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Reusable Launch Vehicles: Evolution Redefined

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Abstract

Conserve, Reuse, Reproduce these are the words using which the present day society is trying to make an impact in reducing the excessive usage of the depleting resources and decreasing time as well as in bringing down the cost and in increasing the efficiency of the products. One of the technology's biggest inventions rather innovation at work is the development of The Reusable Launch Vehicle, in short known as the RLV. Reusability is the main criteria behind this vehicle. The vehicle will return back to earth after its task is completed, and is used for further missions. This invention mainly reduces the cost, time and the specified targets can be achieved with the use of fewer resources.

The idea of RLV made its foundation in the minds of the scientists in the 1950's but bringing that idea into a real launch vehicle took many years as this idea was beyond the hands of the technology of that time. As the technology developed the path for the successful making of this launch vehicle was getting cleared. There were many factors that were to be considered like the low weight structure, heat shield, the propellants needed to be used, the engines etc. but the main aim was to bring out the concept behind its working and building a proper design which are discussed in this paper. With the ever-growing technology RLV's with improved mechanisms like SSTO, TSTO were developed which are also mentioned below. In near future these RLV's would completely bridge the gap between the earth and the sky.

Keywords: Propellant; Propulsion; Aero dynamics; Pay load; SSTO; TSTO; Optimal flight control; Alkali metal thermo electric converter; Time varying sliding mode control (TVSMC); IVHM; Rocket based combined cycle (RBCC); Booster

Introduction

A Reusable launch vehicle (RLV) (Figure 1) refers to a vehicle which can be used for several missions. Once when a RLV completes a mission, it returns to the earth and can be used again whereas the Expendable Launch Vehicles (ELV) can be used only once. This is the main advantage of a Reusable Launch Vehicle (RLV) and this can be done at very low cost.

Though the thought of Reusable launch vehicles started in 1950's, because of low technology development like insufficient thrust-to-weight ratio of engine to escape our gravity etc made their thoughts impossible. Later due to the advancement in the technology the existence of the Reusable launch vehicle became possible. Philip bono proposed few concepts for the development of the vehicle like plug-nozzle engines to retain high specific impulse at all altitudes, use of drop tanks to increase range, use of in-orbit refueling to increase range, use of spherical tanks and stubby shape to reduce vehicle structural mass further. Eugen Sanger also proposed few concepts for advancement of the vehicle like rail boost, use of lifting body designs to reduce vehicle structural mass, use of in-flight refueling. In 1960's space shuttle design process started. The space shuttle has rocket launch, orbital spacecraft and re-entry space plane. In 1986 an air breathing scramjet was planned to build by 2000 but due to research project copper canyon failure it was cancelled in 1993. Few more concepts were proposed in 1990's. In 21st century X-33, X-34 was cancelled due to rising cost. Later these space shuttles were found to be highly expensive and two out of five space-worthy orbiters were destroyed during accidents. Hence orbital reusable launch system is currently not in use.

Figure 1: view of RLV.

Several reusability concepts are single stage, two or more stages to orbit, cross feed, horizontal landing, vertical landing, horizontal take-off, vertical take-off, air breathing, propellant, propellant costs, launch assistance, reentry heat shields, weight penalty, maintenance, manpower and logistics. In this paper we will see the aspects that are to be considered while constructing an RLV, different ways of launching of an RLV, design of an RLV and its working.

Over the past several years many concepts have been proposed for the development of the reusable launch vehicles. When the decision of replacement of shuttle has been taken, interest and excitement was observed to generate a low cost Reusable Launch Vehicle. While

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designing an RLV, main aspects that are to be focused are composite, low weight structure, a well-developed heat shield to protect the system from disintegration while re-entering, improved propulsion, propellants, increased range, high payload carrying capacity. The reusable launch system includes reusable cryogenic propellant tanks, composite structures, thermal protection systems, and improved propulsion and subsystem operability enhancements [1-3].

