Design and Analyses of Guidance Algorithms for Contingency scenario during Powered Descent flight of Chandrayaan-3

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***Abstract*—Chandrayaan-3 became the first robotic Lunar exploration mission by accomplishing safe and soft landing near Lunar south pole on 23 August 2023. The driving factors behind the successful landing were development of powered descent trajectory and guidance and control (G&C) algorithms. This was followed by analyses of the G&C interactions and evolution of guidance strategies and augmentation plans under contingency scenario. The entire course of powered descent from 30 km till touchdown was executed through closed-loop guidance and control with decision and safety logics implemented in onboard autonomous landing sequencer (ALS). This paper brings out guidance strategies for safe touchdown under all possible contingency scenario thereby ensuring best possible propellant margin at touchdown. Also, the guidance schemes for thrust augmentation and time-to-Go computation philosophies towards better propellant optimality during contingency scenario arising from navigation dispersion are brought out which ensured trajectory phase convergence. The mechanization and handshaking of all algorithms together were validated through extensive simulations and ground tests, which led to the successful Lunar landing.**

Keywords - Powered Descent, Thrust Augmentation, Hovering, Contingency Mission scenario, Vertical Descent Guidance, Lunar Soft Landing, TGo

I. Introduction

India's third Lunar Mission Chandrayaan-3 made successful landing near Lunar south pole at 06:05 PM IST on 23 August, 2023 thereby becoming the first lunar robotic exploration to land near the south pole. The objectives of the mission were: a) Expanding the technologies inherited from Chandrayaan-2 spacecraft and 'Develop and Demonstrate' newer technologies that will be useful for future planetary missions b) To design, realize and deploy lander capable of soft landing on a specified lunar site and deploy a rover to carry out in-situ analysis of chemicals.

Lunar landing missions typically consist of a coarse-braking phase to brake the module and kill the horizontal velocity to the maximum extent followed by a terminal descent phase towards a safe landing. Now, the objective is always to optimize the initial braking phase in terms of the change in mass or propellant, whereas the terminal phase should be robust to take care of uncertainties arising from sensors, DEM error, propagation errors etc with the goal of achieving desired soft landing. In the paper, terminal phase of Chandrayaan-3 mission typically comprised of an initial hovering after reaching the region above the landing site wherein the height had to be maintained and velocities had to be controlled at 0 m/s.

During Hovering the Lander is in a stabilized condition since velocities are controlled at 0 m/s and height is maintained by a closed loop guidance.

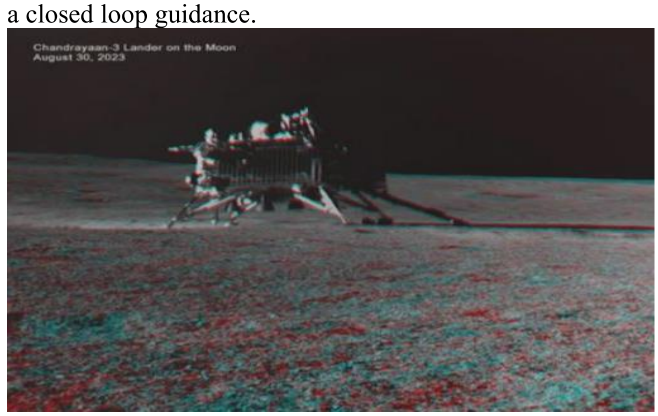

Fig. 1 Chandrayaan 3 on the Moon as viewed by Rover Camera

The altitude and velocity sensors will be able to update the local navigation filter which will take some time to convergence and then finally update the local inertial navigation at the end of hovering. A lower height can lead to inadvertent touchdown if height is not known. Even with height update indicating upper side of navigation error bound, devising guidance strategies to ensure phase convergence, without saturation of commanded engine thrust, and propellant optimality becomes essential.

