FUEL OPTIMAL
TRAJECTORY AND GUIDANCE DESIGN
FOR LUNAR SOFT LANDING AT A TARGET SITE

A thesis submitted

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by

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ABSTRACT

The problem of generating optimal landing trajectory design and optimal guidance laws for Moon landing is solved in this research. First, the lunar soft landing trajectory design problem is formulated and the resulting two-point boundary value problem (TPBVP) is solved using different approaches. Two independent approaches i) direct ii) indirect are used to solve the problem. Two of the gradient free (Particle Swarm Optimization-PSO and Differential Evolution-DE) optimization techniques and a gradient based optimization technique (Sequential Quadratic Programming-SQP: fmincon-MATLAB) have been used to solve the problem formulated using both direct and indirect approaches. A scheme based on the indirect approach and DE is evaluated to be superior for the soft landing trajectory design. The challenge in the indirect approach lies in finding suitable initial co-states with no prior knowledge available about them. In the second part of the research, the challenge related to initial co-states is dealt with and overcome. The co-states are determined using the Differential Transformation (DT) technique, for a given flight duration (unknown) and a target site. The only unknown flight time is determined using the DE technique. This novel computational scheme, called DT-DE scheme, uses Differential Transformation in multi steps to ensure the precise landing at the target site. This scheme is uniformly valid for the performance measures like fuel-optimal, energy-optimal or time-optimal. In DT-DE scheme, the major advantage is that the co-state equations need not be numerically integrated to find the control variables at each computational step. Furthermore, the number of unknowns reduces to one, the flight time, resulting in a reduction of computational time. Another important step of a lander mission is to guide the vehicle

to the pre-selected target site. Towards achieving this, a DT based novel guidance algorithm with real time computational strategy for the determination of flight time is developed. Two guidance schemes (i) fuel-optimal (ii) energy-optimal to realize soft landing at a desired location on the Moon are developed using the optimal control laws. The optimal control laws are obtained as functions of co-states. The DT technique is employed to determine the unknown co-states at each time instant of landing trajectory using the information on the current vehicle state, target landing site (loaded on-board a priori), and the time-to-go. The time-to-go, a critical parameter for any guidance scheme, is computed and updated in real time using a simple strategy that uses the current and end states. Further, the new guidance schemes are compared with other popular guidance schemes. Other features of the proposed schemes are that they do not assume a constant gravity field and independent of the reference trajectory. The proposed methods for landing trajectory design and guidance design have been implemented and the numerical results have been analyzed. Some of the important findings are: (i) The computational time (CPU time) to generate optimal trajectory using the DT-DE scheme is significantly less (35 to 40 s) compared to the CPU time required to generate the solution using the DE technique alone (170 s). (ii)The landing mass achieved by fuel-optimal DT guidance is remarkably close (the difference is less than one kg) to the landing mass of open-loop fuel-optimal trajectory. (iii) The Fuel-optimal DT guidance lands more mass than the energy-optimal DT guidance. (iv) The DT based energy-optimal guidance scheme performs betters than other energy-optimal guidance schemes (v) The simple strategy proposed for the real-time computation of time-to-go performs very well and helps in achieving the target site precisely.