Limitations to Current Methods of Rocket Propulsion and a Prospective of Fuel Effective Photonic Propulsion
March 9, 2018

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To cite this article: https://qasim31wani.wixsite.com/infinitum
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Abstract:

The idea of interplanetary travel is no longer the work of science fiction; it has become a science reality. With the launch of Falcon Heavy, SpaceX, in February, the world is prepared for another space race: The race to colonize Mars!

Colonizing Mars is relatively easy. What’s really hard is getting there! Using current methods of rocket propulsion - chemical combustion and electric propulsion - seems like an improbable means to an ambitious goal. Why is that?

Well, we have been using the exact same type of propulsion system since 1926, though with few scientific advancements. Solid/liquid/hybrid rocket engine as a sole thrust provider to take rockets into LEO, MEO, and GEO has been the norm for decades.

So, what’s wrong with that?

Current Chemical combustion in particular has approached a vertical asymptote with relation to incremental advancements in technology through a function of time. Most people think that the key to a higher exhaust velocity and eventually a higher Δv is building a bigger rocket. That is definitely no longer true! Building a bigger rocket results in a heavier overall spacecraft. A heavier rocket will require a higher thrust-to-weight ratio to displace the weight of the rocket and accelerate at higher multitudes. Chemical propellants (oxidizer + fuel) are
extremely heavy. So storing it in either as a solid state or in liquid tanks inside a rocket with its constituent elements only increases the overall mass of the system. This is not to emphasize on the fluctuating mass of the structure, payload, and the guidance system per mission.

This can be represented mathematically using Tsiolkovsky's ideal rocket equation in free space whose derivation is given below:

\[ F = V_{\text{exhaust}} \times \frac{Dm}{Dt} \] - (1)

Here \( F \) represents thrust. Thrust is a reaction force which is produced by the rocket propulsion system acting at the vehicle’s center of mass. It can also be calculated through the following equation:

\[ F = I_{sp} \times g_0 \times \frac{Dm}{Dt} \]

Here, \( I_{sp} \) refers to the specific impulse of the rocket engine while \( g_0 \) refers to the gravitational acceleration observed by the rocket on the surface it’s situated on. Since we are lifting off from Earth, \( g_0 = 9.81 \text{m/s}^2 \). Here, \( \frac{Dm}{Dt} \) refers to mass flow rate which is the mass of the propellant that passes from the supersonic nozzle through thermodynamic expansion per unit of time.

Using Newton's second law of Motion:

\[ F = m \times v' \] - (2) Here, \( v' \) represents the acceleration of the rocket generated by thrust.

We can now equate (1) and (2) through Newton’s third law of motion:

\[- V_{\text{exhaust}} \times \frac{Dm}{Dt} = m \times v' \] - (3)

Thrust obtains a negative sign because the actual line of motion and the direction of thrust are opposite to each other (Noticed from (3) ).

Simplifying for (3) will give you the following result:

\[ m \times D_v = - V_{\text{exhaust}} \times D_m \]
\[ D_v = - V_{\text{exhaust}} \times \frac{Dm}{m} \quad - (4) \]

Now, integrating \((4)\) will give you the following results:

\[
\int_{V_i}^{V_f} D_v = - \int_{M_i}^{M_f} V_{\text{exhaust}} \times \frac{Dm}{m}
\]

\[ \rightarrow \Delta v = - V_{\text{exhaust}} \times \ln \left( \frac{M_f}{M_i} \right) \quad - (5) \]

This can be simplified to obtain Tsiolkovsky's ideal rocket equation in free space:

\[ \Delta v = V_{\text{exhaust}} \times \ln \left( \frac{M_i}{M_f} \right) \]

Now, in order to calculate the propellant mass fraction or the inert fraction, we must use the ideal rocket \((5)\). The derivation is given below:

\[ e^{-\Delta v / V_{\text{exhaust}}} = \frac{M_f}{M_i} \quad - (6) \]

This refers to a rocket's inert mass ratio.

\[ M_f = M_i - M_{\text{propellant}} \quad - (7) \]