After getting height update, the mission plan will be to vertically descend to a height for Hazard avoidance Camera operation with 0m/s velocity. Then, there will be a hazard avoidance maneuver and then vertical descent to touchdown. In the current scenario multiple height sensors ensure altitude update at initial hovering thereby providing height knowledge to the guidance loop. However, from the perspective of Guidance design, there could be chances of no height information to the loop where the Guidance should be robust enough to handle such eventualities. This paper brings out a guidance strategy for safe touchdown in case there is no height update at initial hovering after reaching landing site ensuring best possible propellant margin at touchdown. Also, the algorithms for guidance strategies in contingency mission trajectory are detailed.

The flow of the current paper is summarized in Section 1. Section 2 briefly describes the contingency scenarios and the evolution of the algorithms. Section 3, 4 and 5 elaborate on the Thrust Augmentation philosophy and guidance strategies for contingency scenario during terminal descent. Section 6 brings out the simulation results carried out for Chandrayaan-3 while Section 7 provides conclusion on the seamless handshaking and mechanization of the proposed and implemented algorithms onboard.

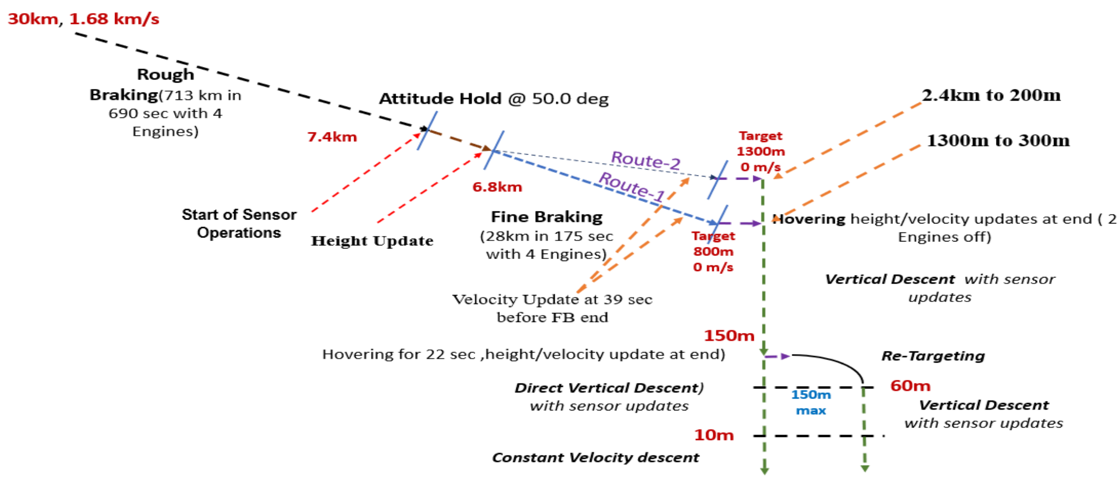

Fig. 2 Powered descent trajectory diagram showing Contingency Scenario

II. Contingency Scenario and Guidance Philosophy

Even though the Coarse braking phase of the powered descent operates with pure inertial navigation, certain decision logics are invoked in case of contingency. As a part of Salvage triggering logic, Background Salvage computation is enabled after crossing 18km and disabled after reaching 300m above Landing site target (800 m/1300 m)

With primary focus on the vertical axis, the acceleration required along vertical axis so as to arrive at target height with zero vertical velocity is computed in real time.

2.1 Decisions in Coarse Braking Phase

Algorithm: Invoking of Salvage Triggering Logic

If $\left(\hat{m}a_{comp} > ThrustComPerEngine_{salvage}\right)$

Invoke Salvage Guidance

End IF

Algorithm: Salvage Guidance Computation

1. *Terminate Absolute Sensor Navigation*
2. *Focus only on converging along the vertical axis. When target height is reached, hover at that height and now start bringing down the horizontal velocity to zero*
3. *When horizontal velocity is near zero, join the Local Navigation path. However, engine cut-off happens in Salvage happens only if the regulated thrust demand reaches down to 365N / Engine.*
4. *All the blocks of RCS thrusters for ΔV will be invoked whenever Engine thrust demand crosses above maximum limit*
5. *Re-Targeting under Salvage will maintain the height while moving horizontally since we are in unknown territory (LHDAC will be operated in 2-D mode)*

