Firefleye

Tunnel Modeling Through Throwable Illumination

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Abstract

Tunnels and caves on the moon surface are completely dark. This makes autonomous navigation a challenge. One solution for this problem is to carry a light source, on the robot. However, this is not a good solution as light intensity drops as $1/r^4$ for area light sources.

This paper introduces a concept of illuminating dark tunnels via throwable lights known as Firefleyes. Unlike LIDARs, which provide only geometrical information via 3D point clouds, the method discussed in this paper provides both geometrical and texture information of dark tunnels.

1 Introduction

The surface of the moon has frequently been explored by rovers and orbiting spacecraft, but the subterranean features have remained unexplored. Recent discoveries of lava tubes and skylights on the moon with access to the lava tubes have brought to light the possibility of sending a mission to explore below the lunar surface. These underground lunar caves are thought to contain ice, and could serve as havens from meteorites, radiation, and thermal extremes.

Underground missions would be devoid of natural light. To navigate adequately in a dark cave, an imaging system will have to be developed to better illuminate the area. The purpose of the Firefleye project is to evaluate the concept of a light-throwing system that could generate a well-lit image of a dark cave under the lunar surface.

The Firefleye system involves a launcher that propels a bright light down a tunnel of unknown size and features. A camera would record a video of the cave as the projectile is launched into it. Software would then composite all of the recorded frames to combine the brightly illuminated areas of each into one well-lit image of the cave and a depth map of the area. This data on what lies ahead of the future rover could potentially be more useful and efficient than the limited depth only values that LIDAR has to offer. A comprehensive series of tests have been performed using several trajectories and light sources to determine the optimal components to be used in any future implementations of Firefleye.

2 Prior Work

The original work that inspired this project was carried out by Uland Wong. In his preliminary test, Uland made a crude light source, shown in Figure 1A, and recorded several images as the light source traveled in a tunnel. He then took the recorded images and applied image fusion to get a result shown in Figure 1B.

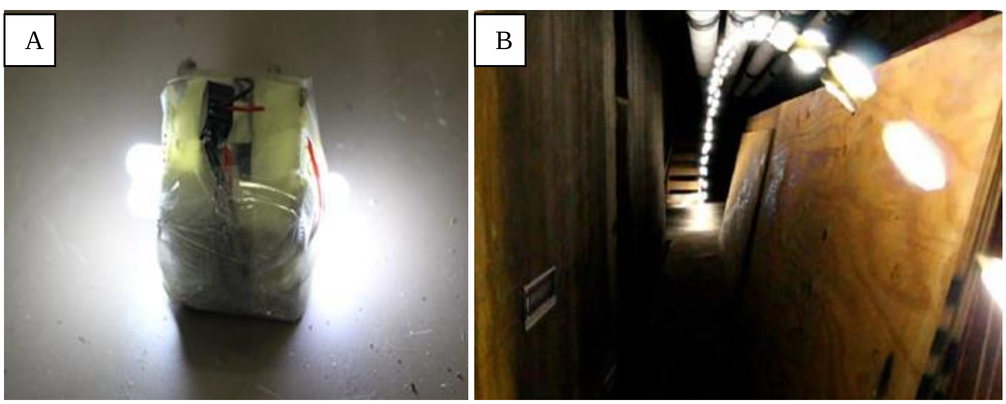

Figure 1: (A) Light Source from Uland's Experiment. (B) Image fusion result from Uland's Experiment

Though this novel idea produced good preliminary results, it has two main issues. First, this experiment uses a crude non-diffused and non-symmetrical light source. This implies that the light source wouldn't behave like a point source, which makes image post-processing difficult. In addition, the light source was only bright enough to light a 0.5 m by 6m by 2 m tunnel (after image fusion).

Second, the right side wall of the tunnel was made up of a non-Lambertian material. In other words, the reflection from that side of the wall is not angle invariant; therefore, the resulting image varies with the camera's view point.

3 Methods

Several stages of setup and preprocessing were done before the analysis of projectiles in a video was done. Description of each step is given in the following sections.

3.1 Projectile Launcher

The first step of the methodology followed in this experiment was to properly setup the projectile launcher. The projectile launcher used was a spud gun with a 2 ft long and 3 in internal diameter pressure chamber, 2 ft long and 2 in internal diameter barrel, and a modified sprinkler valve. Traditional spud guns use a ball valve as a release mechanism for the compressed air in the pressure chamber. Most ball valves are not designed to be rotated easily which makes automating the projectile launcher mechanism a challenge. However, with the modified sprinkler valve system, the projectile launcher mechanism can be shot with less than 1N force.