Substituting \((7)\) into \((6)\),

\[ M_i \times e^{-\Delta v / V_{\text{exhaust}}} = M_i - M_{\text{propellant}} \]

\[ \rightarrow M_i \times (1 - e^{-\Delta v / V_{\text{exhaust}}}) = M_{\text{propellant}} \]

\[ \therefore \frac{M_{\text{propellant}}}{M_i} = (1 - e^{-\Delta v / V_{\text{exhaust}}}) \quad - (8) \]

\((8)\) can also be represented by the following equation:

\[ \zeta = \frac{m_p}{m_0} \]
Through (8), the propellant mass fraction of a standard solid rocket motor booster can be calculated, which is roughly 0.97. This means that 97% of the entire mass of the rocket should be dedicated to just the mass of the propellant while the remaining 3% should be dedicated to the inert mass, payload, and guidance system combined. This, quite frankly, is not possible! That’s why solid rocket motors are always used as ballistic missiles or as side boosters to large spacecrafts.

Liquid rocket engines don’t receive great publicity either. With its propellant mass fraction being on average 0.895, roughly 10.5% of the entire spacecrafts’ mass can be dedicated to areas other than the propellant. Though not idealistic, it’s still better than a solid rocket motor.

Another reason why chemical combustion isn’t very energy efficient is due to it’s low specific impulse - measure of how effectively a rocket engine uses its propellant- of 200-468 seconds. Nuclear thermal rocket boosters on the other hand has an $I_{sp}$ of 900 seconds. In future papers, a prospective of Nuclear Propulsion will be discussed in detail. Though it’s not in its current state-of-the-art, NP shouldn’t be ignored as it holds many assets like high $\frac{T}{W}$, $I_{sp}$, and energy efficiency.

So, using the best rocket propulsion techniques that NASA, ISRO, and SpaceX currently uses will take us to Mars in a 7-8 month long journey (only at Earth-Mars rendezvous). And it will take us 30,000 years to reach Alpha Centauri (nearest star; 4.4 light years away). Other problems like financialibility and environmental hazards are not discussed here but should be considered when discussing about the future of space exploration.
So, what’s the alternative/solution to this fundamental problem?

**Light!** Light consists of packets of energy known as photons. Using these massless photons as the propellant will exponentially decrease the propellant mass fraction by multiple order of magnitudes (~0.003-0.06)! Though it may not seem so obvious, this technology, if consistent economic and public interest shown, will make interstellar travel possible in the near future [1].

Photonic Propulsion uses the momentum generated by photons to provide thrust to the spacecraft through a reflective mirror. There are many types of photonic propulsion systems like Sunlight/LASER/Nuclear photonic propulsion.

**Sunlight for Photonic Propulsion:**

Using available sunlight as a propellant makes the spacecraft fuel-independent. Moreover, the specific impulse of this type of spacecraft is the speed of light. The spacecraft that incorporates this kind of propulsion is called solar sail. The sail is made up of or coated with highly reflective and light materials, like aluminium. The force on the sail depends on the inverse square law: \( F_{\text{sail}} = \frac{A \cos \theta}{r^2} \)

**Light Amplification by Stimulated Emission of Radiation Photonic Propulsion:**
The LASER Beam Photonic Propulsion uses the principle of a photon-pushed sail which refers to a direct momentum transfer of photons generated by a LASER source. These LASER sources can be Earth-based, placed in space or on board generated using nuclear or solar power [2]. The sail is first suspended in space using a rocket, and then a powerful LASER beam is directed at a reflective mirror to propel the sail forward. This is done by using high powered Photonic Laser Thrusters (PLT) which was invented by Young K. Bae. This differs from other solar sails and laser propulsion thrusters in that an amplification process is used. The incident beam that is deflected from the stationary mirror is re-used, with an amplification stage at each reflection. This results in a recycling of energy. Because of this, PLT has been demonstrated to be more energy efficient than any other laser-pushed sail concepts [3]. These kinds of crafts can achieve speeds up to 10% - 30% the speed of light (0.1c = 30,000 km/sec) [4]. So, humans can reach the Martian soil in less than 72 hours.

**Nuclear Photonic Propulsion**

In this type of propulsion, nuclear energy is converted into a blackbody radiation through powerful radiation absorbing shields and reflectors. The nuclear energy generated by on-board fuel provides thrust to the spacecraft. Hence, this is a fuel-dependent spacecraft.

