Evaluation of a steerable 3D laser scanner using a double Risley prism pair

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ABSTRACT

Laser scanners based on Risley prism pair technology offer several advantages, including a multitude of scan pattern generation, non-overlapping patterns, and a conical Field-Of-View (FOV) generating a high data density around the center. The geometry and material properties of the prisms define the conical FOV of the sensor, which can be typically set between 15° to 120°. However, once the prisms are defined, the FOV cannot be changed. Neptec Technologies in collaboration with Defence Research and Development Canada has developed a unique scanner prototype using two pairs of Risley prisms. The first pair defines a small 30° FOV which is then steered into a larger 90° Field-Of-Regard (FOR) by using the second pair of prisms. This presents the advantages of a high-resolution scan pattern footprint that can be steered quickly and randomly into a larger area, eliminating the need for mechanical steering equipment. The OPAL Double Risley Pairs (DRP) prototype was recently evaluated at Yuma Proving Ground with the scanner positioned atop a tower and overlooking various types of targets while dust was generated by a helicopter. Results will be presented in clear and dusty conditions, showing examples of moving a high resolution FOV within the FOR.

Keywords: LiDAR, Risley Prisms, Degraded Visual Environments

1. INTRODUCTION

3D laser scanners, also known as LiDARs, are used in a large variety of manned and autonomous applications that require real-time 3D perception sensors for obstacle detection and avoidance. One such application is aimed at augmenting the situational awareness of helicopter pilots landing in unprepared terrain where poor visibility can be caused by the downwash of the rotors stirring dust, sand, or snow on the ground.

In addition to penetrating obscurants, it is also important to have a scanner capable of sufficient resolution to detect small objects that can cause damage to the helicopter, such as wires, metal rods, fence posts, etc. It is also equally important to have a LiDAR capable of covering as large a FOV as possible. These requirements are difficult to implement in a single compact system. One existing approach comprises the mounting of a LiDAR on mechanical gimbals to steer a small FOV in different directions. The disadvantages are that it adds weight, volume, complexity and cost to the system while introducing added uncertainties due to errors in the angular positions of the gimbals. This article describes a unique and innovative approach where a small FOV scan pattern is steered within a larger FOR through the use of compact optical components.

Neptec has developed the OPAL™ family of laser scanners that penetrate dense obscurant conditions considerably better than the naked eye. They use the Risley prism pair technology, where two superimposed prisms are independently rotated by hollow shaft motors. A laser pulse travelling through the hollow shaft motors is bent by the rotating prisms to form a scan pattern comprising several rosettes. This implementation offers several advantages, including a multitude of possible scan patterns, rapid generation of non-overlapping patterns, and a conical FOV with very high data density around the center. The geometric and material properties of the prisms define the conical FOV of the LiDAR, which can be typically set between 15° and 120°.

It is advantageous for an operator to obtain very high data density at a particular location while also having the flexibility to quickly move the high density FOV to another area in the FOR. Neptec, in collaboration with Defence Research and Development Canada, has developed a unique scanner prototype using a double pair of Risley prisms. The first prism pair generates a 30° FOV which may then be steered into a larger 90° FOR by employing the second pair of prisms. This presents the advantage of a high-resolution scan pattern footprint that can be moved quickly and randomly into a larger area, eliminating the need for mechanical steering equipment. In terms of operational capabilities, the OPAL-DRP can be used aboard an aircraft for operations such as:

- Scanning a landing zone with high resolution information where small threatening obstacles such as posts or wires, will stand a better chance to be detected
- Offering station-keeping capability where the aircraft motions are compensated by the steering mechanism to keep the LiDAR FOV locked on an area of interest
- Tracking a small moving object in the FOR
- Moving the high resolution FOV to a variety of locations in order to provide rapid monitoring of specific areas while approaching the landing zone

This article describes the OPAL-DRP implementation in more detail and provides examples of scan pattern scenarios and applications.