To achieve a successful projectile, the correct pressure and the angle of launch had to be set. These values could change based on the desired range of the projectile. The default setup for our experiment was 10 degrees launching angle and 15 PSI of pressure, which gave us a projectile with a maximum height of 6 ft and a range of 60 ft.

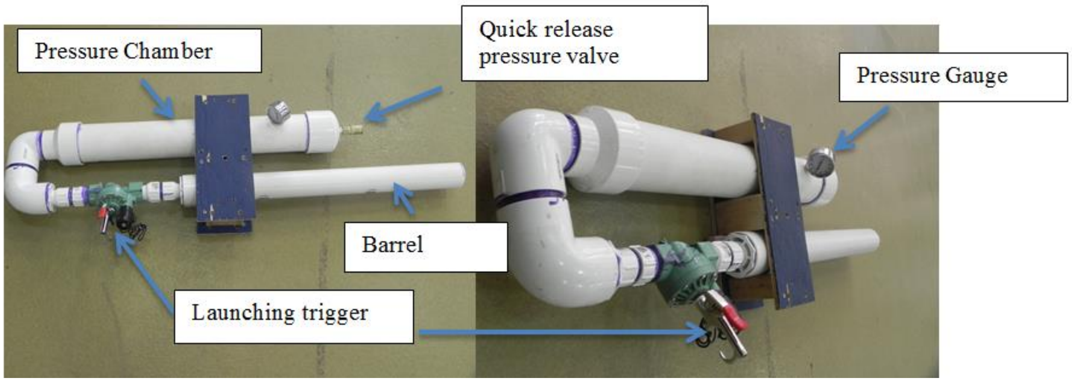

Figure 2: Image of Projectile Launcher (the term "cannon" is also used interchangeably throughout this paper)

3.2 Camera setup

To record the full flight of the projectile a video camera was set next to the projectile launcher on a tripod. To get maximum number of photons in dark environment, the aperture size was set to maximum and all automatic features were switched to manual mode.

Figure 3: Testing assembly consisting of cannon mount, compressor, and cameras.

3.3 Image analysis

Generating fully lit image and depth map requires several stages of processing. The first step performed in this project was the pre-processing stage that included converting videos to image frames and converting RGB images to grayscale. Following that, Image fusion and post processing of light source extraction were carried out finally leading to a good estimation of a depth map. The following subsections go through each process in brief detail.

3.3.1 Video to frame conversion

To analysis each frame separately; a MATLAB based algorithm was used to convert the videos recorded into separated images where each image corresponds to one frame in the video.

3.3.2 Image Fusion

Image Fusion is a process of combining several images into one. This process is done in a way that the fused image would be more informative than each individual images used to create it. In this paper, this was achieved via taking the maximum pixel over all the frames.

3.3.3 Light source extraction

The final result includes a fully lit tunnel. However, the image fusion method fails to remove the light source from the fused image; therefore, post-processing needs to be done to remove the light source from the fused image. This was achieved by tracking the position of the light source and replacing the pixel values with the mean pixel value of the fused image.

3.3.4 Depth Map

Depth map is an image that represents distances of different objects in a scene form a specified view point. For the Firefleye project computing the depth map was possible due to the principle related to Lambertian reflectance (see Appendix 8.1.6).
The input image was a three dimensional matrix where the rows and columns correspond to pixels in one frame and the depth corresponds to the number of frames. Depth map for a given run was found by recording the indices corresponding to maximum pixel values. Since each frame correspond to different time steps in the projectiles flight, the frame number could be taken as the depth of the projectile (the distance from the camera to where it is in the tunnel).

4 Results

The performance of system considered in this paper, which includes projectile launcher, and image analysis algorithms was tested and analyzed separately.

4.1 Projectile Launcher Results

The following results came from a field test in a 300ft+ mining tunnel that was less than 6 feet tall. As displayed above.

