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Nuffield Foundation- Lunar Mission One Project

Research into the Autonomous Final Descent Techniques to be employed by the LM1 Lander

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LIST OF ABBREVIATIONS

LM1	Lunar Mission One
NASA	North American Space Agency
AUV	Autonomous Underwater Vehicle
LIDAR	Light Imaging Detection and Ranging
RADAR	RAdio Detection And Ranging
HDA	Hazard Detection and Avoidance
TRON	Testbed for Robotic Optical Navigation

ABSTRACT

In all Previous Lunar Landings, there has been at least 2 members of crew on board the craft. The Lunar Mission One project aims to land an unmanned probe on the south pole of the moon next to the Shackleton Crater in order to drill for research into the moons origins. To do this the previously used methods of lunar landing must be changed to allow the unmanned craft to know when it needs to initiate the navigation programs. In this paper I investigate two possible methods to aid the craft. The first is when landing, to use radar beacons that would be dropped from orbit in order to allow the craft to detect the position of the landing site. The second is the use of LIDAR to map the terrain of the site and detect problems including gradient and surface roughness of the site. These used in combination should allow the craft to land safely at the crater. These are my proposed systems for final autonomous descent of the craft.

1 INTRODUCTION

The lunar mission project is a high precision mission to the southern pole of the moon. The aim is to launch a probe into polar orbit around the moon, then to land it nearby the outer edge of Shackleton crater at the South Pole. From here the probe will drill ~20m into the surface and take core samples into itself for further analysis. The aim of this is to gather more information about the possible formation of the moon and the rest of the solar system, and also investigate the possibility of a future lunar base.

As the aim is to collect core samples, we must be sure that the probe arrives in the appropriate area of geological interest for proper sampling. This means that we must reliably be able to land within an area of around ~100m^2. Compared to the overall size of the moon this is a very small area to land in and will require accurate course correction in order to avoid rocks and other obstacles in the final stage of descent. In order to allow for these small, precise changes in trajectory the craft must be able to accurately identify its position in relation to the surface of the moon as well as decide what constitutes as a hazard. Owing to its polar location the shadows cast by the crater may obscure direct vision, forcing an alternate method to be used. Also to allow for instant course correction we cannot rely on manual inputs owing to the delay (or the lag in response time caused by this delay) over this distance. Therefore some of the quick reactions must be undertaken by the craft's computers to autocorrect its trajectory, requiring it to know its location and possible hazards.

In this report I will go into detail upon the possible problems which the lander will encounter as well as possible fixes.

2 METHODOLOGY

This project is mainly a literature review and will consist mainly of research papers published by third-parties.

To do this I began by using basic google searches to highlight broad areas of possible interest. I then began in-depth research into these areas through the use of google scholar. This returned several academic papers of interest. I analysed these and then used their references to find other papers of similar topics and used them to broaden my information base. The reference material I ended up using can be found in appendix A.

Another site that I used to help my research was Web of knowledge. This also helped to provide a source of papers which allowed for alternate sources to be found.

3 RESULTS

My initial direction of research was into previous methods of landing onto the moon. Previously the only landings were performed by the 17 Apollo missions. These were a series of manned missions to the moon with the Saturn V rockets.

Six of these missions involved a landing on the moon (11, 12, 14, 15, 16 and 17) [1] using the NASA lunar landing module. This was a small craft containing space for 2 astronauts. It followed a fairly simple method for landing once it had been placed in orbit around the moon. As the craft only had 2048 bits of RAM the automation of the landing procedure was severely limited. Simple programs were activated in succession, each simply taking in readings from instruments on-board the craft before passing them through several equations. These equations output several course corrections which were sent to the engines. This allowed for the easy piloting of safe manoeuvres whilst working with limited memory.

The NASA landing process consisted of 3 separate programs run by the module in succession. [2] [3]
Program 63 is first to activate. It is activated at the periapsis of the lunar orbit, at an altitude of approx. 100KM. It was manually activated by the crew at a predetermined point by mission control. It allows the craft to compute the precise burn time needed to allow the craft to exit its orbit to the following specifications:

- 2100m altitude
- 7500m horizontal distance from landing site
- 120m/s horizontal velocity
- 50m/s vertical velocity

This slows the craft to the point where it is able to safely identify and aim towards a landing site using the next program and as such is called the braking phase. The burn usually consisted of a single extended burn in the opposite direction to motion. This reduced the orbit to a point where it would approximately coincide with the suggested landing site.

