SCOUT- Europa Terrestrial Lander (ETL)

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Abstract: The emphasis of this work is to aid the Lander mission to Europa in the forth coming years as planned by NASA[1] and ESA[1]. The conceptual design of the Lander named SCOUT-ETL is designed to conduct various in-situ scientific analysis and experiments at extremities of temperature and radiation. The major systems involved in the mechanics and control dynamics are cat's hind limb bio-mechanics, Electro-Parachuting [EPC], Thruster Bag Landing System [TBLS] and Field Conversion Radiation Protection [FCRP]. Analysis and studies are carried out in design, control dynamics and reliability of the Lander so as to satisfy the requirement.

Key words: Europa, Electro-Parachuting, Thruster Bag Landing System, Field Conversion Radiation Protection

Introduction:

The scenario of Search for Extra-Terrestrial Intelligence (SETI) got a lot of emphasis on Jupiter's moon EUROPA[2]. A Lander mission is required to conduct scientific analysis and to dig out the real condition of Europa. Here, a new type of Europa exploration Lander is being developed, called ***SCOUT-Europa Terrestrial Lander (ETL).*** The Lander is designed to satisfy the conditions like extreme radiation and temperature exposure, soft landing, stabilization within a short period of time after impact, room for sample storage and scientific analysis. As this is going to be a very expensive mission, it should be utilized to the maximum. SCOUT-ETL is designed to give platform for various scientific instruments. The raw mass of scout (without any scientific payload) including the Thruster Bag Landing System [TBLS], Radioisotope Thermoelectric Generator [RTG] [3] and robotic manipulator weighs about 135 Kg and possible to hold scientific payload ranging between 125-175 Kg. SCOUT-ETL uses Electro-Parachuting [EPC] for its descent entry and Field Conversion Radiation Protection [FCRP] system for protection from the magnetic and cosmic radiations.

Structural Mechanism:

SCOUT-ETL structure (without any payload and instruments) is in the form of a cuboid supported and balanced by four independent landing gears. Structure of SCOUT-ETL is developed from redundant frames having a negative degree of freedom. The system is designed to transform the point load acting upon the main frame into uniformly distributed load, so as to yield a low DESIGN FACTOR which implies that the design meets but does not exceed the minimum requirements. Structural members are made from hybrid titanium composite material[4] owing to its high strength to weight ratio. The landing gears are connected to the main body frame in a way to get the maximum flexibility and to move the main body frame in all directions.

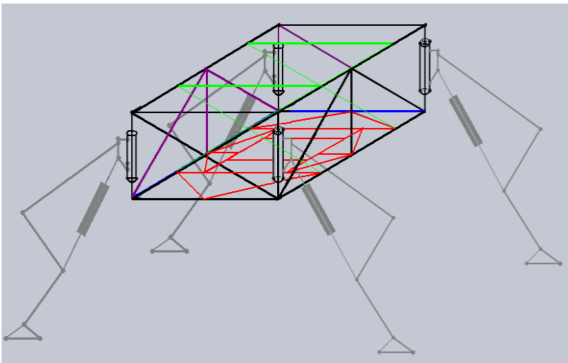


Figure1: Line diagram of SCOUT-ETL, with landing gears and dampers.

The Lander structure is designed to accommodate a pair of cylindrical barrel air tanks made of carbon fiber, mini RTG of 73 W electrical output and 1480 W heat, robotic manipulators and Thruster Bag Landing System. Provisions for TEGA[5] oven is designed under extreme importance of sample collection and processing. Total volume of the Lander main body frame is about 810×10^6 mm^3 in which volume of 594×10^6 mm^3 is allocated for scientific instruments and pay loads. Platforms for drilling machine, video camera and robotic manipulators are developed along with the main structure of SCOUT-ETL with some extrusion. From the force balance equation[6] and rigidity calculations of the system, it is inferred that the system would remain rigid even after impact at a velocity of about 20 m/s.