2.2 Decisions in Attitude Hold Phase

1. *At end of attitude hold phase, guidance convergence assessment to designated landing point within identified landing strip (4 km x 2.4 km) is done.*
2. *Through inertial navigation state vector* ***decision making parameter*** *is constructed and following check is done*

2a. Evaluating if current trajectory is within the ***Box***

If ***Current Trajectory*** *is outside the* ***Box***

Trigger Salvage (Emergency Landing)

Else Move to Step 2b

2bIf Current Trajectory is within the Box

If ***Current Trajectory*** *is Above boundary defined onboard*

Shift the Downrange to target (Latitude) i.e. bring the

tr trajectory within bound ***(shifting the target)***

Else

No Change in Parameter Continue to Nominal Target

End if

3. Selecting Height Above the Target

Valid Sensor Update	Target Altitude 800 m Above designated Landing Site
In Valid Sensor Update	Target Altitude 1300 m Above designated Landing Site

During the terminal phase of lunar landing, it is required to hover first at a safe height for typically 15 seconds and then try to get height and velocity update from absolute sensors at the end of it (represented in Fig 3). This will be followed by descent to a lower height to assess hazard. Height update is critical to know since it can have dispersions contributed by propagation error of inertial navigation. In Chandrayaan-3 mission, it was required to arrive above the landing site with zero velocity which was essential for hovering and absolute sensors' operation. The target height above the landing site is decided by how much time is required to arrive and hence how much the initial dispersion in states grows within this time of flight. The contributing factors are initial error in orbit determination and the inertial sensor inaccuracies. Under nominal height update scenario at initial hovering, Polynomial guidance is undertaken wherein the vertical velocity builds up first and then decelerates back to zero in the process of reducing the height from the current altitude to the target altitude in the designated time of flight which is a function of altitude, range and velocities.

In case height update is not there, normal descent will lead to inadvertent touchdown with large velocity since, initially vertical velocity build-up takes place followed by decelerating it back to zero before reaching target height. The vertical velocity build-up during nominal vertical descent can be as high as -10m/s which is far beyond the module leg capability to withstand. In case guidance gets no height update, it will assume nominal height and descend accordingly. A possible scenario is that actual height is far below the normal height and the lander will touchdown before vertical velocity becomes zero resulting in hard landing.

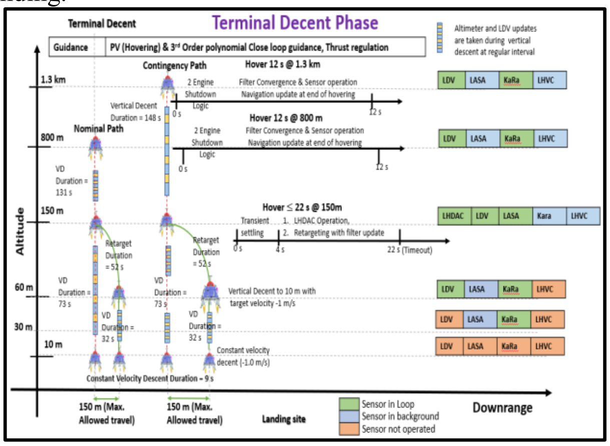

Fig. 3 Trajectory diagram showing Navigation plan and Guidance Milestones during Terminal descent