From these tests, the following results were recorded:

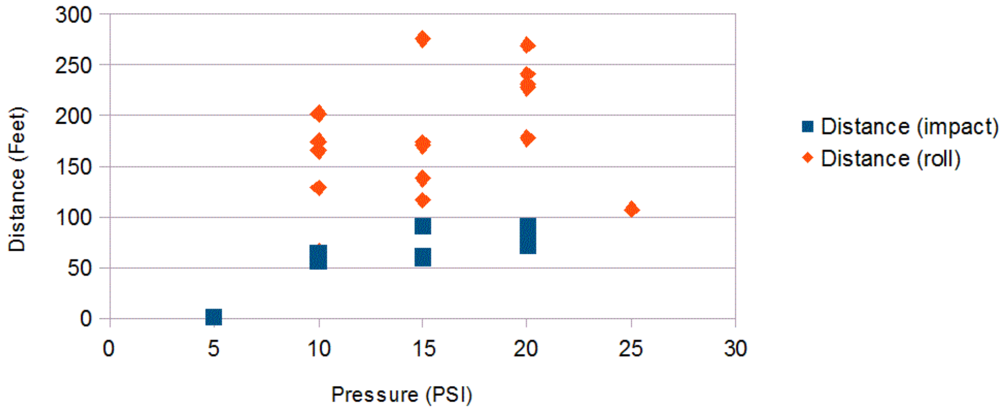

Figure 4: Pressure vs. distance traveled by the projectile at 10 degrees launching angle. The impact distance is the distance the projectile flew in a 10 foot wide by 6 feet tall mining tunnel. This distance is upon first impact of the ground. The rolling distance is the distance the projectile traveled until rest. There are far less impact distance measurements as once the lights were turned off in the mining tunnel, it is very difficult to judge accurate landing position.

4.3 Design Matrix and Design Constraints

Our launcher was chosen using the design matrix given in Table 1. Our launcher was chosen for testing on Earth as opposed to withstanding moon-like conditions. The description of each criterion is given below.

Weight - the overall system weight of implementing a design.

Variable speed - possible firing speeds for the projectile launcher.

Cost - the relative system cost of implementing a design.

Distance - possible firing distance which is important for long tunnels.

Space relevance – future applications in space.

Ease of automation - the difficulty it would be to fully automate this system.

Table 1: Design Matrix for Projectile Launcher

	Flywheel	Spring	Coil Gun	Crossbow	Pressure Gun
Weight	1	10	1	8	7
Variable speed	9	8	6	8	10
Cost	5	4	2	8	7
Distance (x2)	9	9	2	9	10
Space Relevance (x2)	1	8	4	7	6
Ease of Automation	10	8	2	5	9
Total	5.63	7.35	3.88	7.63	8.13

4.4 Software Results

Several tests were carried out at the steam tunnels in the basement of Newel Simon Hall at Carnegie Mellon University and at Bruceton Coal Mines. The following figures show image fusion results for these different tests.

Figure 5: Image Fusion result with a sphere light made up of 18 (1 watt) LEDs (left) and Static long exposure image with 10 W head light (right) at at Bruceton Coal Mines

Figure 6: Image fusion result (12 ft by 6 ft by 60 ft) tunnel with 18, 1 watt LEDs arranged in a plane

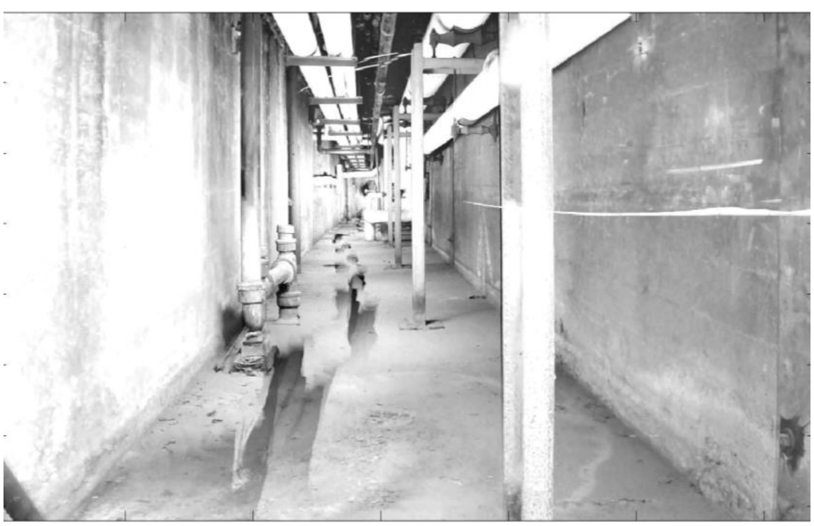

Figure 7: Image fusion result (4 ft by 6 ft by 150 ft) tunnel with 18, 1 watt LEDs arranged in a plane

