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Generation-II Lunar Entry Approach Platform For Research On Ground: a novel concept for low cost, high longevity autonomous operations on the Moon

M. Smat[a] *, A. Russo[b], O. Famutimi[c], I. Puranik[d], A. Osmundson[e], A. Narain[f], D. Bernacchia[g], R. Rughani[h], D. Barnhart[i]

[a] *Viterbi School of Engineering, USC, United States, msmat@usc.edu*
[b] *Politecnico di Milano, Italy, aloisia.russo@mail.polimi.it*
[c] *Viterbi School of Engineering, USC, United States, famutimi@usc.edu*
[d] *Viterbi School of Engineering, USC, United States, ipuranik@usc.edu*
[e] *Viterbi School of Engineering, USC, United States, aosmunds@usc.edu*
[f] *Viterbi School of Engineering, USC, United States, antariks@usc.edu*
[g] *Alma Mater Studiorum - Università di Bologna, Italy, david.bernacchia@studio.unibo.it*
[h] *Viterbi School of Engineering, USC, United States, rughani@usc.edu*
[i] *University of Southern California, United States, barnhart@isi.edu*

* Corresponding Author

Abstract

Lunar exploration generates great interest because it provides a compelling opportunity to demonstrate new technologies that could help build self-sustaining outposts in extra-terrestrial environments, particularly Mars. Success in this challenge depends on developing sustainable and reusable architectures. Many of the diverse lunar missions currently in development have narrowly defined purposes and are consequently only capable of operating in limited areas on the lunar surface and executing specific predetermined tasks. The mass sent up for the mission therefore rarely serves more than a single purpose. The Space Engineering Research Center (SERC) at the University of Southern California has developed the Lunar Entry and Approach Platform for Research on Ground (LEAPFROG) with the primary goal of reinventing the function of a lunar lander such that it has the inherent capability to perform multiple tasks by changing the working configuration of its subsystems, maximizing the functional value of its mass. LEAPFROG is a low-cost testbed primarily for simulating lunar flight conditions on Earth. To address the challenge of reaching different landing sites on the Moon, the team developed a unique guidance, navigation, and control system that leverages the symbiotic relationship between thrust vector control of a central jet engine, and fixed attitude thrusters, allowing LEAPFROG to adapt to different thrust values and environmental conditions. The air-based propulsion provides a low-cost, low-risk, highly repeatable analogue to a monopropellant rocket propulsion system, which will be used in the future while maintaining the same control architecture. Since lunar landers with long mission timelines must be able to self-charge their onboard batteries, LEAPFROG is equipped with solar panels that deploy on-demand. Its origami-based compact solar panel structure extends up to six times its folded configuration, providing the potential to supply power to multiple mission payloads. LEAPFROG's robotic arm can be utilized to manipulate tools and perform tasks like drilling, taking samples, etc. Unlike other robotic arms which are typically held down with flight locks when not in operation, this arm acts as a secondary structure that ensures the stability of fuel tanks during its non-operative mode. LEAPFROG is versatile and affordable. This platform is a robust canvas upon which researchers can rapidly develop and iterate on new technology for lunar missions, ushering us on our path to becoming an interplanetary species. This paper outlines the first and second phase designs of all subsystems, and details all results gathered by various testing of the components.

Keywords: landers, Moon exploration, robotics, thrust vectoring control, origami, self-sustainable systems

Acronyms/Abbreviations

Attitude Control System……………………………ACS

Commercial Off-the-Shelf…………………..……COTS

Degree of Freedom ………………………………...DOF

Electronic Control Unit ……………………………ECU

Lunar Entry Approach For Research On Ground………………………LEAPFROG

Lunar Lander Research Vehicle…………..………LLRV

Micro Electro Mechanical System………………MEMS

Multi-functional SElf-reconfigurable Robotic Arm…………………………………..RAMSEs

Origami Solar Panel………………………………...OSP

Space Engineering Research Center……………...SERC

Thrust Vector Control……………………………...TVC

University of Southern California………………….USC

1. Introduction

In the last decade, the Moon has attracted companies from the private and public sectors due to its ability to facilitate the demonstration of new technologies that could help build self-sustaining outposts off Earth [1]. A path for success in this challenge lies in international collaboration to explore achievable sustainability through use of reusable architectures, and the capability to equitably manage Moon resources to create a permanent Lunar base. In this context, a reusable and completely autonomous lander capable of performing multiple tasks on the Moon's surface can help to accomplish the stated objectives.

Work on the Lunar Entry and Approach Platform for Research on Ground (LEAPFROG) at the University of Southern California's (USC) Space Engineering Research Center (SERC) is directly related to this objective. LEAPFROG started as a hands-on project for students to simulate flight and ground activities similar to the lunar gravitational environment using a repeatable flight system with a jet air breathing engine to simulate flight in lunar gravity. It is a multi-generational project with stepwise increasing complex prototypes, developed for over more than a decade starting from Generation-0 in 2006 and continuing to Generation-II in 2020.