III. Delta V Augmentation

In cases where the guidance thrust shortfall was observed i.e. the commanded thrust was saturated, conditional RCS off-modulation was invoked as a part of thrust augmentation. This was critical for contingency mission scenarios, with upper side Navigation dispersion, in the terminal descent phases as the navigation dispersion being on the higher side RCS ΔV augmentation assisted in ensuring phase convergence for guidance where commanded Engine thrust was already saturated. NGC software had the provision of conditional RCS off-modulation in the terminal descent phases. The scheme is invoked once the regulated thrust demand crosses the maximum saturated thrust. The requirement of one block off-modulation comes primarily in contingency mission path with a module height beyond 1.3km and in nominal path with engine under performance in vertical descent-1 phase. However, if thruster block failure is identified the RCS thrust augmentation logic would be invoked for the other block of RCS. In case of an emergency landing where thrust and state dispersions are very high, both blocks of RCS ΔV augmentation would be called for from the beginning where stress was given to the convergence of the vertical loop thereby ensuring safe landing. However, there was no compromise on the attitude control realization through RCS as, even during off modulation, the RCS modulated based on the attitude error demand from the controller and imparted necessary control torque based on the thruster selection logic table (TSL) onboard. Figure 7 below depicts the NGC handshaking and interrelation with sensors and actuators. The engine thrust regulation is a proportional control logic whereas the attitude control is through PID control.

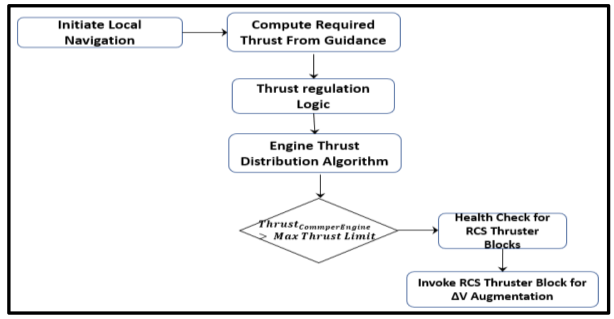

Fig. 4 ΔV Aiding from RCS Off-Modulation

IV. Guidance Strategies For Two-Point Altimeter Contingency At Hovering

The problem of dealing with the no height update(Two altimeters do not give Absolute sensor update) scenario at initial hovering is dealt with considering the 3-sigma dispersion due to propagation error from inertial navigation, craft terminal velocity bounded within the module leg mechanism capability, positive left-over propellant budget under dispersion scenarios and a conducive environment for guidance to handle absolute sensor updates en-route, once available. Different Guidance strategies are studied to ensure a safe landing. Initially a constant velocity descent plan is devised in which a relatively low target velocity (which is of the order of maximum acceptable touchdown velocity for the lander leg mechanism [V m/sec]) is slowly acquired and maintained through velocity shaping. However, with a relatively lower reference velocity, it would take a longer travel time for vertical descent and consume more propellant and for large dispersion case with height on the positive side at 1.4km and beyond, the propellant would be depleted leading to free fall and subsequent crash landing. Hence alternative guidance strategies, by means of a two-step staggered velocity referencing were designed to mitigate the problems with propellant budget for high altitude dispersion case. Under no height update at the end of first hovering, the proposal is to initially vertically descend with a large target vertical velocity (V1 m/sec nearly -10m/sec) and then switch over to a target vertical velocity (V2 m/sec nearly -3m/sec) which has to be the maximum acceptable touchdown velocity for the lander leg mechanism. The duration for which the target vertical velocity can be large will be fixed based on consideration of minimum possible height from surface of landing site due to inertial navigation error propagation as well as the time taken to decelerate back to lower target vertical velocity. Immediately after the expiry of duration with maximum vertical velocity, target vertical velocity to guidance will be changed to the maximum safe vertical velocity acceptable to lander legs.

Algorithm: Guidance strategy for Constant Velocity Descent

If (First Height Update = False) …. this Flag is raised from Local Navigation during terminal descent phase

1. *Enable Touchdown Sensing*
2. *For future prospective sensor update, Select Table corresponding to 1300m to 150m if not already*
3. *Compute the following once*

   m_{21} = *(0 –* V_{cx}*)/* $\Delta t_{threshold2}$,
   m_{22} = *(*$V_{constVD}$*-*V_{cy}*)/* $\Delta t_{threshold2}$
   m_{23} = *(0 –* V_{cz}*)/* $\Delta t_{threshold2}$