Once these specifications have been reached the next program- program 64- is activated. This is known as the visibility phase and aims to position the craft above the landing site so that it is directly visible to the astronauts within the craft. This too had a set of specifications which the computers aimed to reach:

- 30-60m Altitude
- 10m Horizontal Range
- Visibility on landing site

These specifications are more lenient than those of program 63. This is because much more human interaction is to be expected in this phase. During these manoeuvres the astronauts on-board used visual equipment to decide the final destination/landing site of the craft. The visual systems superimposed aiming reticules and angle readouts over the direct view they had of the moon. Using this data they input the appropriate information into the guidance computers to allow for phase 3. The wider range for altitude depended on where the final landing point was decided. If it was further away horizontally the final vertical altitude was less than that of a closer point.

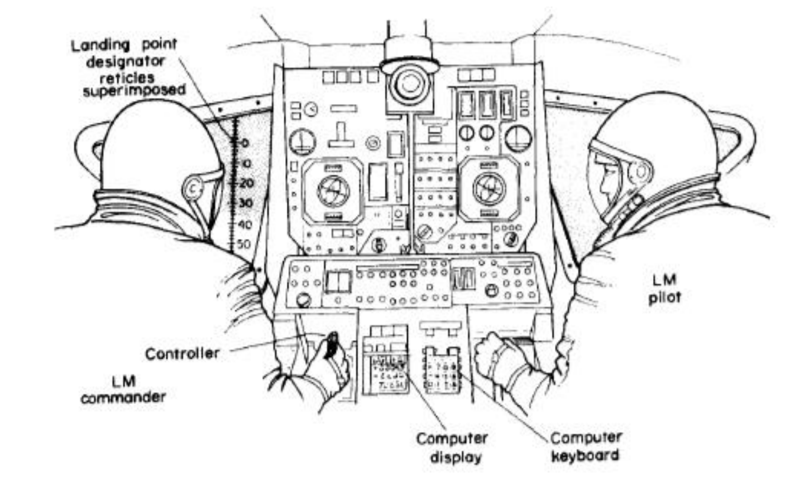

Fig-1 Image of NASA lander interior, demonstrating visual equipment for visibility phase. [2]

The final program, program 66, was activated manually by the astronauts once the site had been decided. This consisted of 2 parts, altitude and thrust. Altitude controls the vertical velocity of the craft and allows it to slowly descend controlled onto the site. Thrust controls the horizontal velocity and kills it to allow for vertical descent. This program works by setting either one or both to auto and the other to manual. The auto setting tells the computer to systematically reduce the speed of each to 0 before landing. Manual gives control to the pilots in the craft and removes any control from the auto system. Even with both parts of the system set to auto, manual control form the pilots is still needed to land the craft. The pilots need to initiate the manoeuvre and decide whether the site is clear or if an abort is needed. This is needed to watch for rocks or if the site is at a too large angle.

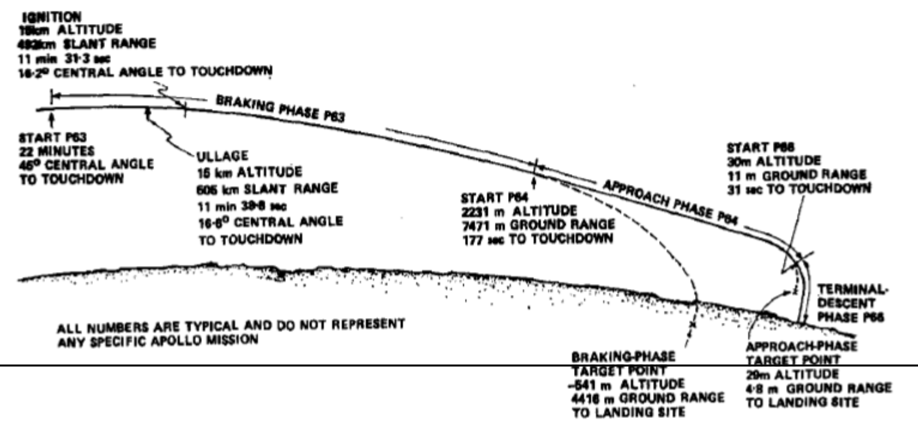

Fig 2- Example of 3 Programs on average mission [2]

This system worked well for manned landings however would need to be adjusted for the LM1 project. As the LM1 project is designed to be unmanned this prior system would present some problems. Firstly with this system manual decision making is required to decide the final landing site. The NASA system requires the pilots to decide the final landing spot. The LM1 lander will need to decide this itself, as there is a delay between the mission control and the lander of up to 3 seconds. This would cause possibly fatal errors if relied upon in the final moments of descent to decide if the site was clear or not. Therefore the lander needs to decide on possible sites before approach. Also this needs to be decided above 50m. This is because below 50m the dust causes poor visibility using conventional cameras and would cause any decisions at that point to be impossible using visual information. Finally the craft must be able to realise its position in orbit. With the Apollo missions the craft exited orbit on the pilots command to arrive in the correct landing position. In LM1 we will need the craft to realise its position in orbit in relation to the landing site. This will allow it to calculate the point of re-entry correctly.

