Review of Autonomous Technologies for a Crewed Exploration of the Lunar South Pole

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The revival of the Artemis program has renewed interest in crewed lunar surface exploration. Past missions and plans for crewed lunar surface exploration have been limited by communication blackouts, extreme terrain, and artificial range limitations experienced on the lunar surface. This paper examines autonomous vehicle designs and technology for the exploration of the lunar south pole. A review of previous missions and designs is presented and evaluated based on the performance of the design to fulfill mission requirements. An evaluation of autonomous lunar rover technologies is also conducted. The autonomous technologies reviewed are LIDAR, image recognition, and optical flow sensors. These technologies were evaluated using a decision matrix to inform mission planners how to increase safety and expand the mission envelope. Using the decision matrix, the author recommends that mission planners use LIDAR on autonomous lunar rovers to increase safety and exploration capability.

I. Introduction

The idea of intelligent-decision-making robots working independently with humans in space has long been relegated to science fiction. Hardware and software advancements have advanced to enable the development of control systems and sensors to meet this goal. One technology that has improved over the years is autonomous rovers. Rovers are on the forefront of developments in autonomous technology, fielding capabilities that aim to augment human ability, yet operate safely and independently in severe environmental conditions.

The application of autonomous rovers designed specifically for use with humans in space is a relatively new concept. Historically, rovers on the Moon or Mars operated with humans in the loop. Whether in the lunar rover and/or remote, humans controlled every action of the rover. An early concept to use autonomy on the Moon was the Scarab rover, a NASA technology demonstrator designed to navigate lunar craters [1]. Recently, the Mars 2020 Perseverance Rover successfully demonstrated autonomy by navigating between waypoints, relying on vision-based autonomous navigation software to achieve this milestone [2].

The next rover autonomy challenge is to accomplish more complex science goals by operating in cooperation with astronauts. Further developments are being incorporated into the Lunar Terrain Vehicle (LTV), a rover under development to carry Artemis astronauts around the lunar south pole [3]. The Artemis program aims to establish a lunar south pole base, in an area that is densely cratered [4]. It is mission critical that a rover is capable of safely navigating rough crater slopes while occluded from orbiting or terrestrial communications.

Lunar autonomous vehicles will greatly impact mission safety and capabilities, as increased sensing will allow the vehicle to better understand the operational environment and execute maneuvers to minimize risk to passengers. These revolutionary autonomous features are enabled by technologies such as LIDAR, image recognition, and optical flow sensors that aid in positioning and sensing of the rover. Accurate positioning and sensing are key to meeting safety and mission requirements. In addition, advances in theory and engineering for autonomous rovers are not limited to the moon and can be applied to improve life on earth.

II. Review of Lunar Rovers

A. Lunar Roving Vehicle

The original lunar rover, the Lunar Roving Vehicle (LRV), launched on Apollo 15, Apollo 16, and Apollo 17 enabled the Apollo astronauts to explore a greater area and collect more distant samples than if traveling by foot.

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The LRV had no autonomous maneuvering capabilities and struggled to stay in contact with flat ground when traveling more than 9 mph [5]. In addition, astronauts were range limited as they could not drive further from the lunar lander than they could walk. This limitation was a safety feature to prevent them from becoming stranded in the event of a LRV mechanical failure [5]. These limitations worked for the Apollo missions, but the Artemis program has more ambitious objectives that require a more sophisticated solution.

B. Scarab Rover

NASA and Carnegie Mellon University began work on the Scarab rover in the late 2000s to demonstrate a range of technologies intended for lunar vehicles. Scarab was intended to fulfill the role of a site surveyor and be deployed at the lunar south pole to collect regolith cores at a variety of locations [1]. Scarab's navigational capabilities and mission planning architecture were designed to have a high degree of autonomous capability, necessitated by the communication blind spots when taking samples near a crater wall. Unlike other rovers designed to take samples from flat areas, Scarab had to navigate to the sample sites, climb steep grades to get there, and dynamically adjust its suspension to level the drill, all while not in communication with earth [6].