Table: 1 Lander's kinematic pair nomenclature

Pair	Form	Class	No. of restraints
Spheric-4	1^{st}	III	3
Sliding -4	2^{nd}	IV	4
Revolute-6	1^{st}	IV	5
Rigid frames-5	-	-	6

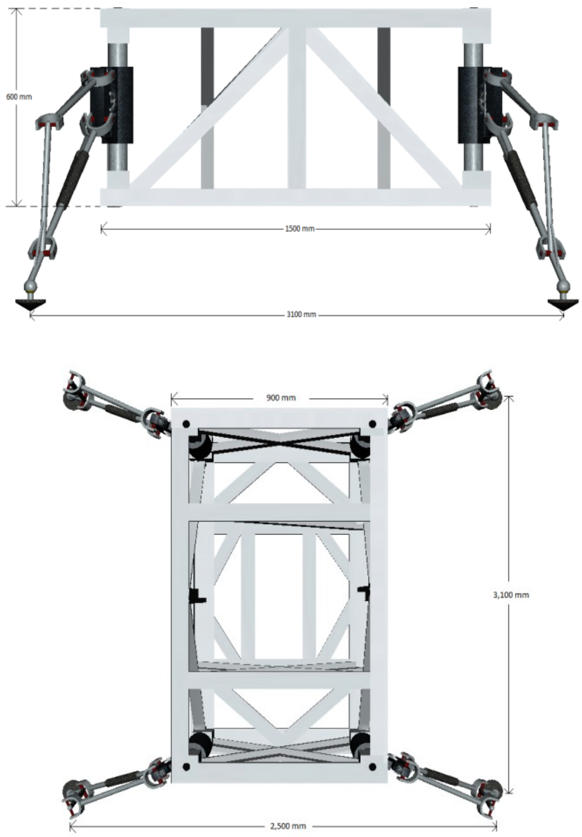


Figure2: Dimensional details

The main body frame of SCOUT-ETL constitute of 38 binary links which are connected as lower pairs, which is applied in Gruebler's criterion

$$F=3(n-1)-2L-h$$

Where,
F- Degree of freedom [DOF]
n- Number of links
L- Number of lower pairs
h- Number of higher pairs

Substituting the values in the above equation will give a negative value of DOF, showing the main body frame is a SUPER STRUCTURE.

As the base of landing gears is fitted with conical disk like structure having 3 DOF, this arrangement aids to the stability of the Lander at any impact angel (β) between 160^o to 20^o in *x, y* and *z* plane.

The main frame is connected with a negative DOF in contrast with the landing gears (Table:1). Landing gears are provided with most flexibility in directional movements. The mechanism connecting the main body frame and the landing gear is designed to have a controllable motion in all directions with reference to the Lander body. SCOUT-ETL is distributed into three chambers in which, one of the chambers is allotted to the system components such as pressurized air barrels and RTG. The main body with the pay loads can be moved up and down about 3000mm to 8000 mm from the ground surface, called as chase clearance height.

Safe landing and stabilization mechanisms:

The mass distribution of SCOUT-ETL is accounted under earth condition and material properties are calculated with temperature compensation.

Dry mass of SCOUT-ETL ≈ 175 Kg [without payload] and the Lander is ejected from the launch vehicle at a known distance from the surface of Europa, then the governing force balance equation, gives

assumptions: drag force has been neglected when the thrusters have been switched on.(but Electro-Parachuting, EPC will produce some considerable drag)

Then, acceleration due to gravity = 1.314 m/s^2
height above the ground = 1 km
(ejection from the launch vehicle)
atmospheric pressure = $1x10^{-6}$Pa

m → mass of the body just before thruster has been turned on
h → height above the Europa surface
g → acceleration due to gravity

Velocity of Lander before impact is given by
V= 51.26 m/s, impact force= 788.4 k N

The system components are designed to withstand a small range of vibration. But this collision would lead to collapse of the entire system, so the descending Lander is decelerated to an optimal range of about 2 m/s to 10 m/s, by EPC and TBLS. However, the electrical and communication components may be subjected to disturbance as the result of impact. The stabilization time should be as minimum as possible after the impact to maintain a constant communication between SCOUT-ETL and the orbiting satellite. A suitable mechanism is employed to satisfy the required conditions of safe landing and rapid stabilization.