The key technological aspects that are to be focused

Utilizing wave rider aerodynamics reduces the vehicle weight. The takeoff weight and the thrust required at takeoff are reduced by collecting the rocket oxidizer in-flight [4]. Reusable Thermal Protection System (TPS) is one of the main aspects to be concentrated as it is one of the most expensive systems of RLV. TPS should be lightweight, durable, operable and cost effective. Metallic TPS, super alloy honeycomb TPS concept are used to get good results. The surfaces are tested by low speed and hyper velocity impacts, aerodynamic heating, acoustic loading. The TPS should be capable of withstanding the heat while re-entering the earth. Some shields may undergo severe damage hence they cannot be used again. The use of sharp materials whose tolerance temperature is about 3600°C helps a RLV to re-enter the atmosphere safely and these materials need not require a constant maintenance [5-8]. The ramjet and scramjet propulsion technology is the most significant propulsion technology. Solar thermal propulsion, hydrogen propulsion are demonstrated by SOTV space experiment. Some other engines include hydrogen/oxygen rockets, turbojets, turbo rockets and liquid air cycle engines. These engines fail to reach the goal which resulted in a pre-cooled hybrid air breathing rocket engines [9]. The propellants of high density compensate for reduced specific impulse. Hydrogen is an environmentally acceptable aviation fuel [10,11]. The development of an RLV aim at the significant reduction of payload transportation costs [7].The design of large–payload SSTO vehicle is based on projections of mature National Aerospace Plane (NASP) technology [12]. The single-stage vehicles which use air-breathing propulsion provide more economical delivery of payloads to orbit [13]. Several new propulsion concepts are being studied to increase the payload capacity [14]. When horizontal takeoff is considered with first stage powered by turbojet engines and the second stage propelled by a rocket engine provides 3 times the payload weight to orbit when compared to the vertical takeoff mode [15].

Single-stage-to-orbit (SSTO)

An SSTO (Figure 2) reaches the space orbit without losing any hardware to reduce weight with the help of fluids and propellants. An aero spike engine configuration can be used as a study vehicle for the conceptual analysis of a single-stage-to-orbit reusable launch vehicle. The vehicle's lifting capability, linear aero spike engine and, metallic thermal protection system and performance can be studied by this configuration [8]. Many studies are going on to provide lower cost access to space [16]. A conceptual design of an advanced RLV is Hyperion in the vehicle vision class. It utilizes LOX/LH2 ejector scramjet Rocket-Based Combined Cycle (RBCC) propulsion and it is a horizontal takeoff and horizontal landing SSTO vehicle [17]. Delta clipper SSTO vehicle implements the SSTO VSM functions in a reliable, cost effective, supportable method [18]. The ballistic SSTO vehicle uses conventional rocket propulsion. For a medium-size cargo this seems to be the prime candidate for future RLV because of its inherent technical operational simplicity by limiting it to just one stage [19]. An SSTO vehicle have a minimum landing speed of 165-kt, use LOX/LH2 propellants, payload sizes of 20,000 lbs to LEO and 40,000 lbs to earth [20]. The propulsion system selected for this is 'pre cooled hybrid air breathing rocket engines' [9]. The major perceptions about SSTO's are regarding mass fraction, performance margin, small payloads, and their sensitivity to unanticipated vehicle weight growth. These can be dispelled by advanced technologies like graphite composite primary structure, Al-Li propellant tanks with reusable thermal protection, autonomous flight control etc [21]. Horizontal-takeoff single-stage-to-orbit (HT-SSTO) has a two dimensional optimal ascent trajectory with aerodynamics and constant thrust which depends on angle of attack and Mach number. The two-dimensional optimal control law can be used in the preliminary design of an arbitrary launch vehicle configuration and provides characteristics of the horizontal-takeoff ascent-to-orbit trajectory [22]. The below figure indicates the diagram of a launch vehicle following the working of SSTO.

Figure 2: view of SSTO.

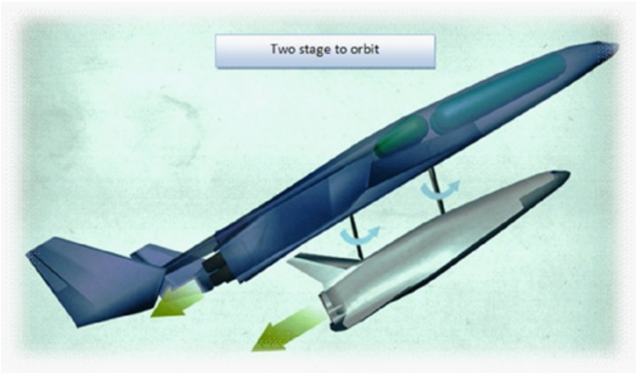


Figure 3: view of TSTO.

Two-stage-to-orbit (TSTO)

