3-D Imaging by Laser Radar and Applications in Preventing and Combating Crime and Terrorism

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ABSTRACT

This paper describes the ongoing research on 3-dimensional (3-D) imaging at FOI. Specifically, we address the new possibilities brought by laser radars, focusing on systems for high resolution 3-D imaging. 3-D laser radar is a viable technology in the effort to prevent and combat crime and terrorism. Real time 3-D sensing is a reality and can, besides more conventional techniques such as stereo vision and structured light, be achieved by range imaging. Current development of 3-D sensing flash imaging laser radars will provide the capability of high resolution 3-D imaging at long ranges with cm-resolution at full video rate. In all probability, this will revolutionise many applications, including law enforcement and forensic investigations. In contrast to conventional passive imaging systems, such as CCD and infrared (IR) techniques, laser radar provides both intensity and range information and has the ability to penetrate certain scene elements such as vegetation and windows. This, in turn, means new potentials, for example, in object recognition and identification and we address some of these new capabilities of 3-D laser radar systems. The results clearly show that 3-D imaging laser radar systems are useful in a variety of situations that can be used in the criminal justice system today to enable technologies for preventing and combating crime and terrorism.

1.0 INTRODUCTION

With 3-D laser radar a new dimension is added to active imaging. In addition to intensity and angular coordinates, also range is included in the image. Range resolved imaging gives the ability to recognize and identify objects and people based on 3-D geometrical shape, as well as other parameters such as reflection and contrast. It also adds the ability to "see" what is hidden behind partly obscuring objects, such as vegetation, camouflage nets, curtains, and Venetian blinds. This ability can be used in surveillance, and for reconnaissance and recognition. The high resolution and accuracy of 3-D laser radar makes it possible to make accurate measurements in a 3-D image, e.g., to identify a person or to make a complete 3-D model of the scene of a crime.

In this paper we present the technique that is used for active imaging with laser radar and give examples of how this technology can be of use in the work to combat crime and terrorism. In section 2 we describe some of the laser radar techniques that can be used for 3-D imaging. We give examples of some applications of 3-D imaging systems in Section 3, and in Section 4 we present some ongoing work concerning the usage of laser radar systems, signal and image processing for recognition, visualization, and modelling.

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2.0 3-D IMAGING LASER RADAR

There are several principles for 3-D imaging laser radar. Basically, a pulsed laser is used for illumination and a detector collects the reflected radiation from the scene. The active illumination with a laser results in complete independence of ambient light conditions (such as day or night), and hence the image contrast is very robust in that respect.

If an illuminating laser pulse hits some partly transmitting material, or some concealing object with gaps in, and is reflected from a target surface behind the concealment, this can be detected by the sensor as depicted in Figure 1. One can think of many applications where it is of interest to observe objects and areas that are more or less obscured by, e.g., vegetation, camouflage nets, curtains, Venetian blinds, or shaded windows. Visible and near infrared (NIR) wavelengths penetrate windows in buildings and vehicles. This can be used for reconnaissance purposes to detect if humans are present in a building or a vehicle. Other applications are terrain mapping, where, e.g., trees, roads, and buildings can be classified. Object recognition is facilitated by 3-D information in comparison to a 2-D image, but also more complex.

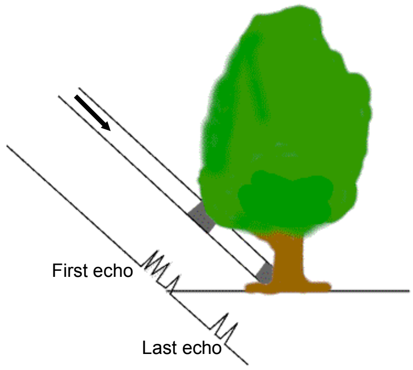

Figure 1. The illuminating laser pulse first hits the canopy of the tree, which results in the first echo. Part of the laser pulse penetrates the canopy and is finally reflected by the stem, giving the last echo.