Assign $V_{refx} = V_{cx}$, $V_{refy} = V_{cy}$, $V_{refz} = V_{cz}$

4. *Raise a marker in ALS to denote the elapse of actual 12s of Hovering1*
5. *Initialize [*P_{refx}*,*P_{refy}*,* P_{refz}*] = [Pcx Pcy Pcz] (current position along x, y, z axis from local navigation applicable during terminal descent phase)*

   Running timer Tau2 =0.0

Then, in every guidance cycle till Tau2 <= Tau_Threshold2, compute

$$V_{refx} = V_{refx} + m_{21} * gStp$$
$$V_{refy} = V_{refy} + m_{22} * gStp$$
$$V_{refz} = V_{refz} + m_{23} * gStp$$
$$Tau2 = Tau2 + gStp$$

6. *Once Tau2 > Tau_Threshold2, Maintain* V_{refx}, V_{refy}, V_{refz} *(no further propagation)*
7. *All the time,* $P_{refx} = P_{refx} + V_{refx} * gStp$

$$P_{refy} = P_{refy} + V_{refy} * gStp$$
$$P_{refz} = P_{refz} + V_{refz} * gStp$$

(*gStp* is guidance cycle in sec, and Tau2 is incremented at steps of gStp)

8. *Select required guidance Gain*
9. *Keep running the time Tau2*

   If Tau2 > NoLargeMassIndTime

   Raise NoLargeMassFitFlag =True

   End
10. Continue till touchdown sensing or when First height update becomes True

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Initial target velocity is required to be large to reduce the flight duration especially when the actual height is far higher than the nominal height due to inertial navigation propagation error. Otherwise if the descent is straightaway with safe velocity for touchdown, it will lead to more propellant consumption and hence the risk of free fall if all the available usable propellant is consumed. During hovering, Position-Velocity tracking guidance is used to maintain height and velocities at zero. This guidance is continued while further descending with staggered target velocities. So, in case no height update comes after hovering, it is designed to have a safe touchdown during further descent. Thus, the initial relatively higher target velocity ensures a reduced flight duration while subsequently higher target velocity safeguards the module leg for a safe touchdown. Acquisition of this higher velocity, V1, is achieved through a step change in the guidance demanded thrust to lower saturation, which is commanded to engine. The duration for which constant velocity descent with higher target velocity is continued is based on a counter which is commandable and to be arrived at based on extensive Monte carlo simulations to ensure propellant margin for dispersion cases. This is followed by a sharp changeover to low velocity regime which is realized by ramping up the commanded thrust to engine to upper saturation which in turn takes time and adds on to net flight duration. As and when height update comes from absolute navigation sensor the same is taken into loop and guidance merges with the nominal sequence with height update towards further descent and touchdown.

V. Height Based Time-to-Go Fit Design During Terminal Descent

Time-to-Go (Tgo) is the key parameter in Polynomial guidance which decides the time required for convergence of the phase in Closed loop guidance. The terminal descent phase is initiated through Local navigation after the completion of Fine Braking phase when the lander module is just above the landing site nominally at 800m which is kept at 1.3km through design in contingency mission trajectory. Based on the inertial navigation error ellipse (~±1.1km) at the end of Fine braking phase the terminal descent would start at 2.4km. Hence, the flight time to come down to 150(second hovering) would be naturally more compared to that in case of 800m. Thus, the decision is taken through a Flag set based on whether the height update received indicates lander craft height above or below 1km.