In the TSTO (Figure 3) launch system, two independent vehicles operate. While the first stage vehicle can return to the launch site for re-use, the second stage can return after flying one or more orbits and re-enter. Stargazer is a TSTO vehicle with an expendable LOX/RP upper stage and a reusable fly back booster. It has a payload of 300lbs to low earth orbit. Advance technology is used in the booster and the thermal protection system. The four LOX/LH2 ejector scramjet rocket-based combined cycle engines are used to power up the booster which is Hankey wedge shaped [23]. We can study the potential benefits of a fully reusable TSTO with a separate ramjet and rocket propulsion system [24]. The Saenger type TSTO vehicle having subsonic air breathing propulsion in first stage and rocket propulsion in second stage can deliver the specified payload mass and was found to be feasible, versatile [25]. Starsaber is a TSTO vehicle with a reusable winged booster and a LOX/RP-1 expendable upper stage. Two hydrocarbons fueled Ejector Ramjet (ERJ) engines are used to power up the booster. This vehicle has a capability of 300lb payload into Low Earth Orbit (LEO) and utilizes advanced technology in structural and thermal protection system materials [26]. To explain the aerodynamic forces, moments, and to determine the proximity flow environment a stage separation wind tunnel tests of a generic TSTO launch vehicle were conducted [27]. Radiance, a TSTO vehicle that stages at Mach 12 has an air breathing first stage and rocket-powered second stage. It takes off horizontally with the help of integral landing gear. Radiance hampered by the high drag losses because of its booster size [28]. TSTO launch systems utilizing SSTO-class vehicle technology, offer a better economic advantage for access to LEO [29]. The below figure indicates the diagram of a launch vehicle following the working of TSTO.

Design of an RLV

The conceptual design of a vehicle has a wide variety of evolutionary technologies and encapsulates the major engineering disciples for a 3rd generation RLV. The employment of new propulsion system is critical to the design of a vehicle [30]. Multidisciplinary analysis and optimization are required to find the best design [31]. Taguchi method is an efficient way of designing with quality, low cost, significant time, resource saving [32]. Through the study of Taguchi method for the optimal cutting parameter for turning operations and by analysis of variance (ANOVA) not only optimal cutting parameters but also main cutting parameters that affect the cutting performance in turning operations are obtained [33].

Body: The body of a RLV has to withstand very high stresses including thermal stresses during re-entry. The plane expands due to the high heat. It also has to cope with the rapid change in temperatures once in space. It changes from-250 degrees in the shade to 250 degrees in direct sunlight. This change in temperature between two sides of the same plane will put a lot of stress on its body. The body is mainly influenced by the location of the slow separation, the shock waves on the surface and pressure level behind the body.

Titanium alloys are being used, being very strong and light. To cope with the high temperatures developed in parts of the wing and fuselage of the spacecraft today, reinforced carbon-carbon composite material is being added to the leading edges of the vehicle's nose and wings to handle the higher temperatures [34].

Wings: The wing of the spacecraft has to be designed so that it provides enough lift to fly to space and also reduce the friction during re-entry

Cockpit: The cockpit is the place where the astronauts will stay most of the time during the journey. It has many double-paned glass windows which can withstand the force of flight, pressure and vacuum. With these double-paned glass windows, passengers would be safe even if the window cracks. A three-part system is used to make the air inside the cockpit breathable. Oxygen bottles are used to add breathable air at constant rate. An absorber system removes the exhaled carbon dioxide in the cabin and another absorber system makes the air free from water vapor. A comfortable, cool, dry cockpit is observed during the whole flight.

Electric power: The electrical power required for the running of the spacecraft has to be taken from batteries. These batteries could be charged, if needed by using solar energy. Researchers are being initiated to find better and reliable batteries, like the lithium-based (Li metal). Its advantages include reduced battery weight and volume which permits greater payloads and greater cell voltage which permits use of fewer cells and results in reduced battery system complexity. Alkali Metal Thermoelectric Converter (AMTEC) power converters can be used to generate 20 kW to 100 kW of electricity [35].

Controls

In RLV, altitude control in ascent and entry flight phases is done by Time-Varying Sliding Mode Control (TVSMC). In entry flight guidance commands aerodynamic angles of bank, attack, and side slip. In ascent flight it commands Euler roll, pitch and yaw angles [36]. An autonomous reusable launch vehicle requires more guidance and control as an adaptive human pilot will not be present in unanticipated conditions. This utilizes the online trim algorithm which provides outer loop with the feasible range of Mach number, angle of attack, for which the vehicle can be rotationally trimmed [37]. An autonomous mission control and management include ground and flight controls [18]. The optimal flight control for re-entry and return flight to the launch site can be studied by a preliminary design of a multistage Reusable Launch Vehicle (RLV). Several concepts like classic optimization methods, terminal control etc, are applied on RLV and studied. A liquid fly-back booster RLV is used to demonstrate the application of these quasi-optimal methods [38].