Although Scarab was not designed to be used alongside humans, the rover was designed to encounter and mitigate the same challenges that a crewed rover would experience. Scarab's autonomous capabilities were focused on navigation and stability, relying on LIDAR and active suspension to detect and navigate obstacles. The rover's control system development focused on maximizing the suspension for stability in order to keep the rover in a stable position at hazardous inclinations [6]. Since 2010, object identification, classification and pathfinding tools have improved significantly; however, Scarab was an early model of how 21st century electronics and software could be integrated to enable autonomous features in real-time on a mobile platform designed for the lunar surface.

C. Lunar Terrain Vehicle

The LTV is under development for the Artemis program by three bidders – Lockheed Martin-General Motors, Northrop Grumman, and Teledyne Technologies. To date, NASA has not publicly announced a winner; however, all three teams have included autonomous capabilities in each proposal [3]. The goal of the LTV program is to produce an unenclosed buggy designed to transport astronauts and equipment across the lunar surface. The NASA contract specifically indicates remote operation and supervised autonomy is required, and prefers a plan to add autonomous features over time [3].

The Lockheed Martin-General Motors team plans to add autonomous systems to the vehicle to allow prepositioning on the lunar surface [7]. This autonomous system inclusion would allow the LTV to be launched separately from the astronauts, and autonomously travel to the Artemis landing site, increasing the LTV launch options, as it no longer would need to be co-manifested with the Artemis crew. Since the project is still in early development, specific technologies that will enable autonomous features have not been made public.

III. Technology

A variety of technologies comprise modern autonomous systems to increase a machine's perception or positioning abilities. No single factor will make an autonomous system inherently successful, but the integration of these technologies provides an ideal set of capabilities for exploration. Autonomous navigation is most successful when the route planning systems know where the vehicle is, relative to its environment. It is important to note that while detailed maps of the lunar surface exist, the ability to determine position via satellite may be intermittent and the need to detect obstacles and determine position locally is key to enabling autonomy. The primary function of these technologies is to determine vehicle location and surroundings to allow onboard systems to plot a course forward. This must be accomplished without continuous terrestrial or orbiting support.

A. LIDAR

LIDAR (light detection and ranging) utilizes the known time of flight of light to determine range and can be used to visualize an environment with accurate distances, relative to the sensor. LIDAR is a key autonomous technology because the technology can observe and digitize an unfamiliar environment [8]. That information can be interpreted by onboard computers to plan a route around hazardous features and determine position based on the terrain. However, LIDAR requires a clear line of sight and works best with vision-based systems, requiring designs to maintain sensor visibility and consider an additional system. The development of 3d LIDAR makes it a key sensor to enable accurate sensing of the environment. 3d LIDAR commonly uses up to 64 individual laser channels to obtain a point cloud of data, enabling the collection of data above and below the plane of the sensor [9]. Recent benefits of 3d LIDAR include cost savings due to scale and equipment size reduction due to ongoing research. Ultimately, LIDAR provides a high level of accuracy and detailed maps of an environment. On the lunar surface, LIDAR is particularly effective at determining topography, allowing for a high level of stability confidence for a rover.

B. Image Recognition

Image recognition software uses digital images and a pretrained computer model to interpret and classify features within an environment. Image recognition software has been used on the Perseverance Rover to enable supervised driving between sampling sites [2]. On the lunar south pole, image recognition software would allow autonomous rovers to classify obstacles and make deviations as needed. However, the Artemis program will explore lunar south pole craters, nearly all of whom have permanently dark regions [4]. Optical systems would require significant illumination, increasing energy consumption at the expense of range, making image recognition a nonviable option for exploring craters. This technology conserves mass, making use of existing engineering cameras, but only has the possibility to be a reliable autonomy tool on illuminated parts of the lunar surface.