As the goal of returning to the Moon grows in popularity, a variety of companies have begun development on new lander designs, each with unique objectives (i.e. Blue Origin [2], Boeing [3], Indian Space Research Organisation [4], Orbit Beyond and Astrobotic [5]). The projects proposed from these companies are capable of landing in selected zones on the lunar surface, and executing different types of exploration or research functions, such as releasing small rovers. Most landers are monolithic in function, that is the mass sent up only executes one task. Our goal with LEAPFROG Generation-II has the aim to re-think the function of a lander so that it can perform multiple activities with the same structure. This includes capabilities such as transforming into a rover to save propellant and enable a larger area of exploration from the landing zone, or unfolding to allow a greater surface area for reflecting RF communications.

2. Previous Iterations

The initial LEAPFROG vehicle Generation 0 was a semester long, student-built proof-of-concept vehicle, fabricated from commercial off-the shelf (COTS) components, and intended to hover and translate for 5 minutes. LEAPFROG Generation I was designed with lighter, more reliable landing legs, and a more stable attitude control system (ACS) designed to hover for roughly 3 minutes. Although successful, Generation I was limited in its capability. Its configuration was not suitable for a payload and it was only capable of hovering and landing. It is replaced by Generation-II whose design aims to achieve multifunctionality.

2.1 Generation 0

Generation 0 was a 20 kg composite fiberglass vehicle equipped with four carbon fibre legs. Its ASC consisted of four cold gas thrusters operated with two high-pressure paintball tanks. Its kerosene powered jet engine, Jet Cat P-200, could generate 50 lbf of thrust. Its avionics system consisted of a COTS microcontroller and a custom-made motherboard that collected data from a three axis micro electro mechanical system (MEMS) accelerometer, three single axis MEMS gyroscope, and a laser range finder. Power was provided to the system via rechargeable Li-Ion and Polymer batteries [6].

High level requirements included a positive thrust-to-weight ratio, and a flight time exceeding 5 minutes. Simulating lunar descent and landing trajectories on earth required offsetting earth's gravity to the moon's gravity and accounting for external disturbance and torques caused by atmospheric effects.

Drawbacks of Generation 0 included that its ACS was designed to act on vehicle pitch and roll, thus neglecting yaw and causing instability in the direction of travel. Additionally, the landing pads on its leg were made of collapsible paper bowl fixed to an aluminium plate that was then bolted to the leg's bottom flange. Although an inexpensive design, they were not reusable, requiring repairs after each landing.

Figure 1 depicts the configuration of Gen-0. Its ACS, including tanks, valves, pressure gauges, and tubing were placed on the structure's underbelly. Its kerosene fuel tanks were placed on the top of the platform along with batteries and electronics, limiting space for potential payloads.

Figure 1: Top and bottom view of LEAPFROG Generation-0

2.2 Generation I

Generation I was the second iteration of LEAPFROG with a greater thrust to weight ratio, extended flight time and improved ACS. This served to increase the vehicle's efficiency and robustness. The requirements that Generation I was designed to are listed in Table 1:

Table 1: Generation I Vehicle Requirements

1	Greater thrust to weight ratio (>1.20)
2	Vehicle can accommodate a 5-10lb payload throughout flight without hindering vehicle operations or affecting flight dynamics
3	Vehicle can maintain semi-autonomous continuous continuous flight for up to 3 minutes
4	Vehicle structure can withstand a drop test from a height of up to 3 feet without suffering major deformation or failure to any of the vehicle's components/structural elements
5	Incorporates an improved cold-gas based Attitude Control System for greater range of motion throughout flight (3-axis, 6 DOF)
6	Maintains in-line safety and abort commands for all anticipated failure modes
7	Serves as an optimal testbed (accurately simulates minimal gravitational lunar environment) for student developed on-board GNC algorithms

To meet these design intents, instead of using JetCat P200, Generation I utilized a JetCat P300 engine. This resulted in a minimal addition of 0.5 lb of weight while increasing the thrust capability of the vehicle. Its revised ACS system included the addition of four thrusters for yaw control.

3. Generation-II

Previous iterations were focused on prototypes for repeatable flight in Earth's gravity. For Generation II we aimed to design a completely autonomous vehicle capable of serving more than one purpose while maintaining the capability of flight testing on Earth. Features included on Generation II include a carbon fibre chassis, JetCat P300 kerosene engine, thrust vector control (TVC) system, cold gas ACS, a deployable on demand solar panel to recharge onboard batteries, and an onboard robotic arm for manipulating different tools, among others. Figure 2 is an illustration of the Generation-II design intended for lunar surface operations.