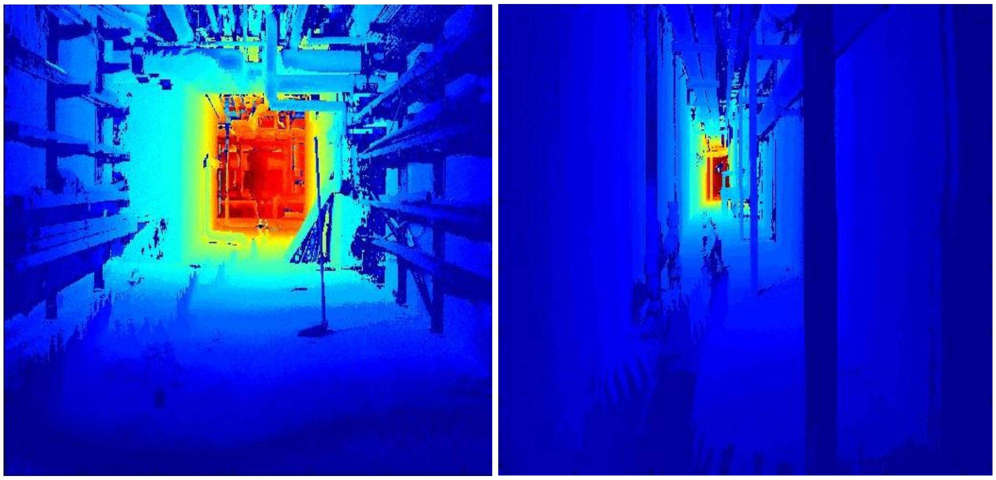

Figure 8: Depth map for Figure 6 (left) and Figure 7 (Right)

5 Analysis

5.1 Choice of projectile Launcher design

There were two main problems with the projectile. The design of the projectile was not done well and the LED's draw too much power for any batteries tested. In the tests carried out, a spherical light source was chosen as the ideal light source required by assumptions made for the software. In field tests that worked well, a high discharge 12 volt Ni-mh battery with 18- 3 watt LED's was able to light a 4 ft by 6 ft by 60 ft tunnel (after image fusion) at a current draw of 8.5 amps. These LED's output 100 lumens each. A small launchable battery that can perfrom at such a demanding current draw is required to make launchable lights sufficiently bright to illuminate large areas.

5.2 Launcher Analysis (design matrix analysis)

Looking at the design matrix, there were many reasons other design were not chosen. For the flywheel design, the weight was a big factor as large flywheels were required and kinetic wheel energy was transferred into the projectile. The spring and crossbow designs were not chosen for testing due to inefficiency of launching distances compared to a pneumatic system. The coil gun had a better projectile launching distance but was rejected because it required about 500 volts to achieve 50 ft of launching distance. It also failed to pass the space relevance requirement because it releases a lot of heat and dispensing that would be a challenge in a vacuum environment. Therefore, considering all the requirements, the pneumatic pressure gun was chosen as the final results.

Looking at the graph of distances fired vs psi, two main points could be infered. The first is that the cannon was consistent within 10 feet at the ideal launch angle of 10 degrees and a pressure of 15 psi. This spread can be attributed to a number of small flaws. The first is a non-air tight seal behind the projectile in the barrel. This leads to inconsistent power. The second is that the barrel induced spin on a spherical projectile. This caused a Magnus effect [7] which caused the projectile to move out of its flight path. A third cause was valve opening inconsistencies. Opening the valve at different speeds caused the pressure chamber to dump air into the barrel at different flow rates, which in turn affected the projectile initial velocity and distance traveled. The final cause of inconsistencies was the pressure gauge on our chamber, which was not accurate for small changes in pressure.

5.3 Image Fusion and Depth map result analysis

Figure 5 through Figure 8 show the outputs for the software algorithm that computes image fusion and depth map. Figure 5 shows a side by side comparison of an image fusion with the diffused light source and a long exposure image with a static head light set behind the camera. As the head light was a focused light, portions of the image in the long exposure image appear well lit than the image fusion case. However, looking at each image as a whole, more texture could be extracted from Figure 5A.

Figure 6 and Figure 7 are image fusion results from a test using a light source arranged in a plane. The video was captured with a subject running with the light source in front of him/her. Even though the image of the subject appears in each frame, when performing image fusion, only the maximum pixel is taken; therefore, the image of the subject is automatically removed without a need for extra post processing.

Figure 8 shows a depth map where blue indicates closer objects and red indicates further objects. Comparing Figure 8 with Figure 6 and 7, it is clear that the depth map was able to capture object details and their relative distances.

6 Future Work

Future work for the Firefleye system will require work on the launcher, projectile, and software in order to achieve better results in illuminating dark rooms and tunnels.