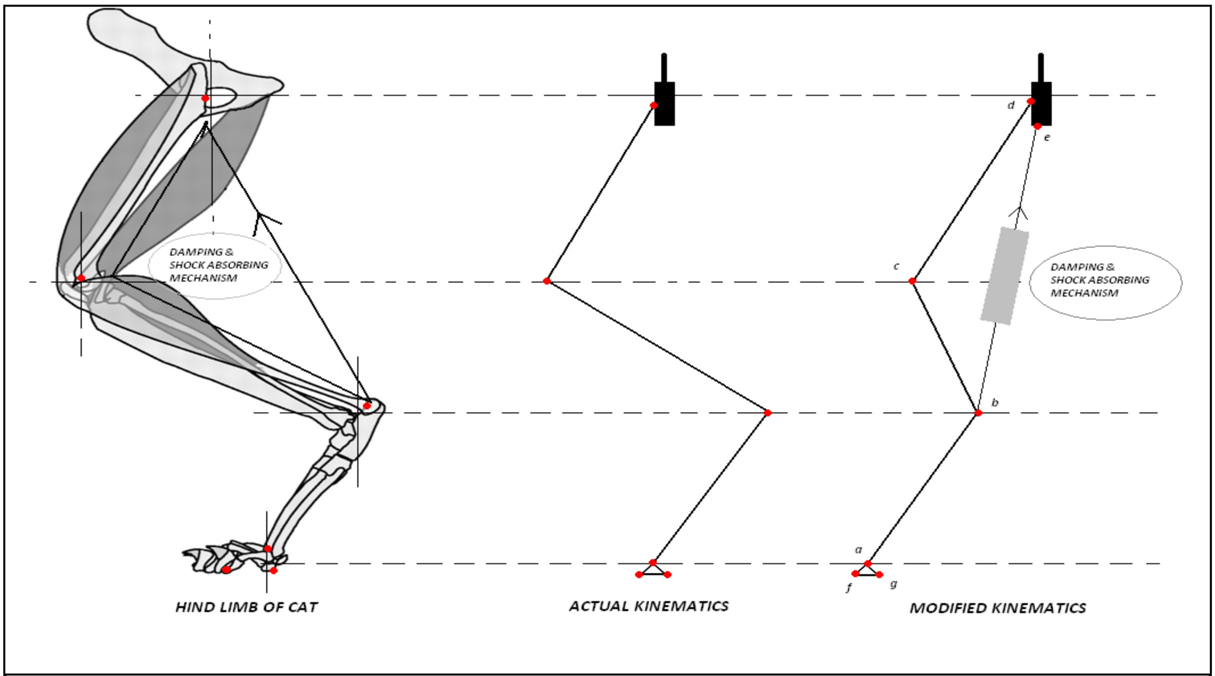


Figure 3: Damping and balancing mechanism extracted from the bio- mechanics of hind limb of cat

Damping and balancing mechanism: As the system is subjected to land at a velocity of 2~8 m/s, a high efficient shock absorbing system should be incorporated with the landing gears. The damping and vibration control mechanism is extracted from the hind limb of a cat in order to ensure safe and smooth landing of SCOUT-ETL. Cats have the ability to land safely with stability under a free fall, even from the top of an eight- storey building* showing its efficient damping mechanism. The kinematics of the cat's hind limb shows that the muscles covering the femur bone acts as a damper bypassing the stress induced in toe to the muscle layer. This energy is later transformed as heat and dissipated; this bio-mechanism is also seen in humans.