In the last few years there has been a fast development of new sensors and sensor capabilities. 3-D imaging laser radars have generally been scanning systems, usually with mechanical scanners. Hence, data collection has been quite time consuming. Furthermore, capturing moving objects has not been possible. A new generation staring systems (flash laser radar) is now being developed, where a complete rangefinder in included in each pixel in the form of a time-resolved receiver and read-out integrated circuit (ROIC). This enables the capture of a complete 3-D image with just one transmitted laser pulse.

2.1 Gated viewing or burst illumination

With the technique of gated viewing (GV), also called burst illumination, the sensor can be a simple camera constructed for the laser wavelength, but the shutter is connected to and synchronized with a short illuminating pulsed laser. With an adjustable a delay setting, corresponding to the time-of-flight back and forth to a desired range, the opening of the camera shutter is controlled. This exposes the camera only for a desired range slice, with the slice as deep as the laser pulse length plus the shutter open time. The delay can be changed through a predefined program, resulting in a number of slices representing different ranges, i.e., a 3-D volume. The set-back of this system is the power inefficiency, since every range slice image requires a total scene illumination. The advantage is the low cost and robustness, since rather simple components can be used. As active illumination is used, GV systems have night capability. With gated viewing, a number of advantages over passive imaging can be listed:

- Suppression of reflexes from atmosphere, smoke, and terrain.

- Potential for detection of optics (e.g., optical sensors or binoculars) at long ranges.
- Target range can be obtained with image information
- Silhouette detection
- Suppression of optically annoying backgrounds (e.g., direct light) by short exposure time and active illumination
- Potential for better weather performance compared to passive electro-optical systems, and possibility to "see" through smoke and haze

Furthermore, it has been shown that a rather small set of gated images can give high resolution 3-D images. By taking the depth information into account, the 3-D volume of an object can be constructed by a few gated images.

2.2 Laser scanner

A straight-forward method to acquire 3-D information about a scene is to scan the object with a single element detector laser radar. With every laser pulse a very small part of the object is illuminated and the time-of-flight is stored. Some detectors give a time-resolved pulse response (full waveform), whereas other detectors only give the time for the pulse return (above a certain threshold). With some systems it is possible to store first and last echo, or even more returns, each echo representing a different target range. An advantage of a scanning system is the possibility to achieve high angular resolution. The main disadvantage is the long data acquisition time, which prevents the capture of moving objects. Scanning laser radar systems can be ground based laser, see Figure 2 [1, 2], or airborne, see Figure 3 [3]. Ground based systems can be used for 3-D modelling and recognition of small objects, whereas airborne systems are mainly used for terrain mapping.

Figure 2. Two ground based scanners that are used at FOI.
Optech ILRIS 3-D (left) and Riegl LMS-Z210 (right).

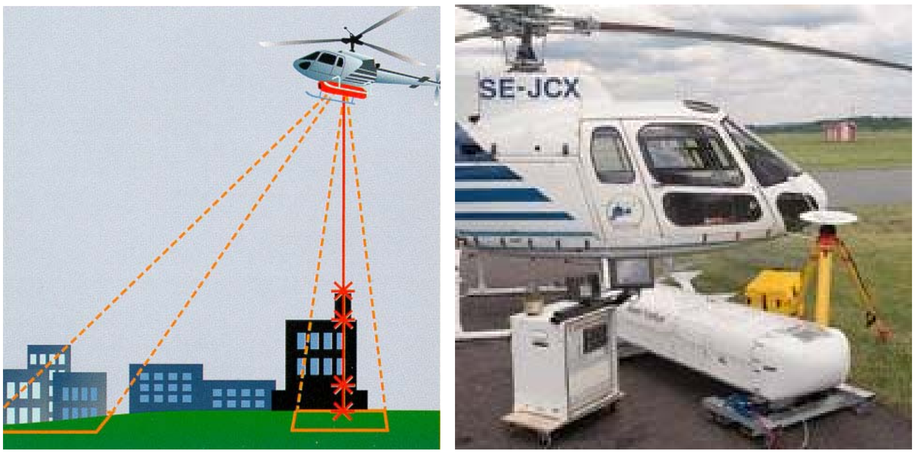

Figure 3. TopEye is an airborne laser radar system for air-to-ground laser scanning. (From [3])