2. DOUBLE RISLEY PRISMS PAIR DESIGN OVERVIEW

2.1 Background

The Risley prism pair approach is not new and has been used for many optical applications requiring the steering of emitted light from a LiDAR system [1] or even the steering of incoming light onto a detector array [2]. A single pair of Risley prisms has also been used to steer laser light at specific angular directions by adjusting the relative angular position of the two prisms. Therefore, in addition to generating specific rosettes patterns through the rotation speed of the prisms motors, it is also possible to concentrate scan patterns in a small FOV. This approach has been previously used, for example, to track targets [3].

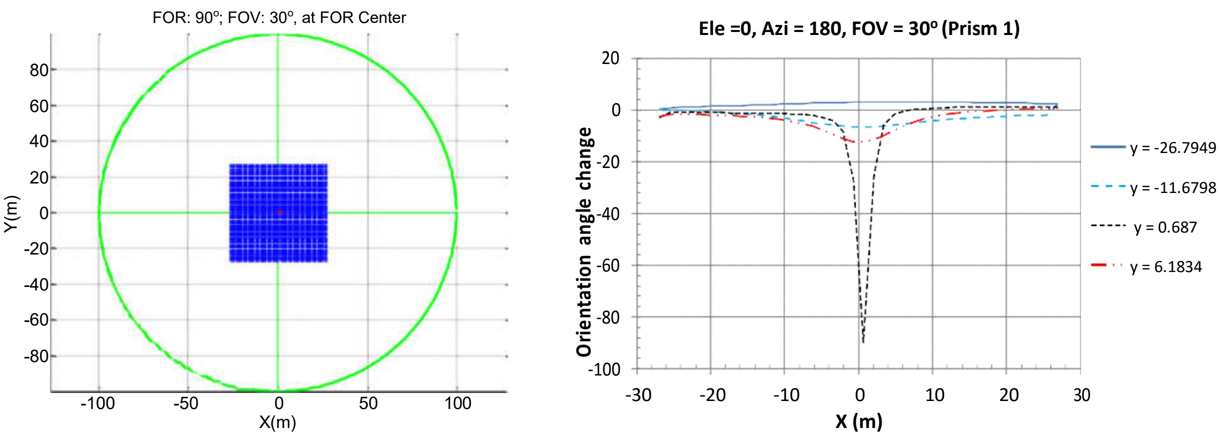
However, there are limitations in the use of a single prism pair to steer scan patterns in a small FOV area [3-5]. The relation between the pointing position of the light exiting the prisms pair and the angular orientation of the prisms is non-linear, which leads to non-linearities in the system control. A specific limitation occurs when the FOV of interest is steered in a zone close to and including the center of the FOR. Under that singularity condition, the change of angular orientation of the prisms can be very large when scanning two neighbouring points.

An example of that condition is given in Figure 1. Figure 1 (a) shows a small FOV area spanning 30° in the vertical and horizontal direction while centered on a larger 90° FOR. A projection at a range of 100m is used in this example. The prisms angular positions are driven to draw a raster scan with the defined FOV. Figure 1 (b) shows the required change in the prism angular position as a function of the data points coordinates. It can be observed that the angular changes become quite large near the center of the FOR, likely exceeding practical motor capabilities. Tracking a target through the FOR center may require infinite rotational velocities of the prisms [4]. Another type of limitation occurs when the small FOV is steered towards the edge of the FOR, although in this situation the angular changes required in the angular position of the prism motors are not as severe as what is encountered near the FOR center. Other approaches have used a third prism to circumvent these singularities [5, 6].