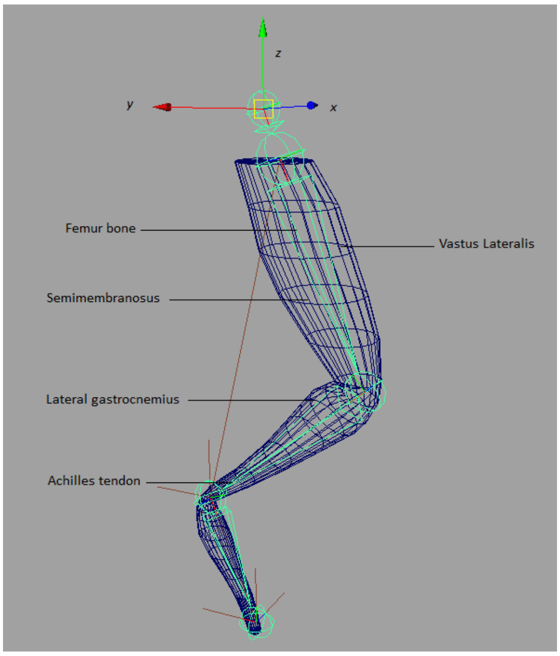


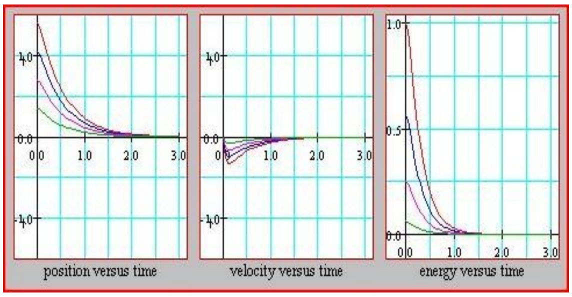
Figure4: Musculoskeletal view of cat's limb.

The kinematics and dynamics from the movement of femur, tibia, meta-tarsal bones and vastus lateralis, semimembranosus, lateral gastronomies muscles are studied and the pure kinematics is obtained as shown in the figure 3. The stress incurred by the toe is transferred to the damping mechanism (muscle covering femur bone). The hind limb kinematics is modified to a similar configuration. The replicated mechanism uses a modified damper which converts the absorbed shock into heat.

Figure5: Equivalent mechanism [Landing gear]

This landing gear's damper is not subjected to any bending moment due to the arrangement as shown in the figure5. Base toe is connected to a spheric pair, which is free to move in all the three directions. The impact angle (β) can vary from 45° to 135° giving provision for alternate landing location. Lower surface of base toe is rugged; the co-efficient of friction is deliberately made high above 2 yielding a large angle of repose.

The physical modeling of the spring viscous damper system gives the frequency response the oscillation damping system. The damping mechanism constitute of a spring and air viscous damper responding to the shock simultaneously. Experimental damped oscillation of the damping system shows that the SCOUT-ETL (from figure 6) will come to rest within 2 seconds after the impact.



$$m \cdot \frac{d^2y(t)}{dt^2} + c \cdot \frac{dy(t)}{dt} + ky(t) = 0$$

This equation[7] describes a damped harmonic oscillator with mass(m), damping constant c and spring constant(k). The time response is made for every ½ seconds.

The value of *m, c* are known and the spring constant (*k*) is varied for the optimal frequency response and from that value, the damper system is designed.

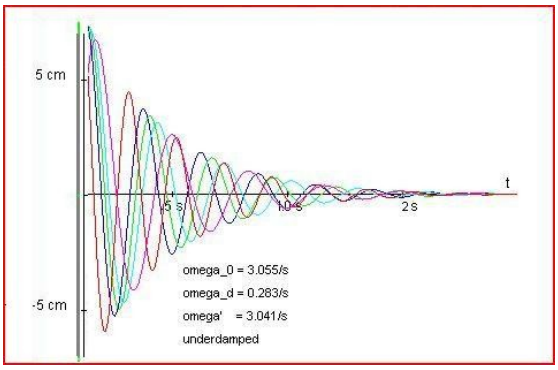


Figure6: Frequency response of damping system.

The frequency response curve is obtained from the governing differential equation,

$$y(t) = y(t = 0) \cdot \exp(-\omega d \cdot t) \cdot \sin(\omega' t + \theta)$$

For ($\omega o > \omega_d$), where $\omega_d = \frac{b}{2m}$

$$\omega' = \sqrt{(\omega_o^2 - \omega_d^2)}$$

$$\omega_o = \sqrt{\frac{k}{m}}$$

ω_o—natural frequency, k—Spring constant

From the above calculations the spring constant is inferred and the high efficient damping system is designed. The mechanism converts the absorbed shock energy into heat and dissipates to the environment. This damping system can withstand up to an impact velocity of 2 m/s to 16 m/s.