Algorithm: Height based Time-to-Go Update

Initialize: VD1flagabove1km to FALSE at Autonomous Landing Sequencer start

Nominal_Mass_in_LNav to True [to check if Re-Targeting and Vertical Descent to 10m are to be carried out with nominal mass or Larger mass. Accordingly, Tgo fit equation will be selected]

If (height >= LocalNav_Height_Threshold (uplinkable)

Set VD1flagabove1km = TRUE

Else

Set VD1flagabove1km = FALSE

End of loop

For Guidance algorithms during VD1, ReT & VD2:

When the phase is start of vertical decent to 150m and VD1Flagabove1km = FALSE

*Time-to-Go at start = C0VD1N+C1VD1N*Altitude_L + C2VD1N*Altitude_*L^2 *+ C3VD1N*Vertical Velocity_L+C4VD1N*Horizontal Velocity_L*

When the phase is: vertical decent to 150m and VD1Flagabove1km = TRUE

Time-to-Go at start = C0VD1C+C1VD1C*Altitude_L + C2VD1C*Altitude_L^2 + C3VD1C*Vertical Velocity_L+C4VD1C*Horizontal Velocity_L

If (100 <= height <=HazardDetectCamOpsHt) or (15 <= height < 100)

Set Nominal_Mass_in_LNav to false

When the trajectory phase is: Vertical Descent to 10m (applicable to descent from 180m, 60m to 10m)

If (VD1Flagabove1km = False)
If ((Nominal_Mass_inLNav = True).OR. (NoLargeMassFit=True))
*Tgo at start = C0VD2_B1KM_M_OK+C1VD2*Altitude_L+ C2VD2*Altitude_L*^{2}
Else
*Tgo at start = C0VD2_B1KM_M_LARGE+C1VD2*Altitude_L+ C2VD2*Altitude_L*^{2}
End If
Else
*Tgo at start = C0VD2_A1KM+C1VD2*Altitude_L+ C2VD2*Altitude_L*^{2}
End of loop

VI. Simulation and Flight Results

Guidance and control simulations were carried out for the proposed guidance strategies by inducing Engine under performance upto 70N to analyze the limit of performance and invoke the Salvage guidance. Initially, due to small velocity build up in the positive direction, difference between vertical acceleration and Salvage Thrust limit-based acceleration is small. Hence it is not preferred to invoke Salvage check at the beginning. This is preferable only after the difference increases to somewhere around 0.5 which corresponds to 18km height. Again, simulations were carried out d without height updates for a lunar landing scenario. A case is considered wherein the initial hovering is at 1km from landing site for a duration of 15 seconds. The 3σ dispersion in height is ±400m due to propagated navigation error from previous phases of descent. In the first part of vertical descent due to no height update, vertical velocity targeted is -10m/s for a duration of 40 seconds followed by target being changed to -3 m/s which is considered as the maximum acceptable vertical velocity for landing legs, as demonstrated in Fig 1. Maximum engine thrust is 1650N and mass flow rate varies from 0.54kg/sec at maximum thrust to 0.26kg/sec at ~40% of thrust. To acquire the desire high velocity regime, the net commanded thrust goes to 720N and ramps up to 1650N(max) to realize the low velocity comfortable for leg mechanism, as shown in Fig5 and Fig 6.

Initial thrust to mass ratio is 1.5m/sec^2 where thrust is around 1400N. When the actual height is 1400m, touchdown happens with -3m/s and with positive propellant margin of around +10kg. If this strategy is not followed, under the same condition, there will be a shortfall of about 26kg propellant for safe touchdown. Simulations were carried out for large height dispersion case, as in Fig 7, where height update was taken en-route to ensure that the guidance merges with the nominal mission sequence followed by safe landing. Here, initial height at hovering is around 2.8km wherein constant velocity descent is invoked due to no altitude update and height reduces to 2.5km with the proposed strategy wherein absolute sensor updates are taken to inertial navigation during the low velocity regime of -3m/sec as represented in local nav height in Fig 6, and nominal guidance law is re-invoked and mission merges with the nominal sequence.

The height dispersion could make the height at Local nav as high as the Target Height +/-1.1km. Vertical descent-1 from these heights led to thrust saturation to 820N. Under this condition RCS thrust (from block 1, each RCS 58N maximum) is augmented to get additional ΔV to realize the guidance demand together with the engine ensuring the guidance convergence. However, without the off modulation non-convergence of phase was observed [Figure 9(a), (b)]. The efficacy of the ΔV augmentation with average RCS thrust and net thrust in dynamics is shown in Fig 10. The peak requirement on RCS 200N augmented thrust comes for ~40s where the engines with 820N capability remain saturated for max 45sec (worst case).