3.1 Systems Overview

A unique Gen-II ACS system that provided interchangeable TVC of the central jet engine with the fixed cold-gas thrusters allowed LEAPFROG to adapt to

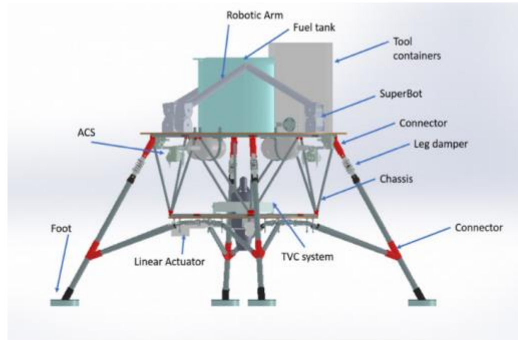


Figure 2: Generation-II Vehicle CAD Rendering

different thrust values and environmental conditions. Long mission timelines for a lander translates to the ability to recharge the on-board batteries, thus a deployable on-demand solar panel was included. We developed an Origami based Solar Panel (OSP) which extends up to six times its folded configuration. Another element which was meant to be multi-functional was the on-board robotic arm which is utilized to manipulate different tools and extend the OSP (Multi-functional SElf-reconfigurable Robotic Arm or RAMSEs). The arms needed a suitable DOF to handle a drill, a shovel, a gripper, or other tools for its primary function. Unlike other robotic arms which are typically held down with flight locks when not in operation, we built in a function where it acts as a secondary structure that ensures the stability of fuel tanks during its non-operative mode including launch, flight, and landing operations.

In the design and consideration of Generation II we realized that some of the innovative multi-functional elements may not be possible to prototype at this time as they are still under study. Thus, the team decided to focus Generation-II for an Earth based prototype on a new structure, a new ACS, the jet engine and the TVC system as primary new innovations for the actual LEAPFROG testbed. In Table 2, the LEAPFROG Generation II project requirements are listed.

Table 2: Generation-II requirements

ID	Project Requirements
R-HLR-01	Shall exploit the multi-functionality
R-HLR-02	Shall be completely built by students by using COTS and USC already developed and tested technologies
R-HLR-03	The overall cost shall be below $20k
R-HLR-04	Shall be totally reusable
R-HLR-05	Shall simulate Moon landing on Earth environment
R-HLR-06	Shall embark a payload to be tested on-board
R-HLR-07	Shall guarantee the payload safety

3.2 Structural Design and Analysis

To accommodate the previously mentioned features into an Earth based flight prototype, the structure of LEAPFROG Generation II required a design with an optimized strength to weight ratio. Additionally, due to the testing which would occur on this vehicle, it needed to maintain modularity to allow for modifications on various components during iterative testing. This was accomplished using 0.5" diameter carbon fibre tubes to construct the chassis and ¼" five-pound density foam core fiberglass composite sandwiches to act as additional structural support and provide a mounting surface for the variety of hardware to be included.

In order to maintain a low cost for the structures, the chassis was designed as an assembly of connected struts as opposed to a single composite structure. The carbon fibre tubes on the chassis uses a 2x2 twill weave pattern and have a wall thickness of 0.048 inches and are manufactured by Rock West Composites. To avoid using a destructive method for connecting the tubes, aluminium connectors from DragonPlate are bonded into the tubes and threaded to one another to form a reliable coupling mechanism, as shown in Figure 4. The configuration of the tubes was designed so that all components that require rigid constraints could be fastened directly to the chassis. This includes the gimbal holding the jet engine, the composite wound cold gas air supply tanks for the ACS, and the engine fuel tanks.

Figure 4: CAD of carbon fibre tube coupling method

The design for the leg assembly was optimized for loading conditions caused by impact due to landing. Using ANSYS Composite PrepPost Modeler, the legs were iteratively simulated using parameterizing inputs and outputs. A result of this simulation is depicted in Figure 3. Parametrized inputs included the diameter, length, and wall thickness of the leg, position of the support struts, and angle of the leg with respect to the vertical. Parametrized outputs included the von Mises stresses on each of the parts made from isotropic materials, including the shock absorber and connector pieces, the factor of safety against failure in the composite leg, and force reactions at the end of the supports to design the suspension system there. The result of this simulation shows best overall results using a filament wound 1.22 inch diameter carbon fibre tube with a wall thickness of 0.145 inches and length of 27 inches.

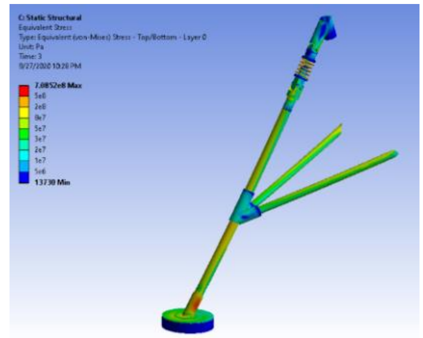


Figure 3: Results of ACP simulation on leg assembly

3.3 Specific design consideration for the Lunar Design Version

Figure 5 shows the lunar design version for LEAPFROG, which is separate from the Earth based flight prototype. Most primary elements were placed on the top platform including the tank, the RAMSEs arm which acts as a secondary structure during the lander operative mode, and the tools the arm must manipulate. The tank is configured to guarantee the symmetry of the top platform center of mass and stability during the lander's flight.