Modified Cardan joint:

The joint connecting the main body frame and landing gear is a type of modified Cardan joint. It has the DOF in all possible direction and can be adopted for any type of landing site with the impact angle (β) ranging from 25^o to 60^o.This joint is adapted with a revolute and a spheric pair. The movement of this joint is electrically controlled according to the requirement.

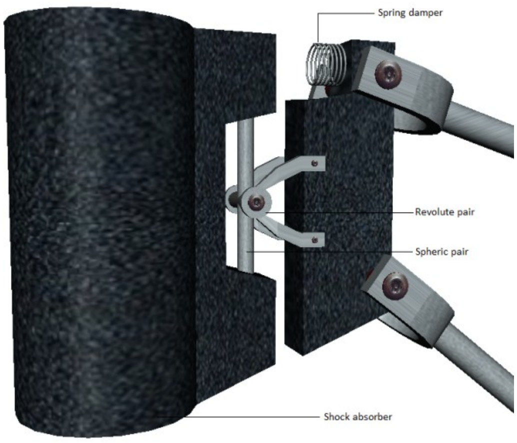


Figure7: Modified cardan system

The spring attached to the cardan is designed for a spring constant of k= 60kN/m and the sliding arrangement which is a shock absorber having damping constant c=60 k N-s/m.

Electro-Parachuting [EPC]:

After ejection from the launch vehicle, SCOUT-ETL starts descent towards Europa surface. The initial stabilization of the Lander is provided by flywheel and then it is subjected to free fall. The aerodynamic design of SCOUT-ETL's radiation shield allows the Lander to follow a defined trajectory. Europa is composed of a very tenuous atmosphere[8] and the drag causing frictional air resistance and deceleration is minimum. The conventional type of deceleration system for descent entry by parachute deployment or aero braking cannot be used in Europa' atmosphere. Here with SCOUT-ETL, deceleration is carried out using the drag produced due to the effect of electrostatic force of repulsion between likely charged ions. Europa is within Jupiter's magnetosphere, and is constantly bombarded by magnetospheric ions (Paranicas et al., 2002), which will lead to both sputtering (Ip et al., 2000; Johnson et al., 2004) and redeposition. Europa atmosphere constitutes of atomic oxygen as positive and negative ions due to sputtering[9]. At locations where the electron density of Europa[10] is measured to be 10,000 electron/cc, the Electro-Parachuting [EPC] is deployed to bring down the acceleration to a small extent.

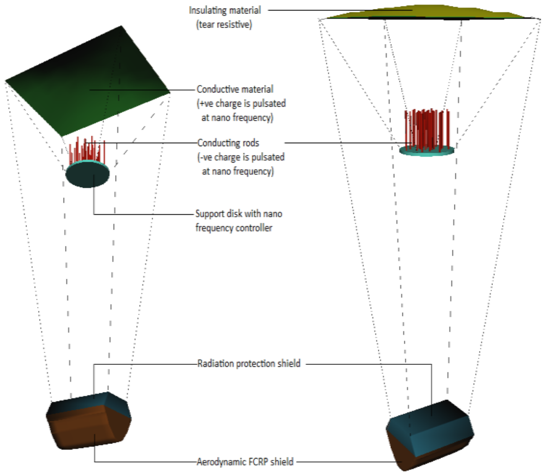


Figure 8: Electro-Parachuting [EPC] system.

EPC system has a conventional type of parachute arrangement where the inner layer is made of flexible conducting material and the outer layer is made of tough insulating material. A disk containing extruded conductors arranged in a matrix form is placed to hang at a distance *x* from the inner layer of parachute. Both the inner conductive layer of parachute and the conductors placed in the disk is connected to positive and negative nodes of the controller system respectively. The electrodes are pulsated with alternate positive and negative charges in nano frequency such that, when the conducting rods are negatively charged, the inner conducting layer of parachute will remain neutral and as the rods becomes neutral, inner parachute layer gets positively charged.