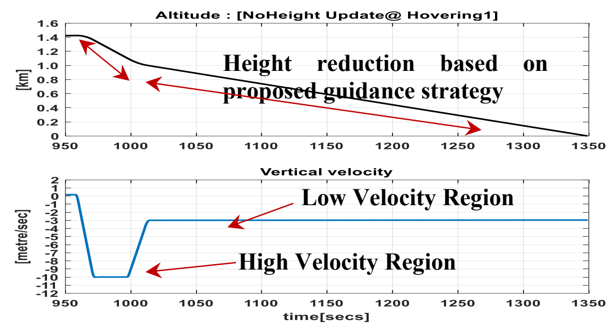

Fig 5 Altitude and Vertical velocity during no height update at initial Hovering

Two of the three guidance laws designed were brought into operation in Chandrayaan-3 flight. One guidance was the Polynomial Guidance and the other was P-V guidance. Salvage guidance was not called for since the deviations in engine thrust was well within limits. P-V guidance was used for hovering and in the final constant velocity descent. All other phases used Polynomial Guidance. The steering commands from Guidance in terms of the desired orientation was tracked by a closed loop control system with the sensor being laser gyro and actuator being eight numbers of 58N thrusters.

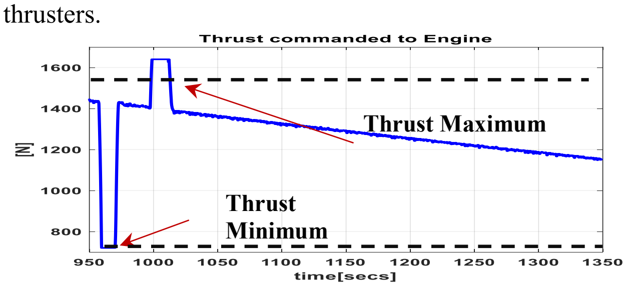

Fig. 6 Net Thrust during no height update at initial Hovering

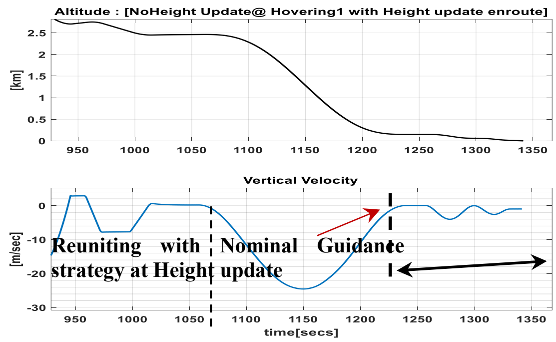

Fig. 7 Altitude and Vertical velocity with en-route height after execution of proposed guidance strategy

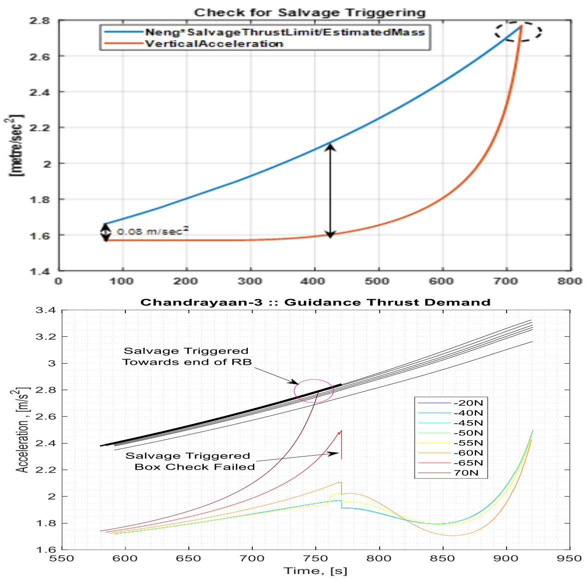

Fig. 8(a) & (b) Sanctity w.r.t the selection of 18 Km point for salvage computation initiation and Salvage triggering