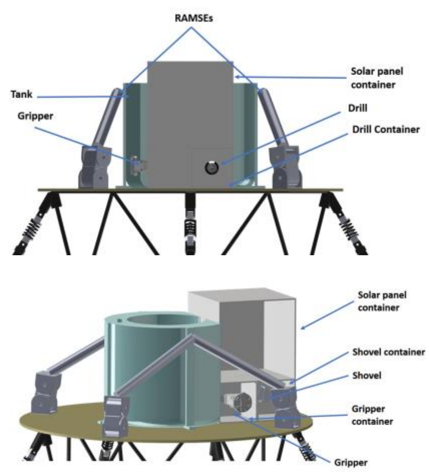


Figure 5: Labeled views of top surface hardware

In the lunar based Generation II design, a proper design of the boxes still must be done because tools are there to show their placement once their design is complete and understand where the grabbing point is for the RAMSEs end-effector. Therefore, once the geometry and mass of the tools are ready, suitable containers must be designed. Moreover, it will be shown the OSP box has to have a smaller height to avoid interference with the RAMSEs motion. All the packages are here screw driven together to prevent relative movement during the lander motion.

3.4 Avionics

The current implementation houses a master onboard computer which controls the cold gas thrusters and communication with the ground station. The master system relays thrust vectoring information to the child microprocessor which controls the gimbal system and thrust from the engine, as seen in Figure 6.

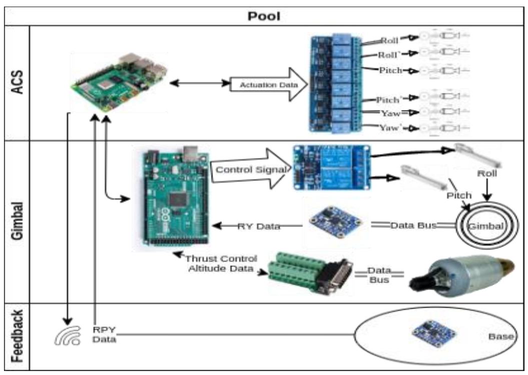


Figure 6: Avionics diagram

Communication is done on a 2.4GHz WiFi channel between the master controller on the vehicle and the ground station. This channel relays telemetry data related to the vehicle like, position, orientation and velocity every 1ms. The local communication between the parent and child processor is done using UART communication where the state of the vehicle (take-off / land / waypoint) is given as input and TVC system moves accordingly to minimize the error in position.

As GPS will not work on lunar surface, the vehicle uses a self-positioning system using the IMU sensor and altitude sensor data. The relative positioning system using inertial measurement unit (IMU) [7] algorithm is implemented. The system loses its accuracy over time, but give fair approximation which is then used for waypoint navigation. The IMU sensor is mounted on the top shelf of the vehicle and is also used to calculate the roll and pitch of the vehicle.

To have a stable flight the ACS and TVC work simultaneously, where the purpose of the ACS is to keep the top shelf of the vehicle parallel to the ground and TVC to provide altitude and translation. A PID controller is implemented for both the systems which take filtered value from the sensors and compute the output to the actuators, as seen in Figure 7 [8].

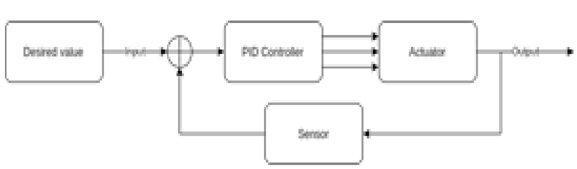


Figure 7: Control loop of the system

The ACS uses cold gas thrusters to keep the vehicle in the desired orientation. The onboard computer uses the IMU data and feeds the actual and desired position to the PID controller which further calculates which thruster to fire and for how long. The default orientation is mostly zero-degree roll and pitch angle while take-off and landing and +/- 10 degree (max) during translation.

The TVC has two subcomponents, the gimbal and the engine. The gimbal is moved using linear actuators to change the roll and pitch angle for the engine. There is an IMU sensor mounted on the gimbal to give orientation values and these values are tallied with the feedback from the linear actuators to calculate the actual gimbal roll and pitch values. The engine is connected to an interface which allows the microcontroller to send desired engine thrust information using servo PWM signals.

To improve the response time of the system we plan to implement a parallel software architecture which allows simultaneous actuation of each cold gas thrusters and linear actuator.

3.5 Propulsion

As illustrated in Table 2, two major requirements for the new vehicle included a greater thrust to weight ratio and a higher payload capacity. In order to fulfill both requirements, the engine was upgraded, with respect to previous LEAPFROG generations, by selecting a kerosene-powered jet engine capable to reach a maximum thrust of 300 N. The engine chosen for Generation II is a JetCat P300 Pro, depicted in Figure 8. This engine is characterized by only one compressor stage and one turbine stage with a single combustion chamber.