2.2 Design Overview

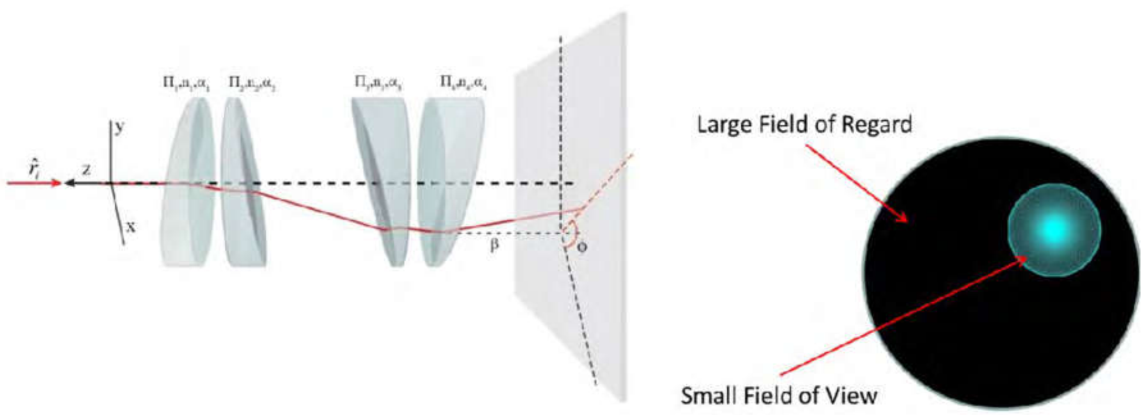
The approach described in this paper uses a double prism pair. Its advantage, when compared to a single prism pair, is not only the avoidance of singularities as described above but also the ease of programming specific scan patterns. A description of the optical design along with the refraction model can be found in [7].

The optical arrangement is shown in Figure 2 (a). The four prisms Π_1, Π_2, Π_3, and Π_4 are rotated independently about the z axis. n_1, n_2, n_3, and n_4 are their refractive indices and α_1, α_2, α_3, and α_4 are their wedge angles. Orientations of the prisms are specified by their respective rotation angles θ_1, θ_2, θ_3, and θ_4, which vary according to their angular rotation speeds ω_1, ω_2, ω_3, and ω_4 controlled by individually motors for each prism. The final pointing direction is defined by the elevation and azimuth angles, β and ϕ, respectively. Figure 2 (b) shows a representation of a small FOV being moved in a larger FOR. In the current implementation the FOR is set at 90°. However, the FOR is not limited to 90° and can be extended to something on the order of 120°. Similarly, the implemented FOV is 30° but can be made to be much smaller if a very high data density is required. A photograph of the OPAL-DRP scanner is shown in Figure 3. To our knowledge, this represents the first LiDAR using a double Risley prism pair. A similar approach was used previously for a free space optical communication system where a double pair of Risley prisms are used to steer light between optical fibers [8].



(a) (b)

Figure 1. (a) Small focused raster scan FOV area generated by a single prism pair. (b) Corresponding change in angular position for prism #1 as a function of the data points coordinates.



(a) (b)

Figure 2 (a) Optical arrangement for the DRP system. (b) Illustration of a small FOV being moved into a larger FOR.

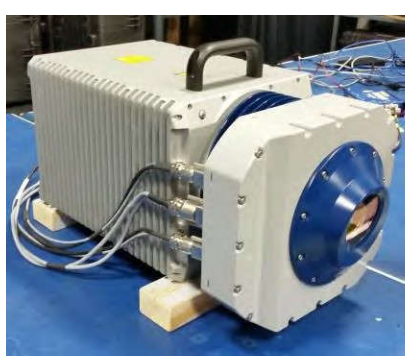


Figure 3. Picture of the Double Risley Prisms Pair implementation based on the Neptec's OPAL-ECR LiDAR.

3. EXAMPLES OF SCAN PATTERN SCENARIOS

3.1 Examples of Simple Scan Scenarios

Through the control of the relative phases between the outer prism pair, various types of scanning scenarios can be generated. Figure 4 shows a few simple examples of scanning scenarios, obtained with the current OPAL-DRP prototype instrument using a small FOV of 30° and a larger FOR of 90°. For these examples, the scan patterns are projected on a plane 100m away from the sensor. Figure 4 (a) shows the positioning of the FOV at a random spot in the FOR. The extent of the FOR is represented by the outer circle. This strategy can be used to interrogate rapidly, in sequence, several points of interest within the FOR. In this example, the patterns in the FOV are obtained for a period of 500ms.