The entire Lander is enclosed in radiation shielded capsule. After jettisoning from the launch vehicle, the radiation shielded capsule enters Europa surface with a velocity, $v = \sqrt{2gh}$ say 51.26 m/s. After initial stabilization, EPC system is actuated. Anode is placed at the center of parachute and positive charge is fed to the anode at a pulse less than a nanosecond. The inner layer of the parachute is made of substrate capable of retaining a lot of negative charge. By the principle of electrostatic force, like charges will repel each other. The positive charge will attract the nearby electrons and in turn increase the electron density. This repulsive force will decelerate the velocity of the descending Lander combined with the wind drag.

$$F = \frac{1}{4\pi\varepsilon_o} \cdot \frac{q_1 q_2}{r^2}$$

where q_1 and q_2 are electric charges, r is the distance between two charges and electric constant[11] $\varepsilon_0 \approx 8.854\ 187\ 817 \times 10^{-12}\ \mathrm{F \cdot m^{-1}}$ .This force can cause a drag which leads to the deceleration of the radiation shield capsule.

Thruster Bag Landing System [TBLS]:

EPC decelerates the descending Lander till up to a distance *h,* above Europa surface. From that point, SCOUT-ETL gets jettisoned from radiation shield capsule and subjected to free fall. The impact force will be more than 400KN, which is enough to collapse the system components. SCOUT-ETL employs Thruster Bag Landing System [TBLS] to achieve safe and stabilized landing at a velocity of 3-6 m/s before touching Europa's upper crust (figure 10).

System Design:

TBLS is designed to produce a maximum thrust of 800 k N. Modified Cold-Gas system[12] of propulsion is adopted in TBLS (figure 9). Deflated air bag is attached to the lower part of the main body frame of SCOUT-ETL.

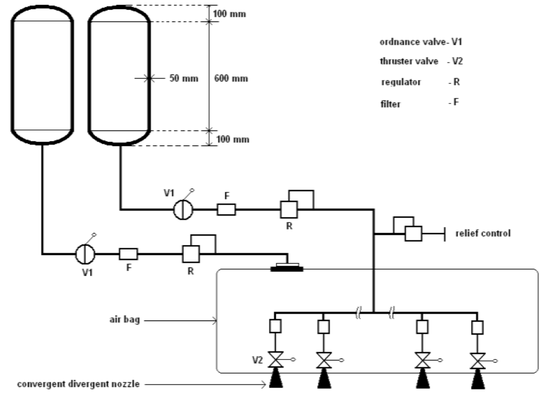


Figure 9: Modified Cold-Gas propulsion system.

Design consideration: Two tanks are fitted with the body main frame occupying one chamber of SCOUT-ETL. Design considerations are listed in table 2. As the acceleration due to gravity is very low of about 1.314 m/s^2 in Europa it leads to design a low thrust producing system for SCOUT-ETL.

Material	Multi Walled Carbon Nano Tube composites [MWCNT]
Max. Pressure	1200 Psi
Area ratio	100
Candidate gas	Helium
Tank shape	Cylindrical barrel

Properties of Helium in Cold-Gas system

Molecular weight	4 g/mole
Ratio of specific heat	1.659
Specific gas constant	2.0769 kJ/kg K
Pulsing I_{sp}	80 s
Min. thrust	0.00454 kg

Table 2: Design consideration

The thickness of the tank wall is calculated from,

$$t = \frac{P \cdot r}{\sigma}$$

Where, t = thickness of the wall, m

P = pressure, Psi

r = radius of hoop, m

σ = maximum permissible stress

The thickness of the cylinder wall is 50 mm and a maximum pressure of 1200 Psi can be compressed in the tank for volume, v = 0.0603 m^3. As there are two cylinders in the system, it is possible to produce the thrust for an optimum period of time in seconds. The gas contained in the tank is maintained at a temperature of 373 K in order to have a high specific impulse.