Figure 8: JetCat P300 PRO

The technical specifications of the JetCat P300 Pro are listed below [9]:

1. Max RPM: 106000
2. Idle RPM: 35000
3. Thrust at max RPM: 300N
4. Thrust at idle RPM: 14N
5. Mass flow: 0.5 kg/s
6. Exhaust gas velocity: 2160 km/h
7. Fuel consumption at max RPM: 0.784 kg/min

The engine is manufactured with its own telemetry and an embedded electronic control unit (ECU), both of which are housed within the engine compartment. The ECU manages the subsystems like fuel pumps and valves using a feedback loop that provides information about the current state of the engine. This information includes revolutions per minute and the temperature of exhaust gases, among other metrics. Another characteristic of this engine is that it doesn't provide an excessive unwanted yaw, which is usually generated in jet engines due to their rotating blades. Consequently, this engine does not affect the dynamics of the vehicle, enabling a more stable flight. The kerosene needed to fire the engine is stored in a set of custom JetTech tanks that are placed on the upper platform of LEAPFROG's structure around the center point of the vehicle.

The JetCat P300 PRO matched the requirements stated for LEAPFROG due to the characteristics described above and its cost compatibility with our budget. However, a future improvement planned for the prototype is the implementation of a rocket engine in place of the current jet engine, in order to take the vehicle closer to an actual lunar lander.

3.6 TVC

The TVC system is a distinguishing feature between Generation II and LEAPFROG's previous iterations. This system exploits the thrust given by the engine in order to control the attitude of the vehicle during the various flight phases. The implementation of this feature recalls the desire to have a highly multifunctional vehicle since the engine is not only used as thrust source for the flight but also to control the stability of LEAPFROG, further allowing a reduction of the usage of the cold gas supply for the ACS. This allows a reduction in air supply, therefore decreasing tank size and consequently vehicle's total mass. The full design of the TVC and its control system has been research theme for a Master of Science thesis [10].

Since the objective of the TVC is making possible the attitude control through the thrust given by the engine, the manipulation of the engine's thrust vector direction was required. The engine's thrust vector is typically aligned with the center of mass of the vehicle in order to control the vehicle's altitude. However, creating an offset between the thrust direction and the center-of-mass, we generate particular torques that, if properly controlled, can be exploited in order to control the attitude. Since the engine mounted on LEAPFROG is monolithic (i.e. all the components are fixed and cannot be relatively moved), the only way to get the motion of the thrust vector is to move the full engine. In our case, this goal is reached thanks to a gimbal ring, a gyroscopic joint characterized by three concentric rings that can move with respect each, where the inner ring is tied to the engine and the outer ring is connected to the chassis. In this way, the engine is free to move with respect the structure with 2 degrees of freedom which means that we can create the offset between thrust direction and center of mass and, moreover, that we can control two different angular rotations of the vehicle, namely, pitch and yaw angles. The relative motion of the three rings is granted by the presence of interconnecting pins that, for simplicity of actuation, have been designed to be aligned with LEAPFROG's principal axis of inertia. The actual motion of the engine is accomplished with the action of two electro-mechanical linear actuators, mounted 90° apart, that drive the engine itself into the desired position. Figure 9 shows the CAD model of the gimbal ring.

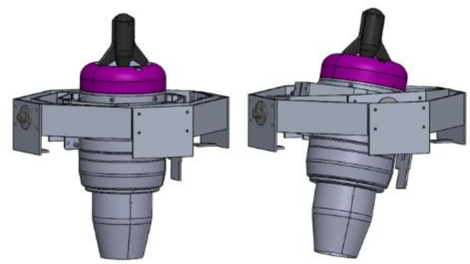


Figure 9: Gimbal ring in (left) rest condition and (right) tilted to the right

The material chosen for the three gimbal rings was Aluminium 6061-T6 because of its machinability, medium to high strength, relatively low density, and affordable price. For the interconnecting pins, the material chosen was stainless steel since they must carry the weight of the engine and transfer the thrust of the engine itself.

The TVC system is characterized also by embedded electronics that makes the flow of information about the current state of the vehicle and also the actuation of the two linear actuators possible.

Since the TVC is designed to control the attitude, the response to the variation of vehicle's attitude needs to be near instantaneous to prevent stability problems. For this reason, after a consideration about the characteristics of the chosen linear actuators, it was decided to limit the tilt of the engine to a maximum of 5°, in order to make the actuators able to provide a fast action. When this maximum angle is not enough to generate the necessary torque, then the standard cold-gas attitude control system takes the command to control the attitude.