2.3 3-D flash laser radar

The development of focal plane array (FPA) detectors with timing capability in each pixel has made non-scanning 3-D imaging laser radars feasible. FPA:s with up to 128×128 elements and read-out integrated circuits (ROIC) are available today[4]. With such a system, the frame rate can be increased to video rate (50 Hz or 60 Hz), to enable also the capture of moving objects. The sensor is not larger than an ordinary camera, se Figure 4, excluding the laser source, which can be fit to the application, and the data acquisition platform, normally a computer. In short range system versions the laser can be incorporated into the camera unit itself. An image example is shown in Figure 5. For each laser pulse the complete waveform is acquired in each pixel, and from this data, the range information can be calculated, as seen in Figure 6.

Figure 4. The flash 3-D sensor, excluding the illuminating laser.
The scale is in inches. (Courtesy: R. Richmond, AFRL, USA)

Figure 5. Example data from a flash 3-D laser radar (Courtesy: R. Richmond, AFRL, USA). Left: A photograph of a truck. Right: One range slice from a 3-D image. The image is slightly processed at FOI.

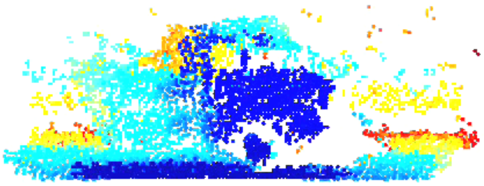

Figure 6. The extracted depth from one laser pulse.

3.0 APPLICATIONS

3-D imaging with laser radar is a fairly new application, and has become commonly used, e.g., for terrain mapping and data collection for 3-D modelling. Some additional applications for 3-D laser radar are listed below:

- Reflectance measurements. From measurements, target reflectance can be calculated. Targets are usually military vehicles or backgrounds.
- 3-D modelling. 3-D models are built from data sets and are used for further simulations in different kinds of applications. Models of both vehicles and backgrounds can be built. Backgrounds can be coordinated with GPS data.
- Multiple views. Data sets (views) from different locations can be stitched together, to increase the point density in the 3-D point cloud, and to improve the ability to uncover partly hidden objects.
- Classification and recognition. Algorithms for classification and recognition are developed. Detected points can, for instance, be compared to 3-D models and/or surfaces (e.g. camouflage nets). 3-D data sets can also be used in algorithms for body shape and motion pattern recognition.

3.1 Penetration

With 3-D laser radar technology it is possible to "see through" concealing objects, but of course there needs to be holes where at least part of the illuminating laser beam has a free line-of-sight from the sensor to the object that is going to be imaged. Using the last pulse mode of a laser scanner it is possible to penetrate for instance a forest [5].

For urban missions, a UGV can be used for "window clearing" and can locate people in dark rooms behind Venetian blinds, see Figure 7. While passive EO sensors have difficulties here, the 3-D laser radar is ideal looking for manlike "objects" in the room or detecting rifle optics etc.

Figure 7. Urban mission doing "window cleaning" and locating people inside the buildings. (Image modified after original found at www.arl.army.mil/wrmd).

3.2 Urban modelling

Airborne laser scanner data has shown to be suitable for creating high resolution 3-D virtual environment models. Such models can be used for a number of applications, e.g., crisis management, decision support systems, visual simulations, etc. Much research and work is currently going on to develop methods for processing and extracting geographic information from airborne laser scanner data. When constructing environment models, a first step is to estimate the ground surface. Different methods have been developed for this. In [6], eight different methods are compared. After having extracted the ground surface, the remaining laser points above ground can be further separated into natural (vegetation) or man-made (buildings) objects using measurements based on height variations [7, 8]. Natural objects will show larger vertical variations than within roof faces of buildings, since the laser beam can penetrate the canopy of trees. Using the elevation data within each segment classified as buildings, 3-D models of buildings can be reconstructed [9-11]. Areas classified as vegetation can be further analyzed to extract individual trees [12, 13]. For the detected trees, different tree attributes such as position, tree height and crown diameter can be estimated. These extracted data sets of information are suitable for construction of 3-D virtual environment models.