The following power per thrust requirements is calculated below by N Rajalakshmi and S Srivarshin of Sri Sairam Institute of Technology, Chennai, India (see ref.):
Here, $\alpha M$ the total mass of the fuel. Considering the above notations, [7]

\[
E_{ph} = \frac{Me^2}{\alpha \delta \gamma} \tag{5}
\]

\[
T_{ph} = \frac{E_{ph}}{M} \tag{6}
\]

\[
V_{max} \approx \frac{T_{ph}}{\alpha \delta \gamma \epsilon} \tag{7}
\]

We know that $T_{ph}$ is 88N and mass is approximately 5kg.

\[
\text{So, } V_{max} \approx \frac{88}{5 \times 9.8} = 1.79 \text{ m/s} \tag{using eqn. 7}
\]

\[
E_{ph} = T_{ph}c = 88 \times 3 \times 10^8 = 2.64 \times 10^{10} = 26400 \text{ MJ} \tag{using eqn.6}
\]

Assuming 10% of fuel is effectively converted into propulsion energy, $\gamma = \frac{10}{100} = 0.1$;

\[
\alpha = \frac{E_{ph}}{\frac{M}{2\epsilon^2 \delta \gamma}} = \frac{26400 \text{ MJ}}{5 \times 9.8 \text{ kg} \times (3 \times 10^8)^2 \text{ m/s} \times 0.1^4} = 1.197 \times 10^{-7} \tag{for } \delta = 0.5 \text{ (using eqn.5)}
\]

Thus, $1.197 \times 10^{-7} \times 5 \times 0.8 = 5.86 \times 10^{-6} \text{ kg} = 5.86 \times 10^{-3} \text{ g}$ of fuel is required.

5.3. Comparison with conventional propulsion

It requires 35.2 kN of thrust for mass of 2000 kg for conventional rockets. That would be provided by:

\[
\frac{1}{300 \text{ kW} \times 35200 \text{ N}} = 10500 \text{ GW} = 10.5 \text{ TW of power}.
\]

\[
V_{max} \approx \frac{T_{ph}}{M} = \frac{35200}{2000 \times 9.8} = 1.79 \text{ m/s} \tag{using eqn.7}
\]

\[
E_{ph} = T_{ph}c = 35200 \times 3 \times 10^8 = 105.6 \times 10^{11} \text{ J} \tag{using eqn.6}
\]

Assuming 10% of fuel is effectively converted into propulsion energy, $\gamma = \frac{10}{100} = 0.1$;

\[
\alpha = \frac{E_{ph}}{\frac{M}{2\epsilon^2 \delta \gamma}} = \frac{105.6 \times 10^{11}}{2000 \times 9.8 \text{ kg} \times (3 \times 10^8)^2 \text{ m/s} \times 0.1^4} = 1.197 \times 10^{-7} \tag{for } \delta = 0.5 \text{ (using eqn.5)}
\]

Thus, $1.197 \times 10^{-7} \times 2000 \times 9.8 = 2.34 \times 10^{-3} \text{ kg} = 2.34 \text{ g}$ of fuel is required.

From the above calculations, it can be seen that the fuel requirements for nuclear photonic propulsion is much less than that of conventional methods of rocket propulsion.

Main constraint to Photonic Propulsion

Besides budget and public interest, this technology faces one main problem - source of energy for the sail. Our calculations show that the energy required to propel the spacecraft forward is equivalent to the current power used by the entire world. This also means that the sail
must have an area of at least a 1000 square meters. As per one source, the sail would have to be the size of Texas, U.S.A [5].

So, unless scientists and engineers are able to build a much smaller PLT with same level of thrust as the desired sail, this method of propulsion will be favorable in the foreseeable future.

**Conclusion**

The 21st century is a great time to live in. With technology improving exponentially, predicted by Moore’s law, humans will in a few decades start building colonies on Mars and other exoplanets. Thus, if long-term research of photonic propulsion is fueled by constant economic interest and public support, it would take us on the ‘ultimate path to fuel independence for spaceflight.’ Making life multiplanetary is what will be mankind's most remarkable achievement.

“Small step for Man, one giant leap for Mankind.” - Neil Armstrong
Reference