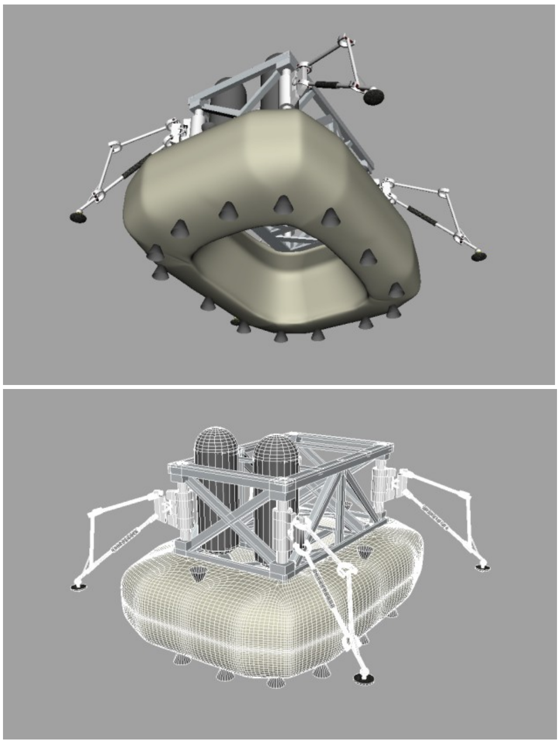


Figure 10: TBLS

The air bag is made of reinforced material which can resist the burst while landing. The lower layer of air bag contains a series of 14 micro thrusters' nozzle of convergent divergent type. The upper part is designed to accommodate 4 micro thrusters in the upward direction. The base toe of SCOUT- ETL has stress sensors, which gives signal to the thruster control system when it touches Europa surface. At that moment, the downward thrusters will be switched off and the upward thrusters are actuated leaving a huge mass of helium with a high specific impulse in order to avoid rebounding and to damp the vibrations produced by impact. As this acts like an air bag, the payloads remain unaffected after impact. Air bag is inflated with gas from Tank 1 and tank 2 provides the thrust. The thrust time ratio is calculated from the thrust equation, so that no gas remains in the system after safe landing.

Thrust Calculations:

From the basic physics, the parameters of free falling condition of SCOUT-ETL is calculated from,

$$V_x + t\left(g_e - \frac{T}{m}\right) = V_a \quad \text{………….. (a)}$$

$$\left(\frac{Tt}{m}\right) = \sqrt{2gx} - V_a \quad \text{……………... (b)}$$

Where, x = Distance from the radiation capsule after being jettisoned, m.

V_x = Velocity at any location 'x' from the radiation capsule after being jettisoned, m/s.

V_a = Velocity just before it hits the ground, taken as 4 m/s.

T = Thrust at a distance x' from the radiation capsule after being jettisoned, N.

t = Time for which thrusters are switched on, s.

m = Mass of the Lander which is 600 kg.

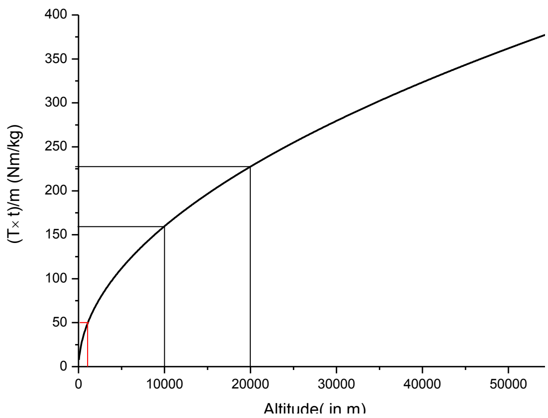


Figure 11: Variation of (*Tt/m*) v/s Altitude

Figure 11 represents the variation of the product of specific thrust and time with altitude as given by equation (b). The lines on the graph depict values of (*Tt/m*) corresponding to a particular altitude. As the thrusters were intended to be started very close to the Europa surface, the values of (*Tt/m*) corresponding to a range of altitudes varying from 60 m to 200 m were noted. From this an estimate of the time for which the thrusters have to be switched on is made. The total thrust generated is distributed over the 14 thrusters installed in the TBLS. Figure 12 shows qualitatively the plot of thrust with time. This is in line with the requirement of low final velocity of 4 m/s (i.e. the velocity of the Lander before it hits the ground).

The curve shows the typical variation of downward thrust with time. As seen from the plot the thrust reaches a maximum value and then decreases rapidly to a very low value which corresponds to condition when the Lander velocity is nearly 4 m/s.