My next area of investigation was in the realm of orbital beacons. These were previously highlighted by the LM1 team as a possibility for the mission. These have never been used in astronomical missions previously, but have been used for Autonomous Underwater Vehicles (AUV's) [4] [5]. These vehicles work underwater in situations where the camera cannot easily see. In these situations the AUV needs to return to the docking port on the ship by itself. To do this it uses Light Beacons.

The beacon itself consists of simply a relay that when it detects a microwave signal it amplifies it and re-broadcasts it at the same frequency. The AUV itself broadcasts a high frequency radio wave from a single point on its outer hull. It then detects the returning wave and uses the time taken to calculate the distance. To do this it uses the following equation:

Distance = (Speed*time)/2

This works because the speed of light is a constant and therefore if the time taken for it to return is measured the distance it travelled can be calculated. It must then be divided by two as the light travelled in both directions. This distance is of little use on its own but the craft first performs a full circular rotation. This allows it to take multiple distances and decide the point at which they all meet to triangulate the location of the receiver (fig 3). This allows for a single receiver and relay.

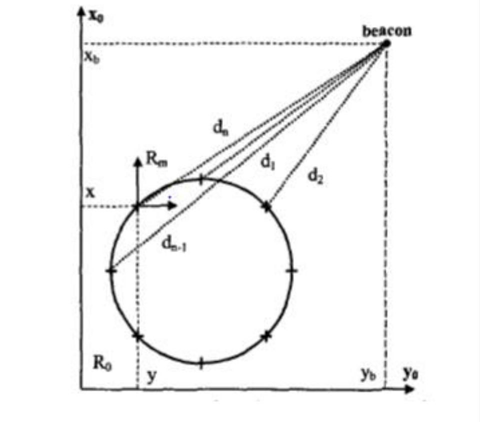

Fig 3- circular rotation pattern [4]

This system is quite effective, however on the LM1 lander some adjustments will need to be made. Firstly the craft is not able to freely rotate in orbit. This would not allow for the same detection patter as the AUV. To overcome this problem, a greater number of beacons would need to be deployed. However if we simply adjusted the receiver to detect a bearing to the returning microwave then we wouldn't need as many beacons. This would allow the craft to detect the definitive position of the beacons to orient itself with the landing site.

I have calculated 2 equations which allow the craft to obtain an X and Y direction to the beacon from the craft:

$$Y = sin|(\theta - \frac{\pi}{2})| \times (L^2 - A^2)$$
$$X = \cos|(\theta - \frac{\pi}{2})| \times (L^2 - A^2)$$

Y and X = coordinate distances to the beacon (m)
θ = bearing to the direction of signal in radians
L = distance to beacon (m)
A = altitude (m)

These equations use the basic trigonometry of the relation between the angle of the lander and the beacon to first work out the direct horizontal distances between the 2 objects, and then converts it into an X and Y coordinate direction to the craft. (My rough workings can be seen in appendix A [9])

These coordinates simply require the craft to know its altitude (which is already a factor in the navigation), direct distance to beacon and bearing from a set direction on the craft. This will allow the craft to orientate itself in relation to the beacons and therefore decide internally when to activate program 63.

The other aspect of the landing that needed research was into hazard detection in the final descent procedures. The craft needs to be able to detect hazards in the landing area and then navigate in relation to these hazards to a final safe landing site. My research produced the possibility of LIDAR for this [6] [7].

LIDAR (Light Imaging, Detection, And Ranging) is a form of radar that uses lasers instead of high frequency radio. This works via the same premise of Radar with each beam being reflected and using the time taken to work out the distance to the point. It can be used to easily create terrain maps and is currently being used in several industry applications. These include forestry for managing the terrain and deep archaeology to see faint ruins buried deep underground leaving only faint lines in the terrain. This has one main advantage over RADAR however as it doesn't require a receiver to return the signal. The surface of the moon is naturally reflective to light as can be seen at night with its reflection of the sun's rays. LIDAR uses this to reflect its lasers back to itself, thus allowing maps of the terrain to be generated.

