A wide angle bistatic scanning LIDAR for navigation

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ABSTRACT

Scanning LIDARs are widely used as 3D sensors for navigation due to their ability to provide 3D information of terrains and obstacles with a high degree of precision. The optics of conventional scanning LIDARs are generally monostatic, i.e. launch beam and return beam share the same optical path in scanning optics. As a consequence, LIDARs with monostatic optics suffer poor performance at short range (<5m) due to scattering from internal optics and insufficient dynamic range of a LIDAR receiver to cover both short range and long range (1km) . This drawback is undesirable for rover navigation since it is critical for low profile rovers to see well at short range. It is also an issue for LIDARs used in applications involving aerosol penetration since the scattering from nearby aerosol particles can disable LIDARs at short range. In many cases, multiple 3D sensors have to be used for navigation.

To overcome these limitations, Neptec has previously developed a scanning LIDAR (called TriDAR) with specially designed triangulation optics that is capable of high speed scanning. In this paper, the reported WABS (Wide Angle Bistatic Scanning) LIDAR has demonstrated a few major advances over the TriDAR design. While it retains the benefit of bistatic optics as seen from TriDAR, in which launch beam path and return beam path are separated in space, it significantly improves performance in term of field-of-view, receiving optical aperture and sensor size.

The WABS LIDAR design was prototyped under a contract with the Canadian Space Agency. The LIDAR prototype was used as the 3D sensor for the navigation system on a lunar rover prototype. It demonstrated good performance of FOV (45°x60°) and minimum range spec (1.5m); both are critical for rover navigation and hazard avoidance. The paper discusses design concept and objective of the WABS LIDAR; it also presents some test results.

Keywords: LIDAR, autonomous, navigation, rover, wide angle, 3D sensor, bistatic optics

1. INTRODUCTION

Driven by the gaming and entertainment industry there have been many technology advances in 3D technology. In the field of navigation, 3D information and display have gained ground over traditional 2D technology in general navigation systems. And it has proved to be indispensable for the navigation systems used by autonomous vehicles, where the 3D information of surrounding terrain and obstacles is essential for the vehicles to drive autonomously. The popularity of autonomous vehicles is quickly increasing with the advances of better and more reliable navigation technologies. There is a growing niche for use of autonomous vehicles, ranging from military transportation as exemplified by the DARPA Grand Challenges, to civilian vehicles like Google's driverless car, to space rovers where the communication delay from vast distance requires the rovers to drive autonomously. The state of Nevada has recently (February, 2012) changed the law to allow self-driving vehicles to operate on its roads.

The popularity of autonomous vehicles has demanded better 3D sensors. Although specific requirements are different in each case, the desirable high level requirements of 3D sensors for navigation purpose can be summarized as followings:

- Large field-of-view: >45°x45°, to see surrounding scenes with wide angle.

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- Short minimal range: <1.5m, to see near obstacles.
- Long maximal range: >1km, for mapping applications.
- Higher range resolution: <1cm, to identify small objects and obstacles.
- Higher frame rate: >1Hz, to provide fast real-time data for steering control.

Depending on the details of an application, there are many tradeoffs among the specifications when designing a 3D sensor. There are a few commonly-used technologies for 3D data acquisition and navigation including stereo cameras, LIDARs and RADARs. Generally stereo cameras can provide a wide field-of-view (FOV), but they are limited to provide short range 3D data. Radars can provide long range 3D data, but their imaging resolution is poor. LIDARs can provide good resolution, but usually with limited FOV and short range performance. As consequence, autonomous vehicles are usually equipped two or more types of 3D sensors, however, it is a continuous goal to reduce the number of sensors used in the navigation systems of autonomous vehicles.

The range limitation for stereo camera is from its triangulation nature of the measurement, i.e. range resolution is limited by the small angle difference for a far object. The resolution limitation for RADAR is from its longer wavelength compared to light wavelength. These limitations are fundamental with little room for significant improvement. The limitation on LIDARs is more technical in nature. With significant advances in its key components and designs, it promises to become the choice of 3D sensor for navigation.