C. Optical Flow Sensors

Optical flow sensors rapidly collect images and compare the position of features within the frame to determine relative velocity [10]. The same class of optical flow sensors are found in computer mice. Optical flow sensors are usually used in autonomous systems as a redundant sensor, to validate onboard positioning instruments such as inertial measurement units or the aforementioned technologies. The optical flow sensor is positioned over a wheel to measure rotations and calculate slippage. In conjunction with onboard maps of the lunar terrain, optical flow sensors can theoretically enable accurate positioning from wheel motion [10]. Real-world accuracy would be greatly reduced in use on the uneven lunar surface and the system would require frequent recalibration. Ultimately, optical flow sensors are a compact solution to increase accuracy of other autonomous technologies but are ill-suited to being the sole navigation aid, due to inherent inaccuracy when dealing with nonlinear systems.

IV. Impact

A. Safety

For human exploration, autonomous vehicles can provide a factor of safety from the environment by using onboard sensors and satellite imagery to predict, detect, and avoid obstacles. These technologies are fundamentally rooted in accurate positioning and environment perception. The first step to creating a safe autonomous lunar rover is ensuring the vehicle is always aware of its location and surroundings. After that, onboard software can calculate and optimize path planning to avoid obstacles and maintain control when traveling at speed, on inclines or crater rims. Unlike the LRV, the goal is that future autonomous rovers can automatically maintain control and contact with the ground by sensing the terrain and making preemptive adjustments, faster and more precise than a human. Finally, autonomy can quickly identify if a slope would cause the vehicle to become unstable, allowing rapid decision making about where to proceed.

B. Capabilities

Part of the LTV proposal offers the ability to land in a remote area to protect the main landing site from damages [7]. Once on the surface, the LTV proposal includes the prepositioning of the vehicle without requiring a preprogrammed path to the landing site or requiring direct communications. Autonomy is one factor to help overcome range limitations in the interest of safety. In the event of multiple failures of redundant systems that leaves crew stranded, a lunar surface spare could be dispatched, with a high degree of confidence in its success, allowing the astronauts to take even more distant samples. Logistically, autonomy offers payload increases, as the vehicles can operate in follow the leader mode and make resupply runs for distant sites.

V. Decision Matrix

A. Objective Definitions & Weighting Factor Justifications:

Mass is the most important factor of any spacecraft. Mass is weighted at 30% because the mass of the sensor contributes to overall spacecraft mass which is limited by the launch rocket capacity. The LTV minimum capability descriptions list an estimate for total vehicle mass of 500kg [3]. The lightest design receives a score of 10 out of 10 points.

Maturity is a measure of how “flight proven” a technology is for use in aerospace applications. Technological maturity is scored according to the NASA Technology Readiness Level (TRL), which assigns a value between 1 and 9 according to the technologies’ position in the development process. The technology with the highest TRL receives a score of 10 out of 10 points.

Cost is the cost of the materials and development work required to develop and integrate the sensor. Technologies capable of using existing commercial parts receive a high score.

Accuracy measures the sensor's error over distances and timescales on the lunar surface. It is qualitative and is a rough estimate of real-world results. Scores are determined according to relative drift.

Selection Criteria			LIDAR			Image Recognition			Optical Flow Sensors		
Objective	Weighting Factor	Parameter	Magnitude	Score	Value	Mag.	Score	Value	Mag.	Score	Value
Mass	0.30	kg	3.5	7	2.1	0	10	3	0.05	8	2.4
Maturity	0.20	1-9	7	10	2	5	0	0	6	5	1
Cost	0.20	$	100,000	3	0.6	0	10	2	200	6	1.2
Accuracy	0.30	reported	great	10	3	fair	4	1.2	poor	1	0.3
Overall Value					**7.7**			**6.2**			**4.9**

Qualitative Score Assignments:	
great	10
good	7
fair	4
poor	1

Image recognition is the least mature and most complex design because it requires a large dataset of lunar features. LIDAR is the most accurate of the three, but still relies on other sensors such as inertial measurement units and gyroscopes, outside the scope of this paper. No one sensor will result in safe and capable autonomous rovers; however, LIDAR offers the best suite of features for autonomously exploring illuminated and unilluminated craters.