Figure 4 (b) shows a scanning scenario where the FOV is moved continuously along the horizontal diameter of the FOR. Figure 4 (c) shows a scanning scenario where the FOV is moved continuously along a circle within the FOR, creating in this example an effective FOV of 60°. The circle diameter is defined by simply adjusting the phase difference between the moving outer prisms. Finally, Figure 4 (d) shows a situation where the FOV is moved along a spiral pattern within the FOR to cover the full FOR. The spread of the spiral is defined by the rate of change of the phase difference between the moving outer prisms. The circular and spiraling strategy can be used, for example, to rapidly scan at a high data density an area of interest, such as a landing zone, for potential obstacles. The OPAL-DRP can also be used to either track a moving target or scan specific locations indicated by an operator. In this case, a solution to the inverse problem is required, that is what should be the angular position of the other outer prisms that will direct the FOV to a designated world coordinate. Such inverse solutions have already been developed and can be found in publications such as the one referenced in [9].

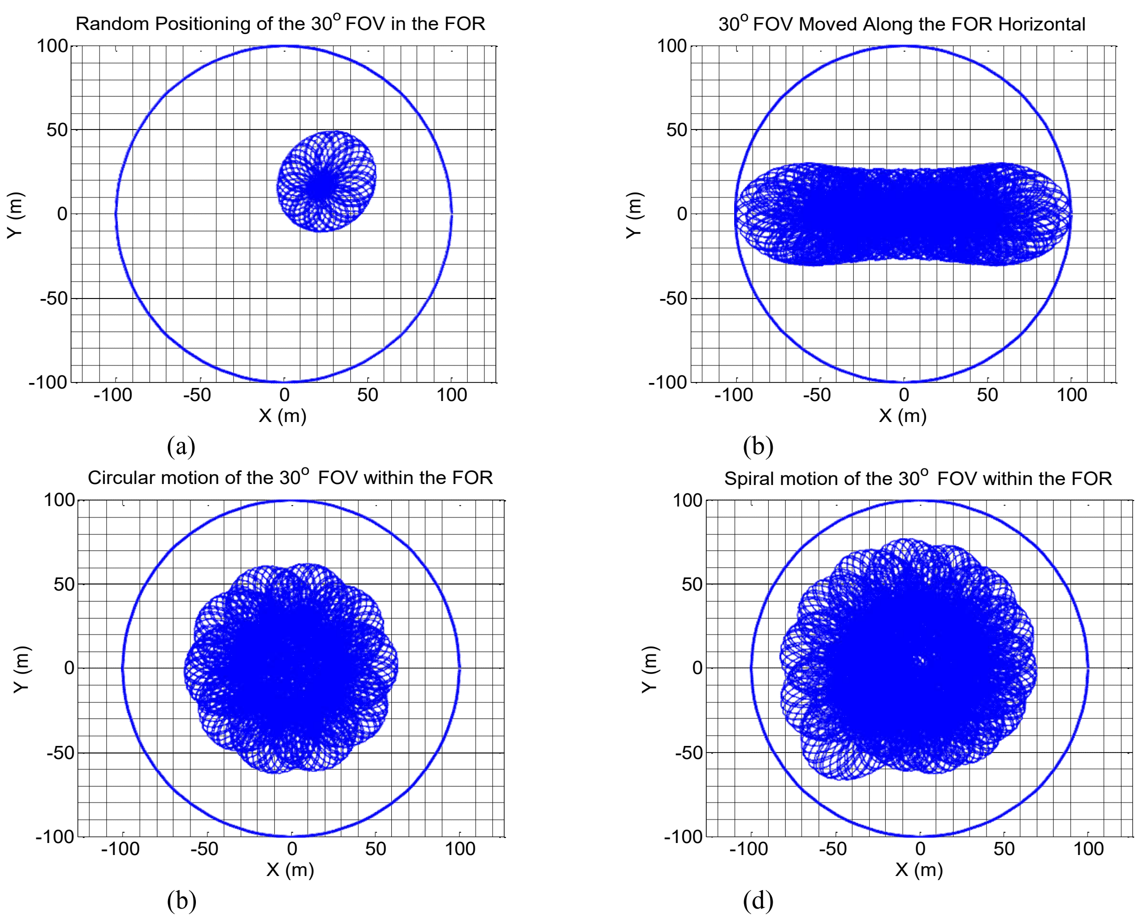


Figure 4. Examples of simple scan scenarios where a 30° FOV is moved within a 90° FOR.

3.2 Data Density

The significant advantage of the OPAL-DRP scanner is its ability to concentrate high data density in a smaller region of the FOR. It is useful to compare the data density obtained from a standard Risley prism scanner producing a conical 90° FOV and the current OPAL-DRP scanner using a 90° FOR. For this comparison, the standard 90° Risley prism scanner