Imaging LIDAR itself can be divided into two groups: flash LIDARs and scanning LIDARs. Although much research has been done in recent years to improve the performance of 3D detector arrays for a flash LIDAR, so far its range measurement performance is still inferior to the performance from a single channel detector. A flash LIDAR also requires a more powerful light source that has to be stronger than the solar background in the entire FOV. Even for a laser with high peak power and narrow spectral width, this requirement is difficult to achieve for a relatively large (much greater than 20°) FOV. A scanning imaging LIDAR takes an image one spot at a time, it requires a laser with moderate peak power, small beam divergence and high pulse repetition rate. Recent advances of a single mode pulse fiber laser has greatly improved performance and enabled scanning LIDAR to be the choice for many applications, where the remaining technical limitation of frame-rate is not considered to be prohibitive.

This paper discusses design concept of a LIDAR with bistatic optics. It describes a LIDAR prototype built as a 3D sensor for the navigation system of a prototype lunar rover. This LIDAR designed with a space application in mind, but the general desirable performance is similar to those on the ground, the focus is on the wide FOV spec and the minimal range spec since the sensor is mounted only a meter or two above the ground (which makes very long range scanning impractical, regardless of the sensor performance) and requires seeing near obstacles. In addition, it requires very tight specs on mass, volume and power consumption of the LIDAR.

2. LDAR DESIGN PARAMETERS AND TRADEOFF

In a scanning LIDAR design, the range performance is primarily decided by three design parameters, the peak power of the pulse laser, the receiver sensitivity and the receiving optical aperture. They are linked by the LIDAR equation as following:

$$P(P \geq P_s) \propto P_0 \times \sigma \times \eta \times \frac{A}{R^2} \tag{1}$$

Where $\boldsymbol{P}$ is the peak power of LIDAR return signal from a diffusive target with reflectance of $\boldsymbol{\sigma}$, $\boldsymbol{P_s}$ is the LIDAR receiver sensitivity, $\boldsymbol{P_0}$ is the LIDAR launch pulse power, $\boldsymbol{\eta}$ is the total transmission of LIDAR optics, $\boldsymbol{A}$ is the receiving optical aperture and $\boldsymbol{R}$ is the range. The maximum range is obtained when the return signal power $\boldsymbol{P}$ is equal to the receiver sensitivity $\boldsymbol{P_s}$.

In a design, the tradeoff between the receiving aperture size and the laser power has to be carefully considered. For example, given the same receiver sensitivity a large aperture will reduce the need for a bulky laser, but it will require large scanning optics, which generally reduces FOV and scanning speed. Figure 1 shows the maximum range prediction by LIDAR equation for a typical scanning LIDAR, the receiving aperture is assumed to be 20mm and the receiving sensitivity is 0.1μW. To reach a maximum range of 1km over 80% diffusive target, the required peak power of a pulse laser is about 2.5kW. Two things related to the LIDAR receiving signals can be assessed from the LIDAR equation: firstly, if a LIDAR is designed to have a range from 1m to 1km, even without considering the reflectance variation of targets, the required dynamic range from $1/R^2$ effects alone is 60dB, which is a difficult number to achieve with high speed receiver electronics. Secondly, the required 2.5kW laser launching peak power is 2.5×10^{10} (104dB) times more than the receiver detection threshold, any scattering from internal optics (e.g. window scattering of the launch beam) can interfere with the return signals generated by near targets.

As a result LIDARs designed for long range (>1km) normally have to disable their receiver for the first a few meters to avoid spurious trigger signals. Clearly, conventionally designed LIDARs will be difficult to meet both near and far range as a desirable solution of a single 3D sensor for general navigation purpose.

3. CONCEPT OF BISTATIC LIDAR

One basic principle of designing a scanning LIDAR is the auto-synchronization of launch beam and return beam, i.e. the instantaneous field-of-view of LIDAR receiver must always overlap with the launch laser spot on targets during scanning. This task can be accomplished by both monostatic optics and bistatic optics. In a monostatic LIDAR optical design, the launch beam and the return beam are co-aligned before and after passing through scanning optics, for example, a launch laser beam can be introduced into a system by a small mirror in the center of a receiving telescope as seen in Figure 2(a). Most scanning LIDARs use the monostatic optical design because of its simplicity from overlapped launch and return beams.

In a bistatic LIDAR optical design, the launch beam and the return beam are separated in space by two lenses side by side as shown in Figure 2(b). On the focal plane of the receiving lens, the return light from a nearby object is focused off the lens optical axis and the return light from a far distant object is focused on the optical axis. There is a triangulation relation between the angles of the launch beam and the return beam, but they are practically auto-synchronized if targets are far enough.