Concerning the control system related to the TVC, we decided on the implementation of a controller based on Sliding Mode theory. Sliding Mode Control is a non-linear control system that has been shown to be characterized by a very good ability to handle complex non-linear system that contain uncertainties and disturbances. These characteristics were appropriate for our case due to the uncertainties about LEAPFROG's dynamics and flight behaviour that could be hardly manageable by a simple linear control system. The sliding manifold designed for TVC control system is described using (1):

$$S = Wq_e + w_e \qquad (1)$$

Where,

$$q_e = q - q_d \qquad (2)$$

is the quaternion error and

$$w_e = w - w_d \qquad (3)$$

is the angular velocity error. W is a positive diagonal matrix that gives a weight to the quaternion components. From the sliding manifold equation, the control torque expression can be derived, which is:

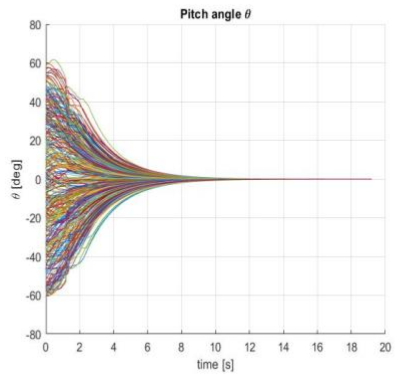
$$T_d = I\left[-kS - W\left(\frac{1}{2}\langle q_e \times\rangle\omega_e + \frac{1}{2}q_{e4}\omega_e\right)\right] + \langle\omega \times\rangle I\omega + \tau \qquad (4)$$

Where I is the principal inertia matrix, k is a positive constant, tau = -k*sign(S) and the corner brackets represent a skew symmetric matrix. In order to verify the effectiveness of the designed control system, Simulink simulations were performed. Figure 10 exhibits the results of a Monte Carlo simulation showing that, despite the limitation on the tilting of the engine, the TVC system is still able to restore a large set of attitude offset with different initial conditions.

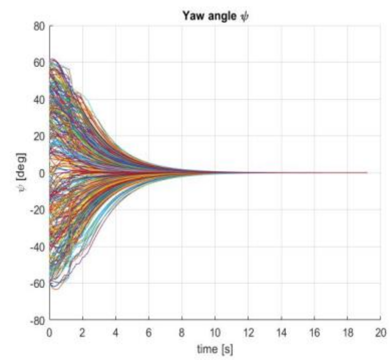
3.7 Attitude Control System

The thrust for the cold gas ACS comes from pressurized air. The current ACS uses paintball air tanks to hold the air, pressurized to 3000 psi. These tanks hold 48 cubic inches of air and come with a built-in pressure regulator, which can be adjusted to three different pressure levels (450, 650, or 850 psi). The tanks are currently regulated to the lowest pressure setting, as higher pressure creates an issue where the thrust force will drop off as long as the thruster is fired continuously, due to the tank not being able to output enough air to maintain the high pressure. This behaviour is shown in Figure 11. And while high pressure does come with higher thrust, it also means the tanks will run out of air faster. The current thrust of one thruster, with the regulator set to 450 psi, is about 3.5 N.

The thrust is actuated using solenoid valves. The LEAPFROG currently uses Valcor V27200 solenoid valves, which have a pressure rating of 4500 psi. The valves are in a normally-closed configuration, meaning that the valves open when receiving current, and remain closed otherwise.



(a)



(b)

Figure 10: Pitch angle control (a) and yaw angle control (b)

The positioning of the thrusters for Generation II is inspired by the ACS design for the Lunar Lander Research Vehicle and the Apollo landers [11]. This configuration consists of eight thrusters, positioned such that there are six thruster couples; one for positive torque and one for negative torque about each of the three body

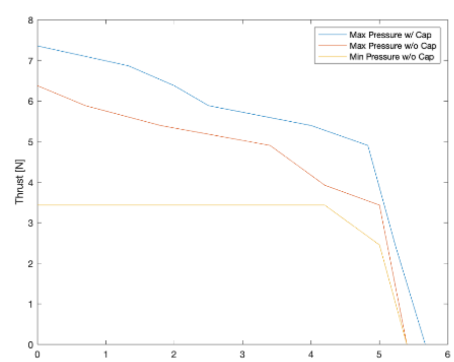


Figure 11: Thrust over time for a 5-second pulse, with regulator set at max (850 psi) and min (450 psi) pressure

axes. Thruster couples are common in attitude thruster designs, as they are necessary to generate a pure rotation without unwanted translation.

This configuration is shown in Figure 12. Note that the LLRV had 16 thrusters rather than 8. The other 8, which are not included in the LEAPFROG design, were simply mirrors of the standard set, for redundancy in case of a contingency.

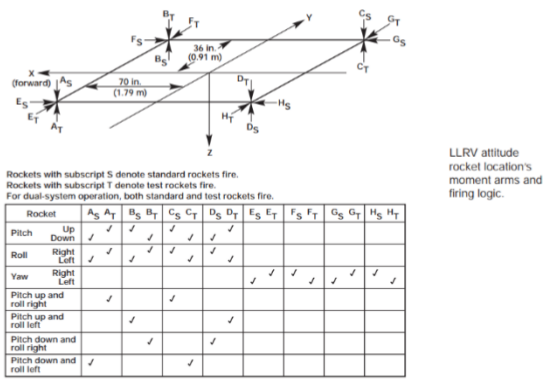


Figure 12: ACS of the Lunar Lander Research Vehicle

The ACS currently uses a Proportional-Derivative (PD) controller. This is a very common type of control which combines a proportional error term and a derivative error term, multiplied by their respective gains, to determine a control variable, c, which determines the amount of control action taken. The control algorithm can be summarized with the equation

$$c = K_p x_e + K_d \frac{dx_e}{dt} \quad (5)$$

Where x_e is the error term, i.e. how far the measured state variable x_m is from its desired value x_r:

$$x_e = x_r - x_m \quad (6)$$

K_p and K_d are the proportional gain and the derivative gain, respectively.

