated
Gas core reactor rocket	10 - 20	10^3 - 10^6	*?*	*?*	2:Technology concept formulated
Nuclear salt-water rocket	100	10^3 - 10^7	half hour	*?*	2:Technology concept formulated

Method	Effective Exhaust Velocity (km/s)	Thrust (N)	Firing Duration	Maximum Delta-v (km/s)	Technology readiness level
Fission sail	?	?	?	?	2:Technology concept formulated
Fission-fragment rocket	15,000	?	?	?	2:Technology concept formulated
Nuclear photonic rocket	300,000	10^{-5} - 1	years-decades	?	2:Technology concept formulated
Fusion rocket	100 - 1,000	?	?	?	2:Technology concept formulated
Antimatter catalyzed nuclear pulse propulsion	200 - 4,000	?	days-weeks	?	2:Technology concept formulated
Antimatter rocket	10,000-100,000	?	?	?	2:Technology concept formulated
Bussard ramjet	2.2 - 20,000	?	indefinite	~30,000	2:Technology concept formulated
Gravitoelectromagnetic toroidal launchers	300,000:GEM	?	?	<300,000	1:Basic principles observed & reported

Testing

Spacecraft propulsion systems are often first statically tested on the Earth's surface, within the atmosphere but many systems require a vacuum chamber to test fully. Rockets are usually tested at a rocket engine test facility well away from habitation and other buildings for safety reasons. Ion drives are far less dangerous and require much less stringent safety, usually only a large-ish vacuum chamber is needed.

Famous static test locations can be found at Rocket Ground Test Facilities

Some systems cannot be adequately tested on the ground and test launches may be employed at a Rocket Launch Site.