illuminates the full 90° FOV while the DRP moves the 30° FOV along the horizontal diameter of the FOR. Figure 5 shows the 3D data distribution and 2D projection on a plane for data acquired at a constant range. The blue dots correspond to the data distribution of the standard 90° conical Risley prism scanner while the red dots correspond to the data obtained from the DRP scanner moving the 30° FOV along the horizontal of the FOR. For each case, the data is acquired over two seconds duration at a rate of 200kHz.

Figure 6 compares the data density profile obtained from the standard 90° Risley prism conical scanner with the OPAL-DRP scanner. For the case of the conical scanner, the data density distribution will vary with the elevation angle, which is the angle between a given point and the FOV center. For the case of the OPAL-DRP, the data density will also vary with the elevation angle and will be limited to the stretch corresponding to the motion of the small FOV along the horizontal. The data density is expressed in terms of the number of data points per second and per unit of 1°x1° solid angle. It can be observed from the graph that the difference in data density becomes significant, reaching a factor of 10 in the region between 10°-30°. It can also be observed that the density becomes more uniform for the OPAL-DRP in the region between 0°-25°. The uniformity of the data distribution can also be optimized with the selection of the motor speeds controlling the angular displacements of the prisms.

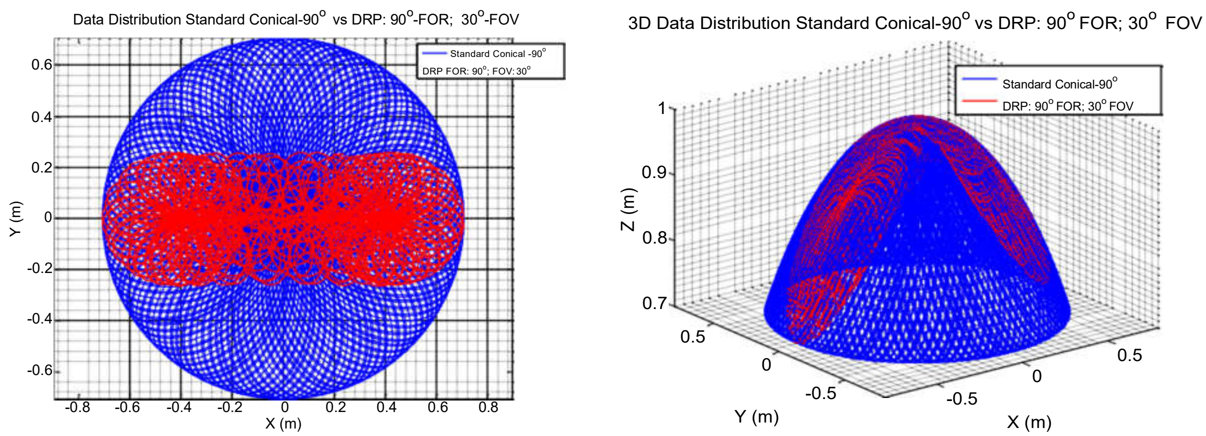


Figure 5. Comparative data density distribution between a standard conical Risley prism scanner and the DRP using the small FOV along the horizontal.