In order to get something comparable to scalable thrust, we use Pulse-Width Modulation (PWM). Each thruster fires in pulses of fixed frequency, where the pulse ‘on’ duration is variable. This way we can control the total impulse produced by each thruster, effectively scaling the average thrust and acting as a way to "throttle" the control output.

Testing of the PD controller with PWM control commands on the LEAPFROG Gen-I platform resulted in the platform effectively returning to its original orientation after being perturbed, with minimal overshoot.

4. Specific designs for the Lunar Vehicle RAMSEs, and OSP

The RAMSEs preliminary design as well as the OSP design for the lunar based design activity, was a realization of a Master of Science thesis research project [12]. Here they will be described in more detail.

4.1 RAMSEs

As stated in Table *2*, one aim is to look at changing a single monolithic functioning lunar lander into a multi-functional platform that uses various techniques and new technologies to extend the use of the mass embedded in the makeup of the landing platform. RAMSEs is designed to implement different functions from flight to ground (i.e. to collect samples, to drill, to dig). As an example, a robotic arm is typically held down with launch and flight locks, and its sole purpose is manoeuvrability upon release. In this case, it has been investigated on how a robotic arm during flight serves as the “secondary structure” that holds one element of a fuel tank on a lander, and then upon landing, the arm “detaches” from the fuel tank, through jointed at its based becomes a manoeuvrable element. To prove its utility a preliminary design of a 7 degrees-of-freedom (DOFs) Multi-functional SElf-reconfigurable Robotic Arm (RAMSEs) arm extendable up to 14 DOFs on the LEAPFROG platform would be performed. Therefore, the robotic arm would be capable to choose a suitable tool for any activity programmed a priori and it will also serve as the motive force to unfold the origami based solar panel, further extending the multi-functionality of our new lander design. In Figure 13 the RAMSEs arrangement is shown: the robot is made of two different manipulators with 7 DOFs each.

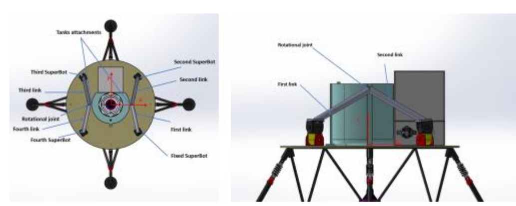


Figure 13: RAMSEs CAD rendering

The main manipulator, which is permanently attached at its base, is the right one, referring to the inertial frame on the upper platform, in red in the previous figure. This is used alone for manipulating the OSP since its extended length should be enough to reach a fixed point just upper the tank, and should not be too long to reach the soil as if it has to perform soil activities. Indeed, in this case, it has to extend its length of double due to the lander height and the second robotic arm will detach its end-effector from the platform to link itself with the main robotic arm end-effector. This movement is perfectly symmetric to the axis origin. When the RAMSEs has to perform soil activities, its has 14 DOFs. Each manipulator is made of:

- 2 SuperBot units with 3 rotational joints each
- 2 basic trusses (*links)*
- One rotational joint between the two links

The fixed base is the first SuperBot tilted at 45°, as well as all SuperBot modules; the end-effector of the first arm is the second SuperBot. The configuration is symmetric for the other arm as mentioned before. Links are simply modelled as full tubes. The two links are connected in the CAD with a hinge, since the most appropriate rotational actuator will be chosen a posteori by considering this research results. Moreover, the joint position limits are set as 0±180° like the widely available COTS actuators.

Of note, "SuperBot" is a self-reconfigurable system of a 1Kg, 3 DOFs robot made up of two interconnected aluminium alloy cubes of 84x84x84 mm. Each module has three main parts: two end-effectors and a rotating central part. It has three rotational joints in total which corresponds to 180° yaw, 180° pitch and 270° roll.

The RAMSEs physics is simulated trough Simscape, an extension of Simulink which helps to develop control systems and test system-level performance. In the future, this part will be exchanged with the real hardware. On the other hand, for the controller Simulink environment is used: starting from points that the end-effector should follow, called waypoints there is a supervisory logic which calculates where the end-effector should arrive at, then the inverse kinematics is calculated, to provide joints positions in space and with a closed loop, the forward trajectory is computed to find the end-effector placement.

In Figure 14 the sequence of OSP manipulation is shown. The first is when the manipulator is still in its initial configuration while in the second one RAMSEs reached the position of the OSP deployment on the top of the platform. Note that the additional torque provided by the panel has to be taken into account when the real prototype will be designed.