To design a LIDAR that can work well for both near and far range, the receiving signal level for near targets has to deviate from the LIDAR equation. Bistatic optics offers flexibility in the design to optically manage the level of the return signals from close targets. Figure 3 shows the return signal from bistatic optics compared to monostatic optics, the signal level at near range drops off quickly because the imaged laser spot at the focal plane of the receiver lens moves off the receiver due to the triangulation effect, but the signal level from targets further than 50m is close to the signal level from monostatic optics because of the small angle difference of the triangulation effect.

Neptec has conducted extensive design studies of bistatic optics, focusing in two areas: compact bistatic scanning optics that is capable of high speed scanning and the methods to increase the return signal level from near targets. Neptec has used this technology in its TriDAR and OPAL products. TriDAR has been flown into space for a docking experiment with the International Space Station. OPAL uses the effect of bistatic optics to reduce the dust scattering signals in a sand storm and has been tested as a landing LIDAR for helicopter operation. The design and operation of TriDAR and OPAL are discussed by the previous papers [1] [2]. Based on these successful implementations, Neptec developed a new bistatic optics called wide angle bistatic scanning LIDAR (WABS LIDAR). While WABS LIDAR design retains the benefits of bistatic optics as in TriDAR and OPAL, it offers significant improvement on three major performance specifications

- Large FOV: FOV increase from 30°x30° to 45°x60°.
- Small optical footprint: size of optical base-plate decreases from 31cmx32cm to 11x18mm.
- Large optical aperture: the effective receiving optical aperture increases 30% to 40% at different scanning angles for similar sizes of the scanning mirrors.

4. WABS LIDAR PROTOTYPE

Neptec implemented the WABS LIDAR design and built a prototype LIDAR as shown in Figure 4 under a contract with Canadian Space Agency (CSA). The project was a prototyping extension to a feasibility study for the design of a LIDAR for use aboard the Russian Luna Resource rover, a future lunar prospecting lander / rover mission. It has since been used for testing parts of CSA's rover navigation systems as shown in Figure 5. Rover sensors are typically relatively low to the ground which gives rise the specific key requirements are: <1.5m for minimum range and >45°X 45° for FOV. Given the LIDAR design will eventually be used on a space rover, it is also required to choose components that minimize the mass, volume and power consumption. For this design, one of major constraints set out was to use a laser source that consumes <5W electrical power.

The WABS LIDAR prototype uses a pulse fiber laser with a wavelength of 1534nm, the laser source weights <1.5lb and has a size of 90mm x 70mm x 20mm. The laser source itself is a Class 3B device, but it is limited to less than 10mW for eye safety. The LIDAR uses two galvanometers to scan X- and Y-mirrors over FOV of 45°X 60°. To achieve the required maximum range from the low power laser, the receiving optical aperture has to be optimized with the distance among the scanning mirrors and other optics designed to be as small as possible. The X-mirror is also a double-sided mirror that provides the key bistatic auto-synchronous scanning geometry, keeping the pointing of the output laser and detector synchronized. A 200μm InGaAs APD is used as the receiver detector with additional optics used to increase the effective area of the receiver, which gives a balanced performance between short range and long range.

The purpose of the prototyping extension was to establish the feasibility of key technologies that made up the proposed Luna Resource LIDAR design. Primarily, optimization focused on reducing the Mass, Power and Volume (MVP) of the sensor over established designs. Reductions of mass and volume were achieved through reducing the footprint of the scanning optics. Power optimizations focused on utilizing optics efficient enough to allow the use of a very low input-power fiber laser. Further efficiencies were also realized through the development of a digital control scheme for scanning the galvanometers, which recognized significant power savings over previous analogue designs.

The major performance specs of the WABS LIDAR prototype are summarized below:

- FOV: 45° (vertical) X 60° (horizontal)
- Minimum Range: 1.5m
- Maximum Range: 100m
- Range resolution: 2cm
- Sampling rate: 5kHz to 10kHz
- Mass: 8.5kg
- Power: 38W
- Volume: 40cm X 18cm X 20cm

Due to limitations in scope, the processing and Time of Flight (TOF) detection electronics were re-used from previous programs. Since these two subsystems make up more than 1/3rd of the current prototype, we believe further significant MVP reductions are achievable through the optimization of these subsystems.