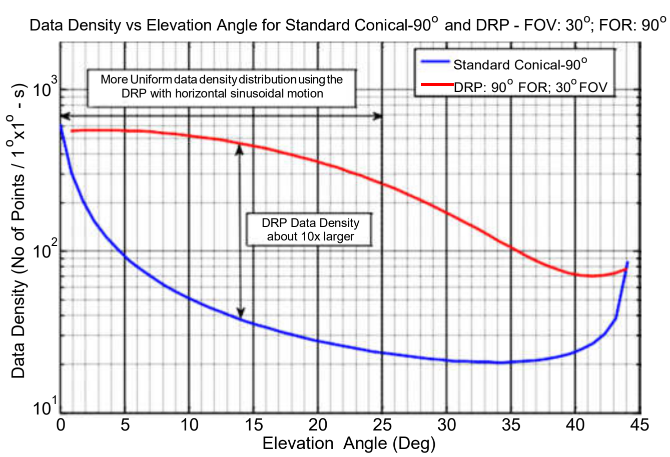


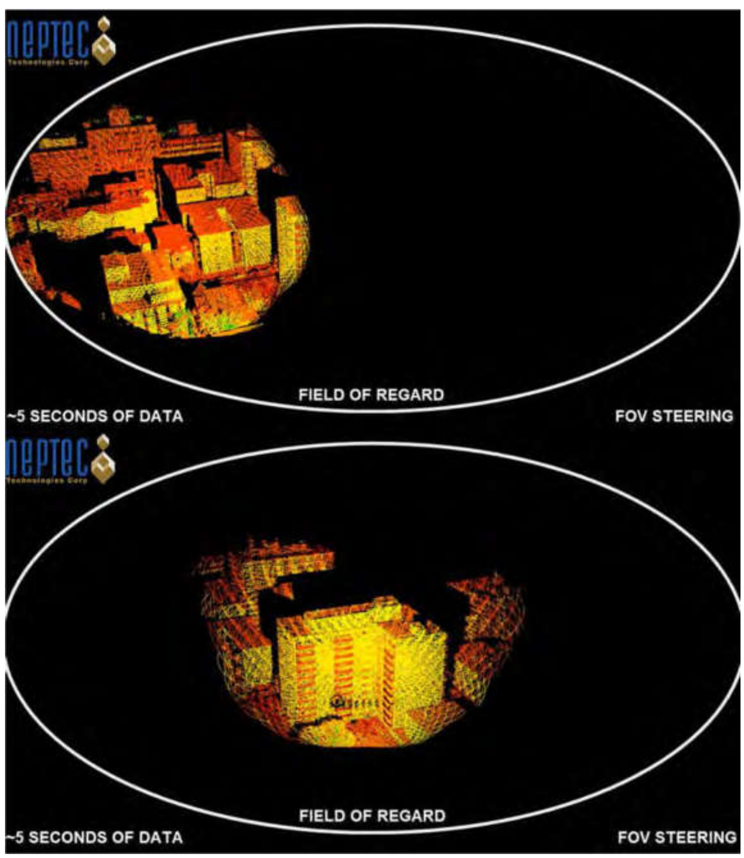
Figure 6. Comparative data density (No. of data points / 1°x1°-s) versus elevation angle for a standard conical Risley prism scanner and the DRP moving a 30° FOV along the horizontal of a 90°FOR.

4. TEST DATA EXAMPLES

4.1 Urban Environment

The DRP was tested in an urban environment as shown in Figure 7. Figure 8 illustrates the steering capability of the DRP prototype. In this example, the images are obtained in an urban environment with a slant range not exceeding 250m. The DRP is installed on a balcony at the top of a building, looking downwards at other buildings. The elliptical contour shown in the figures represents the limits of the FOR. The images show the data acquired in the 30° FOV while the FOV is moved along the horizontal of the FOR. The images hold about 5 seconds of data acquired at a rate of 200kHz. In this example, the data is collected from left to right. The correspondence of the 3D data with the actual environment can be seen from the photo in Figure **7**.