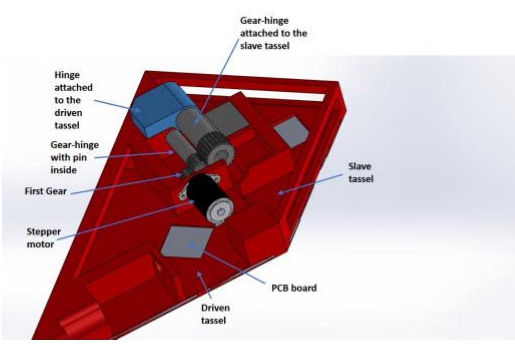


Figure 14: OSP driven and slave adjacent tassels

The OSP dual situation is the drill manipulation. Here the RAMSEs is working with all the components, achieving 14 DOFs. Since the gripper point for the drill is the more distant with respect to the other tools, it represents the worst case scenario by the RAMSEs workspace. The sequence of the RAMSEs movement is illustrated in Figure 15. Is important to note that is achieving all the prescribed points and it reaches the ground with the correct orientation. The only drawback is that there is a little interference with the OSP box; however, this does not represent a major issue, since a suitable container must be designed. Therefore, this represent a requirement to follow for the OSP box design.

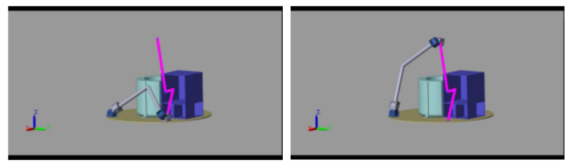


Figure 15: Trajectory following simulation for OSP handling manipulation

4.2 Origami Solar Panel (OSP)

Since the OSP has to be realized in the SERC laboratories, the advantages of using the reconfigurable soft robotics cannot be exploited due to the technology's high-difficult implementation and hardware. Since the OSP structure contains the solar cells, the electronics, the power-managenent and the mechanical deployment hardware, a considerable width must be considered for the design of a thick origami structure design.

It has been decided to have a deployment fully mechanical: the system is 1DOF, therefore only one actuator is needed to fold and unfold the panel. The chosen actuator is a stepper motor and to transfer its motion until the valley, a series of three gears have been designed through Lewis method.

There are six elements in total (*Tassels*) connected through a series of geared-hinges. Among the actuated tassels there are three gears. Details about the actuated tassel and the slave one are shown in Figure 16.

A test-bed model has been realized in SERC laboratories with different 3-D printing sessions: the gears and hinges are printed with MAKERBOT PLA, while tassels are printed with Stratasys ABSplus-P430 and P400-SC

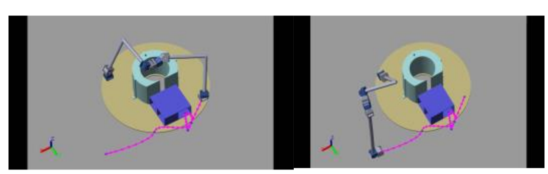


Figure 16: Trajectory following simulation for drill manipulation

Soluble Concentrate for the support printing material. Test-bed serves to prove the design concept.

Due to COVID-19, only a manual test has been done without the hardware for the mechanical deployment. However, this proves the design is suitable for these compact structures. The unfolding manual procedure is shown in Figure 17.

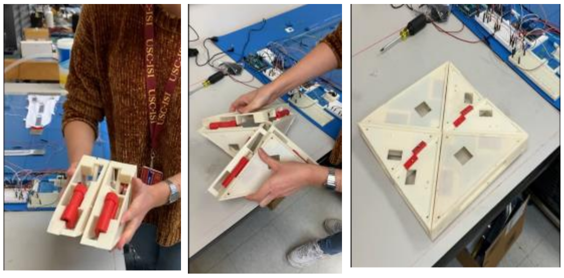


Figure 17: Manual unfolding test

5. Conclusions

This project endeavoured to upgrade the design of the next generation of LEAPFROG for multifunctionality. With new features such as the integration of a TVC via a gimbaled jet engine, cold gas ACS, robotic arm and origami-based solar panels, LEAPFROG Generation II is capable of both performing as an Earth-based lunar lander prototype extension of LEAPFROG, and a design point to look at extending lunar lander functionality.

6. Future Work

Some future work considered would be modifications to the structure to make it more robust, including protection to the vehicle and its components from a free fall by adding a roll cage, modifying the legs of the lander to allow the vehicle to land and take-off from an inclined plane, and the addition of a mechanical fuse to protect hardware during iterative testing.

Additional fail-safe hardware can be added which takes control at the time of failure and lands the vehicle safely in the event of operating system or code errors. Redundancy can be added as part of sensors on board to get better accuracy and in case of a sensor failure.

The current system uses WiFi for communication which allows higher bandwidth at the cost of distance. Multiple channels on the radio frequency can be used instead which allows longer distance for communication and dedicated band for a specific type of communication.

The flight controller uses independent PID controllers for each component, which does not allow all the components to work in synergy. Instead a complicated controller like model predictive controller (MPC) can be implemented which might give better control and stable flight with an added advantage of a fuel-efficient system.

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