The launcher discussed in this paper was a testing rig for the throwable lights. A future launcher will require many changes. To increase consistency, the launcher will need to be fully automated. An automated system would involve a pan/tilt mechanism for the launcher and cameras. A mechanism to reload the cannon, open and close the main valve, and fill the pressure chamber will need to be developed. By automating all of these tasks with a robust system, the repeatability and consistency of the cannon will increase which allows more accurate testing of the cannon. Another main topic that will need to be looked into is the development of a space rated cannon. A space rated cannon will take many different considerations that the current cannon did not take which would allow it to function in a zero atmosphere and near absolute zero temperature range.

The projectiles will also require a number of changes. Although the light sources were able to withstand being fired from a cannon and repeatably work, the lights were not bright enough to illuminate large areas. To fix this, a new electrical system will need to be implemented into the lights. The main problem of the old system is the lack of a small, high discharge battery that can supply the necessary energy needed for high power LEDs. Large battery tests of the current LEDs showed that the LEDs themselves illuminated large tunnels, but scaling down the battery to a compact size caused problems in the power supply to the LEDs. A new battery/capacitor system will need to be found or another method of illumination in order to make these projectiles work. The design of the light itself should also be changed into a light that can be put together neatly as this will allow the weight to be minimized.

The software for this system will need a better implemented depth map. The current depth map estimation gives relative values of depth in the current depth map being processed. Future depth map estimation will quantify depth into a real value that can then be used for modeling dark spaces in which the Firefleye system is used. The method required to do this will use position tracking by trajectory estimation. Position tracking of the light source will record the position, velocity, and acceleration of the projectile in (X,Y,Z) coordinates. By implementing position tracking, a quantifiable depth map will follow which will then lead to modeling of tunnels, caves, and subterranean features.

7 Conclusion

In this paper an investigation of the use of throwable lights for dark tunnel illumination was done. This was achieved by shooting spherical diffused light sources, to mimic ideal light source behavior, via the use of pressurized spud gun, and video capturing the flight trajectory of the light source.

The data presented in previous sections show that, when firing at ideal pressure and angle, the projectile launcher achieved an average range of 60 feet with a standard deviation of 5 feet. It was discovered that the projectile light source became too dim within 20 min during testing due to issues with the drain rate of the batteries powering the onboard lights. Using the same LED lights and a bigger battery, a greater success was achieved lighting a larger tunnel. The lights in this case were mounted on a plane, and video capturing was done while human subject was running down the tunnel with the light source. The image fusion software surpassed established performance metrics.

Testing in environments similar to lunar caves led to a conclusion with 95% confidence that projectiles illuminate 90% of a cave approximately 6 ft high 12 ft in width and 150 feet in depth compared to a long exposure image taken with a static cell phone flash light set behind the camera. Projectiles were launched a maximum distance of 200 ft on Earth, which translates to an estimated 1200 ft on the moon. Testing conditions are similar enough to known properties of caves on the moon to show that the tests were valid for obtaining information about the composition of the walls of lunar caves as well as for improving navigation for a rover in these tunnels.

8 Acknowledgements

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9 References

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10 Appendix

Below are summary explanations of various concepts and ideas that were not thoroughly explained when mentioned in previous sections of this report.

10.1 Software: Image Fusion and Depth Map

10.1.1 Image fusion

Image Fusion is a process of combining several images into one. This process is done in a way that the fused image would be more informative than each individual images used to create it. Several of the methods for image fusion are described below. Titles 2.1.2 through 2.1.5 are image fusion variants.

10.1.2 High Dynamic Range (HDR)

High Dynamic Range (HDR) is a method of taking several low dynamic range images and creating one high dynamic range image. In photography dynamic range stands for the luminance range of the image. This method is used by many photographers in image post processing. Many image processing tools such as Photoshop, GIMP, Matlab, and more have this method integrated in them.

10.1.3 Mean/Average method

The Mean/Average method is one of the simplest ways of performing image fusion. The process involves taking all input images and averaging each pixel over the inputs.

10.1.4 Weighted Average Method/Exposure Fusion

This method is an improvement on the Mean/Average method and was proposed by T. Martin et. al [1]. This method assumes that all the frames are perfectly aligned and computes the output image by keeping only the "best" parts [2]. The fusion is done by first computing a weighted average along each pixel in all frames using equation 1 then substituting that in equation 2.

$$\widehat{W}_{i,j,k} = \left[\sum_{k'=1}^{N} W_{ij,k'}\right]^{-1} W_{ij,k'} \qquad (1)$$

$$R_{i,j} = \sum_{k'=1}^{N} \widehat{W}_{ij,k}\, I_{ij,k} \qquad (2)$$

Where $R_{i,j}$ is the fused image at pixel (i,j), W is the weight, $\widehat{W}$ is normalized weight, N is number of frames, and Ik is the kth input frame[2].