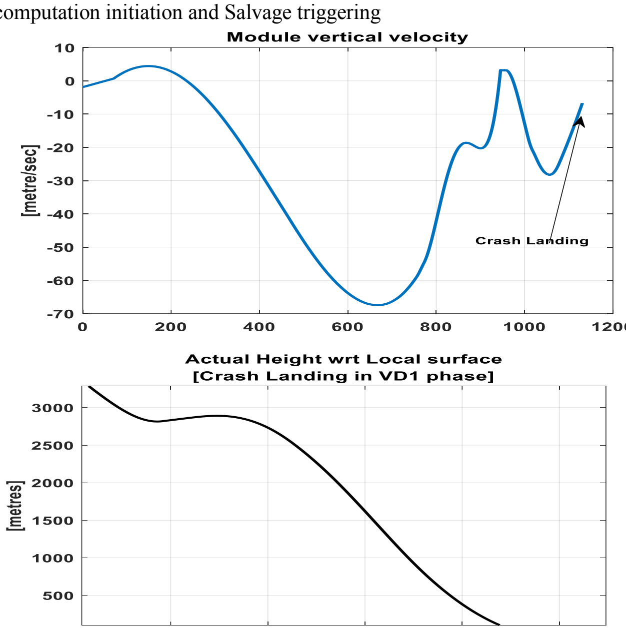

Fig. 9(a), (b). Penalty with No RCS Off-Modulation for Thrust Augmentation

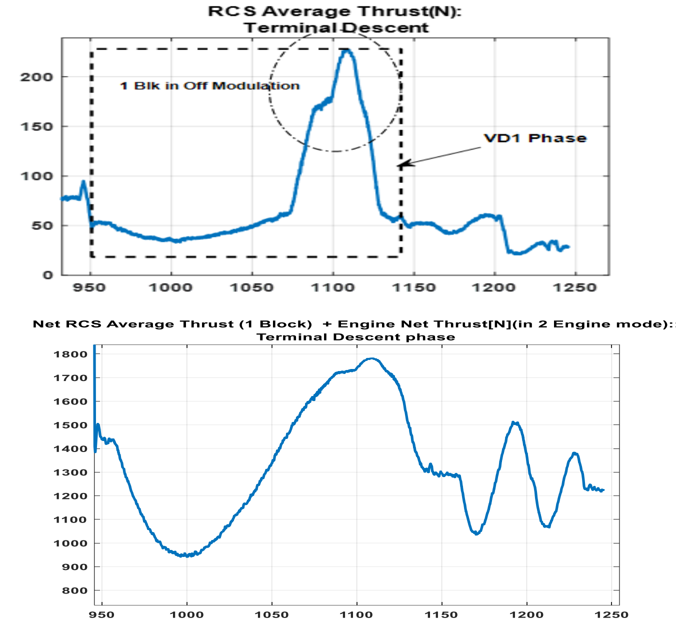

Fig. 10(a), (b) Efficacy of RCS Thrust Augmentation during Vertical Descent phase of Contingency Mission path

VII. Conclusion

The guidance strategies adopted for Chandrayaan-3 contingency scenario during powered descent have been presented in this paper. The Salvage guidance served as an emergency landing feature while real time retargeting proved to be a graceful degradation at Precision braking start in the trajectory. The RCS Thrust augmentation ensured robustness in phase convergence in the contingency mission paths with inertial navigation dispersion beyond 1.1km even when the commanded thrust was saturated for ~40sec thereby adding confidence on the Guidance margins available. The height based Tgo design was inducted onboard towards aiming propellant optimality considering the propellant consumption in case the module landed up at a height below the specified target height as per landing sequencer, based on absolute sensor update. Moreover, the guidance design and strategy for no altimeter update at hovering further added to the resilient G&C approach for Lunar landing mission thereby serving as a benchmark for ISRO's future landing operations

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