Figure 7. Picture of the scan area



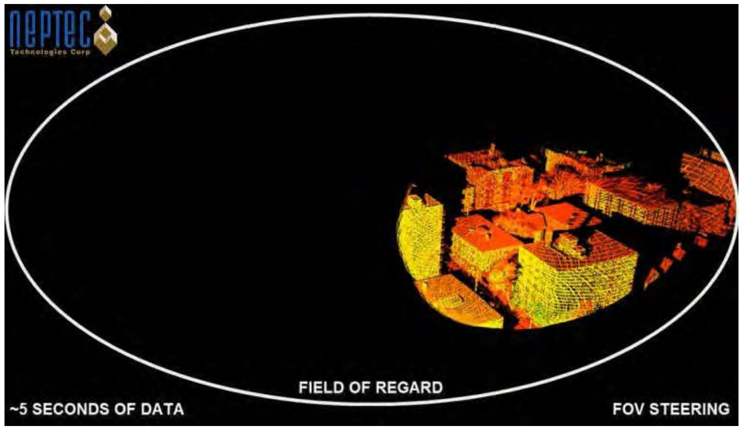


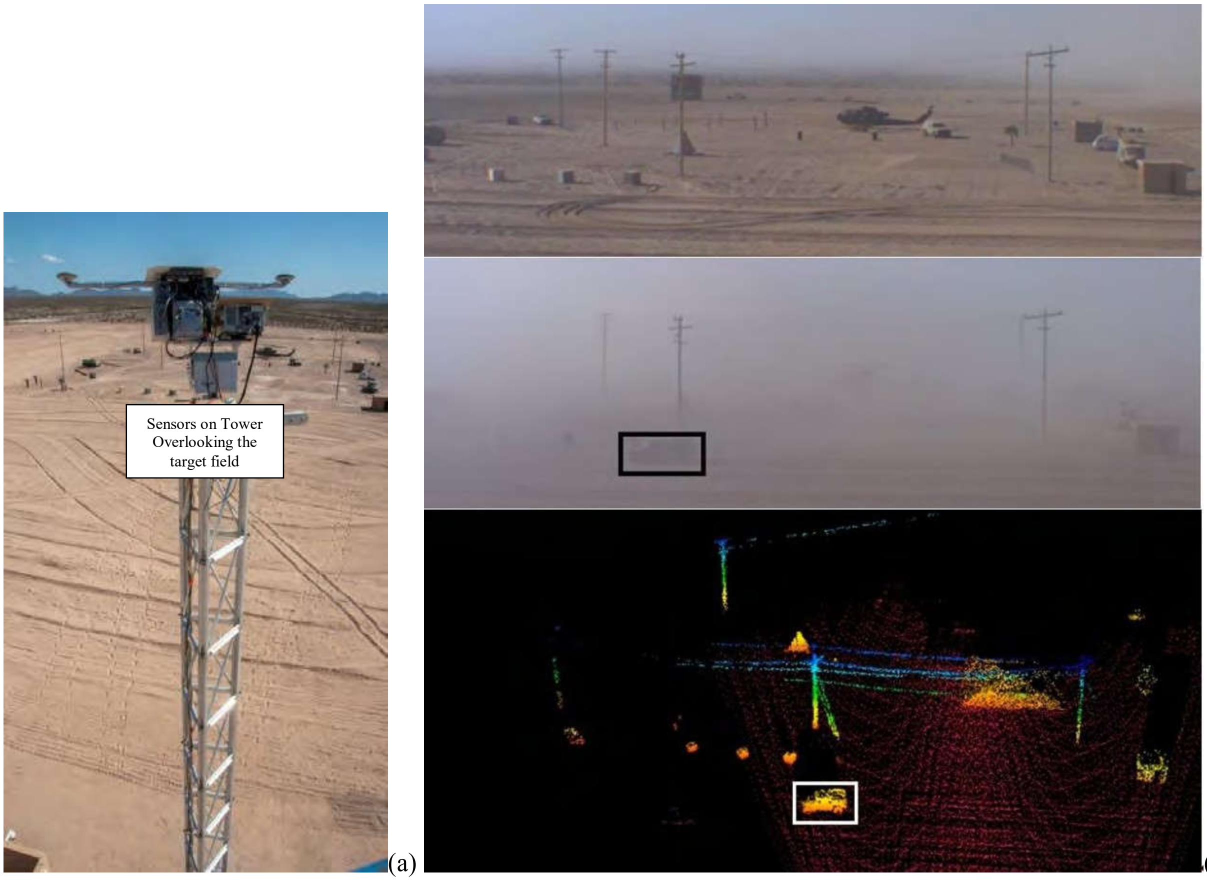
Figure 8. Data acquired with the DRP while the FOV is moved along the horizontal of the FOR.