The WABS LIDAR was tested extensively before it is integrated into the rover navigation system. A typical test scan is shown in Figure 6 to give a qualitative impression of the type of data achievable with the WABS LIDAR. The photograph in Figure 6 shows the setup used to acquire the scan. This 60° x 45° scan was taken from the roof and shows the area behind the Neptec facilities. This scan was gathered at eye safe laser powers and shows data returns out to distances beyond 140m (utility pole highlighted). A neighboring building is also visible at a range of 80 – 140m. Data missing from the building to the right is due to obscuration from the trees in the foreground.

5. FUTURE IMPLEMENTATIONS

The achieved maximum range and sampling rate are not limited by the optical design itself, they are from settings designed to meet the specific requirements for the Luna-Resource Vision System. The technology of pulse fiber lasers has made great progress in recent years; the available state-of-the-art pulse fiber lasers in reasonable small packages can provide >5 times laser peak power at 10 times PRF (laser repetition frequency). The current WABS optical design can provide over 1km maximum range and 100kHz data rate if a pulse fiber laser with 2.5kW peak power and 100kHz pulse repetition frequency is used. Given the high efficiency achieved by fiber lasers, such laser can still have an average power below 1W.

Although there is no laser safety requirement from the final space rover application, a laser-safe device was desirable for ground test and other possible ground deployments of the WABS LIDAR. For this reason, the maximum average laser power out of the LIDAR window is set to be 9mW, which is less than Class 1 limit of 10mW for the laser wavelength according to the laser safety standards [3] [4]. Future designs will employ more powerful lasers to increase maximum range, while maintaining Class 1 classification through the use of scanning interlocks which ensures that the laser is only emitted when the beam is moving sufficiently fast. Neptec is currently targeting this sensor technology towards use in areas in which Neptec sensors are currently in use such as rover navigation applications, space rendezvous and docking missions, and ground-based defense initiatives.

6. SUMMARY

In many navigation systems, multiple 3D sensors have to be used to cover both short range and long range. The Neptec WABS LIDAR is designed to be a 3D sensor that can cover full ranges for navigation applications. In order to achieve the ability to cover full ranges, it utilizes unique bistatic optics to optically control the amount of return signals received by a LIDAR. For a given receiving aperture size, the design also offers wider FOV and more compact scanning optics that is critical for high speed scanning. Neptec built and tested a prototype of WABS LIDAR as the 3D sensor for the navigation system of a CSA's lunar rover prototype. It met all requirements including wide FOV, short minimum range and a laser with low power consumption. Based on the WABS design, Neptec continues to work on new LIDAR product that will produce LIDARs with more compact size, lower power consumption, and better performance.

Acknowledgements

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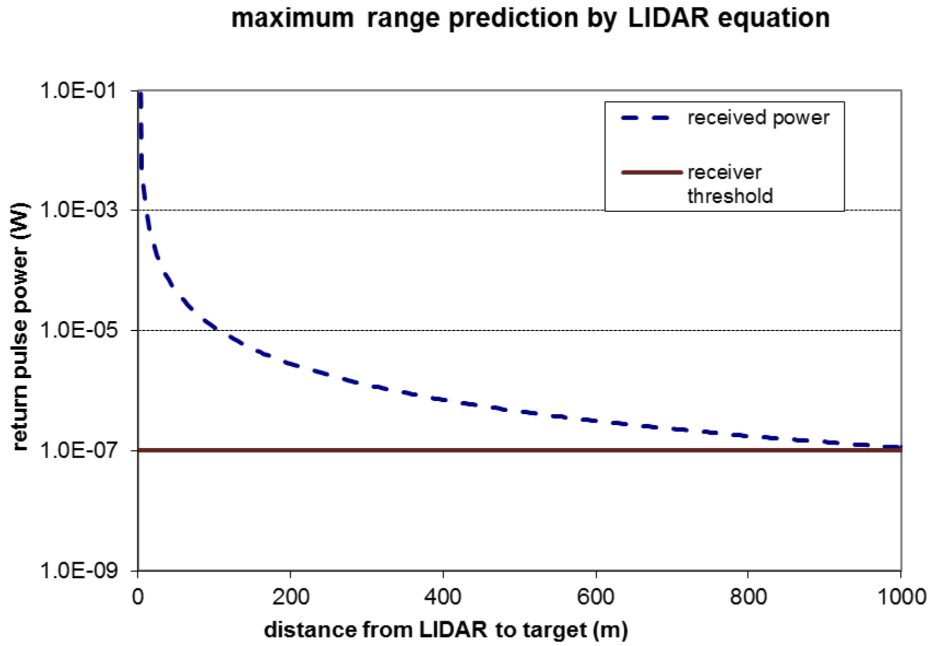