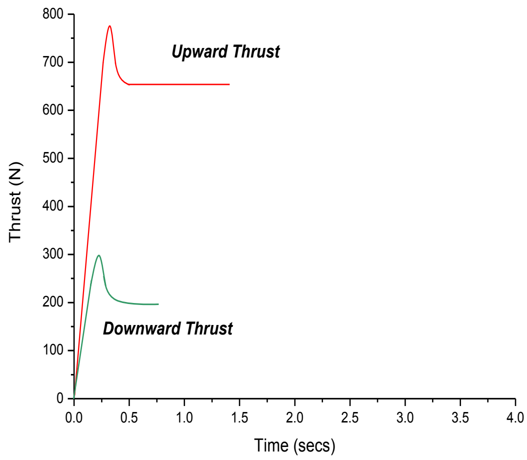


Figure 12: Qualitative plot showing variation of thrust v/s time.

As the base toe approaches the ground, the upward thrusters are switched on leaving the downward thrusters off. All the remaining mass of the gas is forced out through the upper thrusters of TBLS, this in turn reacts in a small period of time around 0.8 to 2.9 seconds after impact resulting in the suppression of rebounding. The components receive a very low vibration as a result of TBLS. Moreover, those vibrations are scattered by the damping mechanism incorporated with SCOUT-ETL.

Stabilization and dynamics control:

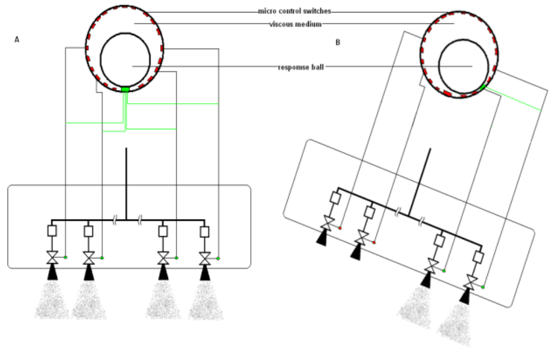


Figure 13: stabilization and dynamics control system.

The control system consists of a series of micro switches located at the inner wall of a sphere. A ball of considerable mass is enclosed within the sphere. The cavity between the ball and inner wall of the sphere is filled with a viscous fluid. The ball has an accurate response to the gravity acting on it. When the ball touches a micro switch, it will actuate the solenoid control valve of the corresponding thruster. SCOUT-ETL after undocking from the radiation capsule is subjected to free fall and allowed to follow its own trajectory for a short while and then the TBLS is deployed. The gas from tank 1 inflates the air bag of TBLS, the movement ball over the switches due to the effect of gravity, actuates the corresponding thruster. This processes continues to work, till the Lander stabilizes and all the thrusters are actuated as it gets stabilized giving out maximum thrust for deceleration.

Field Conversion Radiation Protection [FCRP]:

Radiation protection shield capsule is made of mu-metal (Nickel+Iron) combination, which has high permeability. The lower part of this capsule is designed aerodynamically and the upper part is designed to accommodate the EPC system. Europa environment is subjected to an intense magnetic field of Jupiter magnetosphere[9]. Electric field is passed through the radiation shield capsule; this field will convert the incoming magnetic field into an equivalent amount of electromotive force (emf). The entering magnetic field from strong magnetosphere of Jupiter will be converted into equivalent emf. So this leads to protect the internal components of SCOUT-ETL from the high intense magnetic radiation. The generated emf is stored and used in EPC system. This capsule serves for protection from electromagnetic radiation and thermal radiation.

Conclusion:

SCOUT-ETL comprises of all the requirements needed for a Lander mission for Europa. Each system and sub-systems like Electro Parachuting [EPC], Thrust Bag Landing System [TBLS], Field Conversion Radiation Protection [FCRP] capsule and damping system are designed exclusively for SCOUT-ETL to carry out Europa mission. The major considerations such as less mass, more space for scientific payload and less consumption of energy can be satisfied with SCOUT-ETL.

Future work:

1. The system design should be modified according to the scientific payload.
2. The calculations are made, without taking drag into account. Computations have to made taking drag effect and numerical model have to be developed for intensive study.

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