The Laser runs several scans across the surface, detecting the distance between itself and the surface. Using this it can generate a terrain map (fig 4) which is then run through several internal algorithms. The first of these simply smooths out the direct measurements into a basic terrain map (fig 5). This is then checked for the angle gradient of the surface. If it is greater than around 10° then it could be unsuitable for a landing site as the craft could be unstable for drilling. These areas are ruled out and marked as a dark area (fig 6). The program then checks the roughness of the surface. Objects greater than 30cm can be a problem for landing and could tip the craft on landing. The system checks for any possible obstructions, and marks them on another version of the map (fig 7). The program then combines these two maps and produces a final image of safe landing sites (fig 8). A site then can be chosen from this by either a program or ground control for the final safe landing site of the craft.

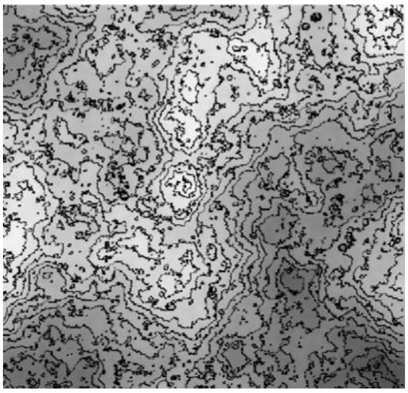

Fig 4- direct measurements from LIDAR [7]

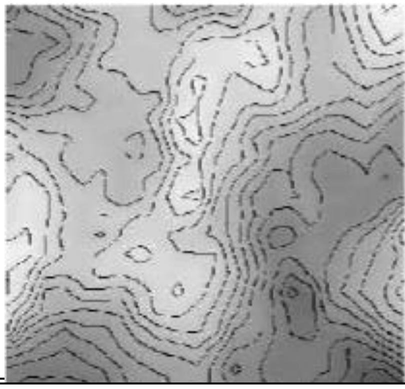

Fig 5- Smoothed terrain Map [7]

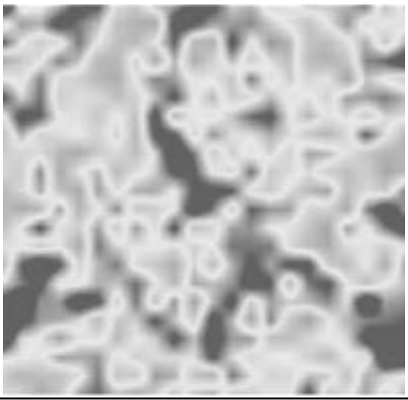

Fig 6- Angle Map (darker = steeper) [7]

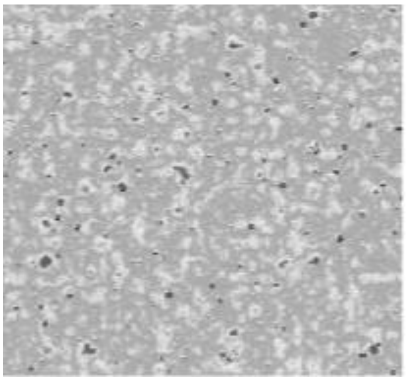

Fig 7- Roughness Map (dark patches = objects over 30cm from surrounding terrain [7]

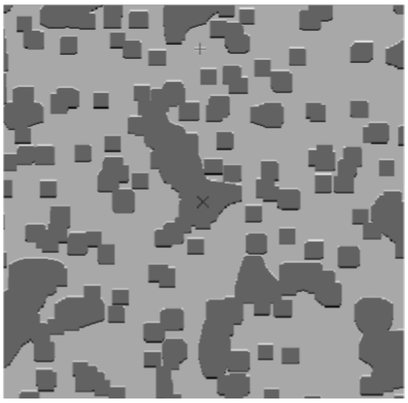

Fig 8- Final Designated Safe Sites [7]

This is a process known as HAD (Hazard detection and avoidance) and is one of the two times the LIDAR system will be used on descent. It will first be activated in in the Braking phase of descent. This will be about 3-5 km above the surface. This gives the craft time to make an accurate map of the terrain and decide on a final landing site. This is the initial use of LIDAR. It is then used during the Visibility phase for HRN (Hazard Relative Navigation). This is a different process to that of HAD. This involves using the Lasers of the LIDAR to track the features around the decided Landing site. This allows the craft to detect its position in relation to these features and then navigate through to landing. It tracks the positions of identifiable objects such as hills or larger rocks and works on a principle similar to that of facial tracking, by looking for similar shaped objects and then tracking their movement.