4.2 Degraded Visual Environment Applications

Performance evaluation of the OPAL-DRP LiDAR was performed at Yuma Proving Ground in September 2016 as a Canadian contribution to the Joint Capability Group on Vertical Lift Degraded Visual Environments (DVE) Informal Working Group (IWG) and as an addition to the US ARMY RDECOM Degraded Visual Environment Mitigation Program. The OPAL-DRP design incorporates the same obscurant penetration capabilities of the OPAL^{TM} commercial LiDARs. A more detailed description of the obscurant penetration capabilities can be found in [1, 10].

Figure 9 (a) shows the OPAL-DRP installed at the top of a deployable tower at a height of 30 feet, along with a differential GPS and IMU system to geo-reference the LiDAR data. The OPAL-DRP is overlooking a collection of near-field obstacles, including boxes, hydro poles, wires, etc. An approaching helicopter generates the dust.

Figure 9 (b) shows a scan example. Assessment of the dust penetration capabilities of the OPAL-DRP is done by comparing 3D LiDAR images with visual video recording obtained from the same position at the same time. The two video images at the top of Figure 9 (b) show the near-field obstacles in the absence and in presence of dust. The image at the bottom has been obtained at the same time as the image obscured by the presence of dust. The OPAL-DRP was set at a fixed position while performing a horizontal scan operating at 25 kHz. The vehicle shown in the middle picture within the rectangle was absent from the clear scene; it is clearly detected by the OPAL-DRP. Generally, after a helicopter pass, the OPAL-DRP will detect the obstacles before the naked eye can.



(a) (b)

Figure 9. (a) Picture of the OPAL-DRP installed on a tower. (b) The two video images at the top compare the scene in absence and in presence of dust. The OPAL-DRP LiDAR image at the bottom has been obtained at the same time as the image obscured by the presence of dust. The OPAL-DRP was set at a fix position while performing a horizontal scan operating at 25 kHz. The vehicle shown into the rectangle was absent from the clear scene.

5. SUMMARY & CONCLUSION

A Double Risley Prism Pair (DRP) LiDAR was prototyped and evaluated for its capability to move a high data density FOV within a large FOR. The approach offers several advantages, including reducing the need for heavy and costly steering mechanical gimbals, allowing a quick high-density survey of an area of interest such as a landing zone, tracking of a moving target, and offering a high-density inspection of random areas as determined by an operator. In addition to those capabilities, the obscurant penetration of the OPAL-DRP was demonstrated in controlled test environments.

The instrument is currently a prototype and future development will include a full integration of the outer motors/prisms as well as the control mechanism, allowing for faster motion of the FOV. As well, smaller FOVs and larger FORs should be evaluated in view of providing higher data density regions in very large FOR areas.

6. ACKNOWLEDGMENTS

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