B. Score Assignments:

The following score assignments are determined according to sample technology that can be adapted for aerospace use. The LIDAR examined is the Velodyne Alpha Prime, one of the longest range and highest point density LIDARs. The Perseverance Rover image recognition system is being examined because it is the only precedent autonomous system to what could be found on the LTV. The optical flow sensor is evaluated as a commercially available sensor that costs several hundred dollars.

1. Mass

LIDAR uses a mechanism to spin beams of light around an environment. The mass of the sensor is only 3.5kg; however, accompanying cabling and mounting hardware increases the total mass requirements. A score of 7 out of 10 points was awarded because the sensor is less than 1% of the total expected LTV mass of 500kg [3].

Image Recognition uses existing engineering cameras to observe the environment. These are high quality cameras and are pointed in desirable directions. This minimizes the need for dedicated driving cameras. A score of 10 out of 10 points was awarded because of the ability to use existing hardware.

Optical Flow Sensors are small and light and commercial sensors are on the order of 0.1 kg. The weight of an Optical Flow Sensor combined with the required enclosure and wiring is miniscule compared to the total weight of the vehicle. This sensor was awarded a score of 8 out of 10.

2. Maturity

LIDAR is a mature technology. LIDAR is used on earth observation satellites in space and in autonomous vehicle navigation on earth. LIDAR would need to be adapted to the lunar environment. Because the technology is sound and proven, it was awarded 10 out of 10 points.

Image Recognition on the lunar surface has not been attempted before and by virtue of the nature of image recognition software, a large dataset of features would be required to develop a reliable model. Although Image Recognition systems have been used on Mars, it is unknown how it would fare with lunar terrain. Since this technology requires significant investment to become viable on the moon, a score of 0 out of 10 points was awarded.

Optical Flow Sensors have been demonstrated in similar applications with positioning an autonomous vehicle on earth. Integration and testing with flight hardware along with developing the required software is required for use of Optical Flow Sensors on the moon. Due to the current limitations, Optical Flow Sensors are awarded 5 out of 10 points.

3. Cost

LIDAR is an expensive sensor with 300m range sensors costing approximately $100,000. Using inferior sensors is a viable option to reduce cost at the expense of point cloud resolution and range. A score of 3 out of 10 was awarded based on LIDAR's cost relative to the other systems.

Image Recognition is a software feature that has yet to be developed for lunar applications though the physical costs to implement this technology are marginal. A score of 10 out of 10 was awarded because the technology has the capability to be amortized across a future fleet of lunar rovers.

Optical Flow Sensors are an inexpensive and simple sensor that is mass produced. Optical Flow Sensors received a score of 6 out of 10 because the sensor is simple but requires further development and integration with aerospace hardware.

4. Accuracy

LIDAR received a qualitative score of great because it creates a dense point cloud that can easily be interpreted by a computer. The development of 3d LIDAR with 64 beams or 128 beams has greatly increased range and resolution. This amount of information enables a high level of accuracy.

Image Recognition received a fair score because it determines position and obstacles visually, which is subject to inaccurate classifications due to unexpected obstacles or poor lighting conditions. As previously stated, Image Recognition requires images of the lunar surface to train a computer model which is subject to gaps in the dataset that result in unintended behavior.

Optical Flow Sensors received a score of poor because they are subject to a high degree of drift on the uneven lunar surface. Poor accuracy is a result of the sensor improperly tracking features between frames.

VI. Conclusion

A review of past and proposed lunar vehicles designed with autonomous or human-transport capabilities is performed. Three possible technologies to enable autonomous lunar rovers are explored. A decision matrix is used to compare technological utility. LIDAR is selected as the optimal technology due to high accuracy and functionality in unilluminated areas. Furthermore, autonomy is found to be greatly beneficial to astronaut safety and mission capabilities. The author strongly recommends that the LTV is designed with autonomy as a primary goal. Future autonomous vehicles on celestial bodies will greatly benefit by developing orbital and surface-based positioning and communications infrastructure.

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