Figure 1: Maximum range prediction by LIDAR equation

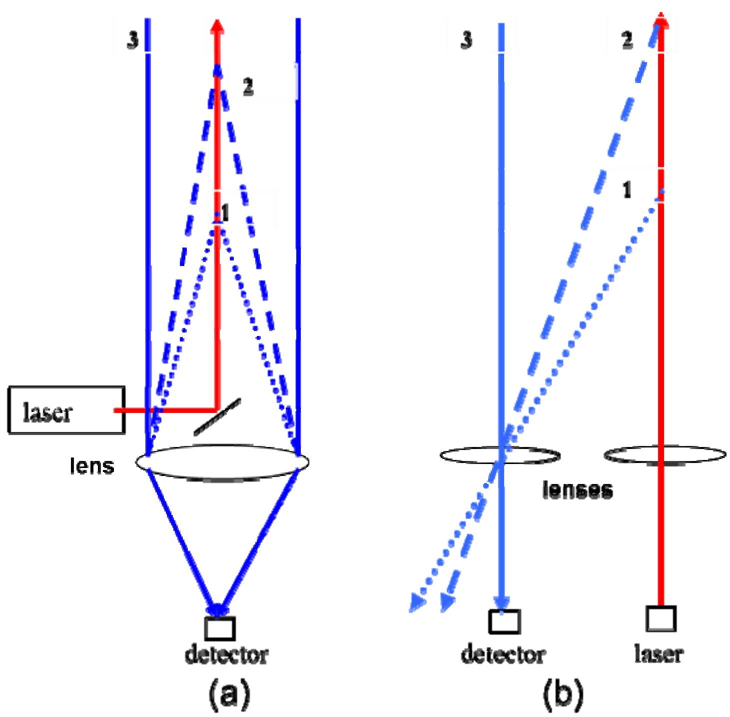


Figure 2: Optical rays from near target (1), medium target (2) and very far target (3) in monostatic (a) and bistatic (b) of LIDAR launch optics

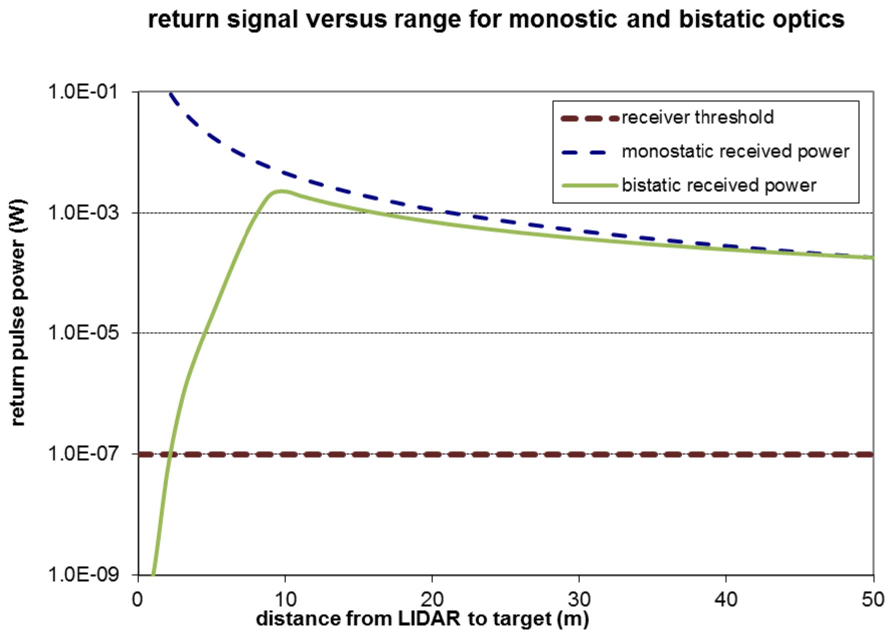


Figure 3: LIDAR return signal level versus range for monostatic and bistatic optics