10.1.5 Image Fusion via PCA

Principal Component Analysis (PCA) is a mathematical tool for performing a linear transformation of data in N-dimensional space into a new set of coordinate systems called principal components. Usually, the first principal component is computed in a way that it gives the maximum variation along its axis. Skipping all the mathematical jargon, PCA boils down to an Eigenvalue Eigenvector problem where the Eigenvector associated with the maximum Eigenvalue gives the first principal component.

In terms of image fusion, one can take each input image as different dimensions (i.e. if one has N frames then this becomes an N-dimensional problem where the pixels are data point in this high dimensional space). Therefore, applying PCA on the frames would transform the data into new N dimensional space where the first axis (first principal component) contains the majority of the information (usually more than 90%). As a result, one can take this first component as the fused image.

This is implemented in 4 easy steps

- Import all the images as column vectors and create one huge matrix, "im" (i.e. if we have N frames that are Mpx by Kpx, then each frame would create an M*K by 1 column vector creating one huge matrix of M by N matrix).

- Compute the covariance matrix of matrix "im". This computes the covariance between each pixel over all the frames. This covariance matrix has dimensions N by N

- Now perform Singular Value Decomposition (SVD) on the covariance matrix. This returns Eigenvectors (N by N matrix) and Eigenvalues (N by N matrix).

- Use the elements of the first Eigenvector (i.e. the first column for the Eigenvector Matrix) as weights and do a linear combination of all the frames, which gives the fused image.

Sylvia et al. [2] published a paper in 2006 that used PCA based image fusion.

10.1.6 Depth Map

Depth map is an image that represents distances of different objects in a scene form a specified view point. For the Firefleye project computing the depth map was possible due to the principle related to Lambertian reflectance.

A Lambertian [3] object has a property that the apparent brightness of a surface to an observer is the same regardless of the observer's angle of view whereas the luminous intensity obeys the Lambert's cosine law. Lambert's cosine law states that radiant intensity is proportional to the cosine of the angle between the surface normal and observer's line of sight [4].

10.2 Mechanical

No previous attempts at pneumatic launchers in space exist. Prior to this research, there has been no reason to have portable launchers in a space environment. However, there are many different types of launching mechanisms that function on earth and can be applied to use in a lunar environment.

10.2.1 Flywheel

A flywheel launcher uses two flywheels to launch a projectile, impulsively transferring their rotational energy to the projectile to propel it forward. This method is not practical for use in space because the entire system would necessarily be very heavy.

10.2.2 Coilgun

A coil gun uses inductor coils to accelerate a ferrous projectile, which is reliable and variable in power but typically inefficient, which is not ideal in an environment where battery power is a measured resource.

10.2.3 Spring Launcher

More realistically, a spring-loaded system requires little power. This kind of system is simple and reliable when designed properly and can function in space conditions very well.

10.2.4 Pneumatic Cannon

Another viable option is a pneumatic launcher, which would use the expansion of compressed gas to propel a projectile down a barrel. This is a simple and reliable system if there is a source of compressible gas. Guaranteeing a source may be a problem in the absolute cold of a lunar environment, though compressed air has previously been used for unrelated (propulsion) purposes in space environments. While it is difficult to find discussion directly related to the effect of lunar conditions on maintaining a gaseous state pneumatic systems, the use of such systems in space exploration is definitely not unheard of**.**

10.3 Electrical

The basic principle motivating launchable illumination is that the distance of a light source from an object largely determines the intensity of the light when it reaches that object. U. Wong suggested that the falloff with distance from any reasonable light was actually much more severe than that of an ideal point source, suggesting that mounting lights, however bright, directly on a rover is not a viable method for cave exploration as it limits how much information can reasonably be obtained about a particular path before attempting to traverse it [5]. Another way of avoiding this problem is the use of technologies such as LIDAR, which has been used for many other applications in robotics and space exploration [6]. While useful for generating depth maps of the lunar terrain, LiDAR cannot provide the information about cave wall composition and texture that traditional cameras provide. The shortcomings of these more traditional methods provide reasoning for light sources that can travel along a cave wall and produce clear images of their environment.