General working principle of RLV

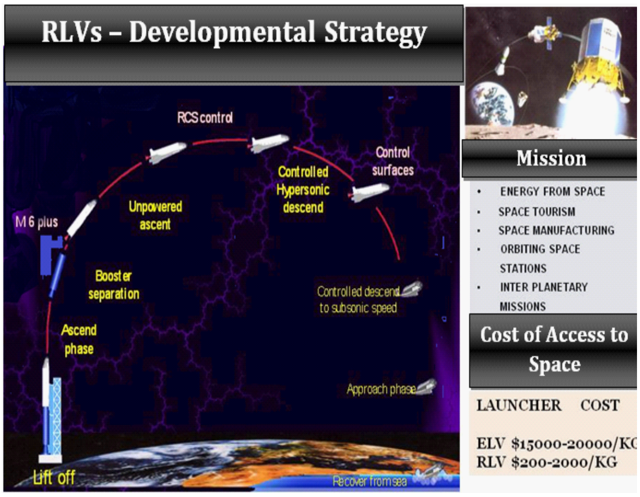
The working of a RLV can be divided into 4 stages

First stage–subsonic and supersonic stage: The RLV with its payload takes off from the runway and climbs to about 100,000 feet or 30 km using conventional jet-engines, or using a combination of conventional jet-engine and ramjet engine, or using another plane to carrier pull the plane to a lower height and using a booster rocket. Air which is compressed by the forward speed of the aircraft combines with fuel and undergoes subsonic combustion. Ramjet operates by this principle. It doesn't have or use very less moving parts compared to a conventional jet-engine with thousands of moving parts. The compression of air before burning of fuel is done in the ramjet by the addition of a diffuser at the inlet, while it is done by the turbine in conventional jet-engine. The plane is accelerated to a speed of mach 4 or mach 5 and the flow inside the engine becomes supersonic. Then the scramjet is powered up.

Second stage-Hypersonic stage: When the space plane is at an altitude of about 100,000 ft and at a velocity of about mach 4, the scramjets are fired. Scramjets are basically ramjets. They introduce fuel and mix it with oxygen obtained from the air which compressed for combustion. The air is compressed by the shape of the inlet and forward speed of the vehicle.

When hydrogen fuel is injected into the airstream, hot gases expand due to combustion. Flow through the scramjet engine is faster than the speed of the sound at operational speeds. Combustion and ignition takes place in milliseconds at this speed. The Scramjet engine takes the RLV to even greater heights and to speeds of up to Mach 15. At Mach 15, the RLV is at a great height that there isn't enough oxygen to sustain the scramjet engine. At this point the rocket engine fires up.

Third stage-Space stage: When the rocket engine fires by mixing oxygen from the onboard storage tanks into the scramjet engine, thereby replacing the supersonic air flow. The rocket engine is capable of accelerating the RLV to speeds of about Mach 25, which is the escape


RLVs – Developmental Strategy

Mission

- ENERGY FROM SPACE
- SPACE TOURISM
- SPACE MANUFACTURING
- ORBITING SPACE STATIONS
- INTER PLANETARY MISSIONS

Cost of Access to Space

LAUNCHER	COST
ELV	$15000-20000/KG
RLV	$200-2000/KG

Figure 4: RLVs developmental strategy.

velocity. It takes the RLV into orbit. The rocket engine takes the RLV to the payload release site and the required operations are done. Once this is over it enters its last stage–the re-entry stage.

Fourth stage–Re entry stage: Once the RLV finishes its mission in space, It performs de-orbit operations to slow itself down, thereby dropping to a lower orbit and eventually entering the upper layers of the atmosphere. As the vehicle encounters denser air, the temperature of the ceramic skin builds to over 1,000°C, and is also cooled by using any remaining liquid hydrogen fuel. It is here that the structure of the plane undergoes heavy thermal stress. If the heat shields do not protect the plane, it would simply burn off to the ground. Once it reaches dense air, it can use its aerodynamics to glide down to the landing strip. It can also use any remaining fuel to fire the ramjet or conventional jet (depends on the design) and change its course. Once on the landing strip it engages it slows down using a series of parachutes and engages the brake.

The figure (Figure 4) explains the different working stages of an RLV. The general cost estimation for an expendable launch vehicle varies from $15000 to $20000/KG but whereas a reusable launch vehicle cost just varies between $200-$2000/KG. Thus it makes clear that the launcher cost of an RLV is low when compared to ELV.

Conclusion

A reusable launch vehicle should be constructed in such a way that it can be reused for several missions whereas an Expendable Launch Vehicle (ELV) can be used only once and it is very expensive. From the previous experiences and knowledge, a future reusable launch vehicle should be constructed within low cost. Constructing a reusable launch vehicle using Integrated Vehicle Health Management (IVHM) technologies and its basic objectives offers saving in the operation costs. Autonomous reusable launch vehicles are considered to be low cost alternatives. Future RLV are to be developed through an extensive flight demonstration.

This article provides an overview on what aspects should be concentrated on, while constructing an RLV such as weight, thermal protection systems, increased propulsion, propellants, payload capacity etc, gives an idea on design and different working stages of RLV. Researchers are being done on the development of the Reusable launch vehicles and the budding students who are interested in this stream; this provides an added advantage to gain better knowledge, which would open opportunities in building up much advanced version of RLV. As we all know, to make an advanced version it is very important to anyone, on understanding the various current advancements in it and having a grip on the basic aspects of RLV.

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