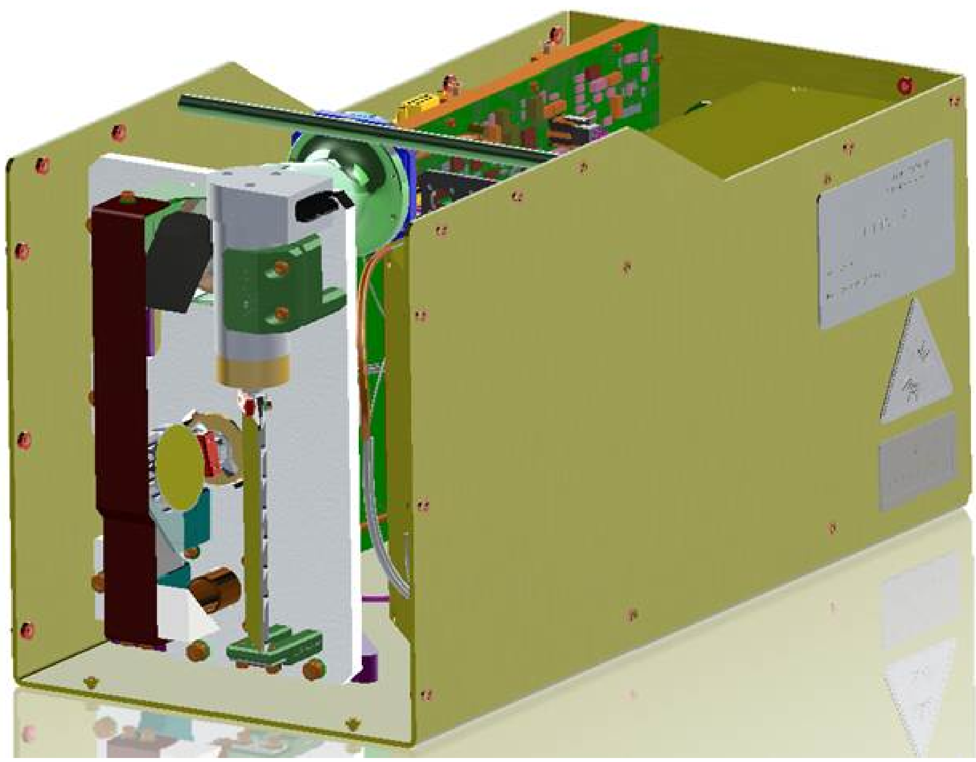
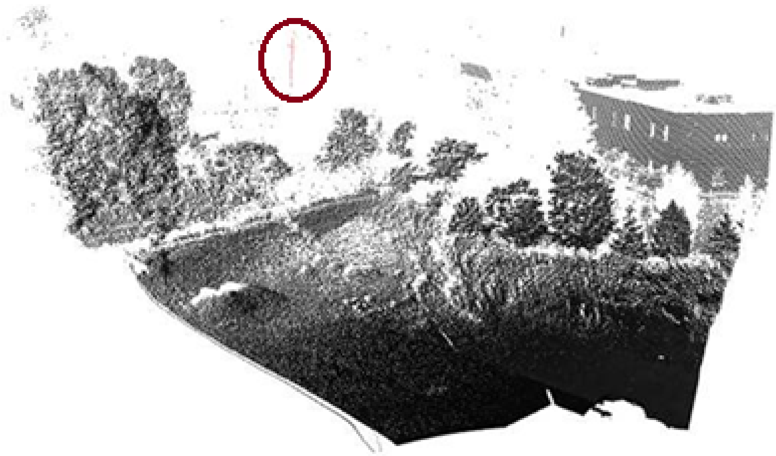


Figure 4: Neptec WABS LIDAR designed for navigation system of a lunar rover prototype

Figure 5: NEPTEC WABS LIDAR (top white box) used in a navigation test by a CSA lunar rover prototype



(a)

(b)

Figure 6: 3D scan example of WABS (a) and corresponding photo (b), the range of the utility pole is 140m