This also helps by combatting the previous problem of dust. As the LIDAR system can make the terrain map at an altitude of 3-5 Km above the surface, it will not be affected by the dust. This means that during the final descent of the craft, the landing site is already known to be clear of obstructions, allowing the crafts guidance systems to easily land without relying on impossible visual feedback.

These two factors will allow the craft to decide upon a safe landing site and then position itself correctly according to the two parts of Program 66 to land upon the site. This technology is undergoing testing by NASA currently using a piece of equipment called TRON [8] (Testbed for Robotic Optical Navigation). This simulates a possible lunar surface and is currently testing the possibility for LIDAR systems. It consists of a miniature model of a possible lunar surface and uses a robotic arm to simulate the descent towards it. The smaller scale allows for the parts to be tested whilst still requiring minimal space.

The results from these initial tests can be seen in figures 4-8.

4 EVALUATION

If further research into the topic is required areas of interest could include:

1) How my equations would change to encompass the curvature of the moon.
2) How the craft could accurately drop the beacons onto the landing site.
3) What level of human choice would be best for the approved landing sites of the craft? E.g. should the mission control chose which of the ‘good’ sites the craft should land at or should it be left to the craft
4) What wavelengths of radar would be best for the beacons, and what wavelengths would be best for the Lasers in the LIDAR.

5 CONCLUSIONS

To conclude, I believe that the previous programs made by NASA can be mostly reused. The main aspects of each program are still relevant to this mission and each one still works for an unmanned mission. The majority of the information required for these programs was taken in by the computer systems themselves, allowing for the autonomous programs to calculate the appropriate thrust maneuverers. The main alterations will be to allow the craft to activate these programs by itself in the correct positions in orbit and to detect safe landing sites. As such we just need to replace the human pilot's judgement with the systems suggested.

To combat the initial problem of working out its position in orbit relevant to the landing site. The idea of radar beacons from orbit would allow for long range detection of the landing site and allow for the initial start of the programs for landing; a minimum of 3 would be needed to allow for accurate triangulation of the area. They would reflect high frequency radio waves transmitted by the craft back to a receiver on the craft. The craft then uses this in several equations to triangulate its position in orbit in relation to the beacons. This would cause the craft to exit the orbit in a good position and allow for accurate passage to the possible landing area at the Shackleton Crater using the previous NASA programs.

Finally the use of LIDAR to make a terrain map of the landing site would allow the craft to decide itself on a safe landing site and therefore not require the manual decision making previously required. It will use several scans of the site to create an accurate terrain map of the area. It will then eliminate all areas of danger. This will allow it to land in the region of interest whilst still avoiding all obstructions itself.

With this combination of methods the craft should be able to safely and reliably land on a site of geological interest for the mission

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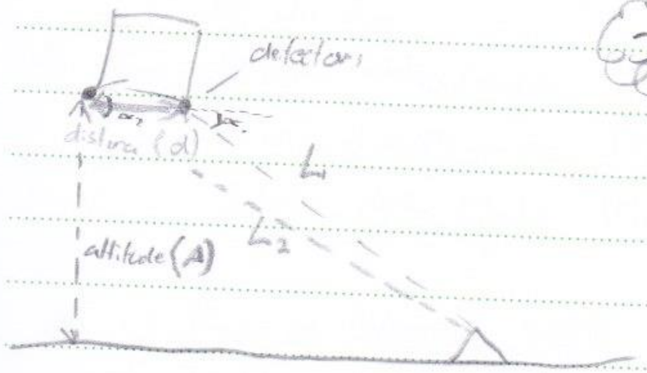
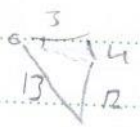
[9]
My rough calculations for the 2 equations of triangulation using the beacons

Triangulation Using Beacons - Calculation

x view

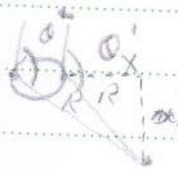


$\theta = 0.927$



$\theta_V = \Delta R 4$

Y view



$$L_{(1/2)}^2 - A^2 = R_{(1/2)}$$

$$\cancel{x_{(m)} = L_1^2 - A^2}$$

$$\sin|| = \frac{y}{R}$$

$$Y = |(\theta_1 - \frac{\pi}{2})| \times R$$

Strip Sin

$$Y = \sin|(\theta - \frac{\pi}{2})| \times (L^2 - A^2)$$

$$x = \cos|(\theta - \frac{\pi}{2})| \times (L^2 - A^2)$$

θ rotational Velocity

Need: altitude
distance to sensor
horizontal bearing $(0 - \pi)$
Which side it's on

Result = $x + Y$ distance to sensor

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