3.3 Recognition

Object recognition in images has been extensively studied in the computer vision community the last decades. In the general case, it is an extremely hard problem, since it relies on context-dependent background knowledge and thus tightly interconnected to the artificial intelligence problem. In certain specific cases, object recognition is practically applicable thanks to restrictions to a specific class of objects, external conditions, and/or incorporation of a priori information. Examples are face recognition, modelling of buildings, and military target recognition. Still, even with these restrictions, the applications are limited. An inherent problem is that the 2-D projection (i.e., and image) of a 3-D object does not contain much information on the object's 3-D structure, even if much of it can be regained by different "Shape from X" techniques [14](i.e., various techniques for extracting 3-D information from 2-D data).

Obviously, a sensor acquiring 3-D information gives a huge advantage in this respect. However, 3-D object recognition is not yet as well explored as in 2-D, as the sensors are not as widespread as 2-D imaging sensors. Therefore, the current applications are somewhat limited for most people. This is due to change as systems for capturing 3-D information become less expensive.

Whereas 3D-to-2D correspondence, Shape from X, and illumination (including shadows and reflectance) all are important problems in 2-D object recognition, other problems need to be considered in 3-D recognition. The two most immediate are probably surface reconstruction and model-to-surface (or point scatter) matching. Recently, significant progress has been made, by exploiting new data representations. The spin-image representation introduced by Zhang and Hebert [15] has been exploited by Vasile [16] to achieve automatic detection and recognition of military targets. A spin-image is a representation of a small patch of an object's surface, with the useful property that it is invariant to rotation, i.e., regardless of from which direction you look at an object, the spin-images will be the same. The same spin-image representation has been further developed by Ruiz-Correa et al. [17], combining spin-images into symbolic surface signatures used to learn shape-classes. Even though their results are impressive, application to real-world problems are yet to be seen. However, the potential for reliable object recognition (at least when restricted to certain classes, like military targets) is huge and applicability within reach.

Even if systems for automatic object recognition are not yet available in cheap commercial-of-the-shelf (COTS) products, there are situations where manual interaction is acceptable. Consider the following scenario, successfully applied in facial identification at the Netherlands Forensic Institute. An unknown person A is observed by a surveillance camera, and the problem is to determine if person A is identical to an (available) person B. A traditional approach is to capture an image of person B, where the imaging conditions (illumination, camera position, head pose) are as similar as possible to the conditions when capturing the image of person A. The two images are then (manually but computer-aided) compared, the result often being a matter of opinion.

Instead, assume that we make a 3-D scan of person B's head and create a 3-D model. We identify a small set of points (maybe four) on the head of person A and mark the same points on the 3-D model of person B. We can then visualize the 3-D model in the same frame as the surveillance image, taking into account the camera parameters, and try to align the 3-D model to the image. In almost all cases where the persons A and B are different, the alignment will fail due to differences in the 3-D structure of the two heads. Naturally, a good match does not, with the currently available a priori information, imply that the two persons are identical. Nevertheless, the capability of excluding people from a list of suspects is also important in a forensic context. This technique is also used in the area of crano-facial identification.

4.0 EXAMPLES

In this section we give describe in more detail some of the relevant work that is being done at FOI. Images of object hidden behind vegetation and other kinds of camouflage are presented. Also, some examples of urban modelling, as well as examples of visualization and recognition are given.

4.1 Penetration through vegetation and camouflage

As mentioned above, the ability to record the last echo with a 3-D laser radar, makes is possible to reveal objects that are partly concealed. Experimental data collected with scanning 3-D laser radar systems shows that an illuminating laser pulse can penetrate through several tens of meters into vegetation, and enable imaging of objects that are, e.g., behind a forest line [5].

The capability to "see through" vegetation can be enhanced by imaging the scene from several viewing angles and then stitching the views together. This is illustrated by the scenario in Figure 8, where eight views of a fairly dense group of trees were recorded from various viewing angles. A Volvo V40 is placed behind the trees. In Figure 9 the combined point cloud is rotated, revealing the vehicle that is hidden behind the trees.

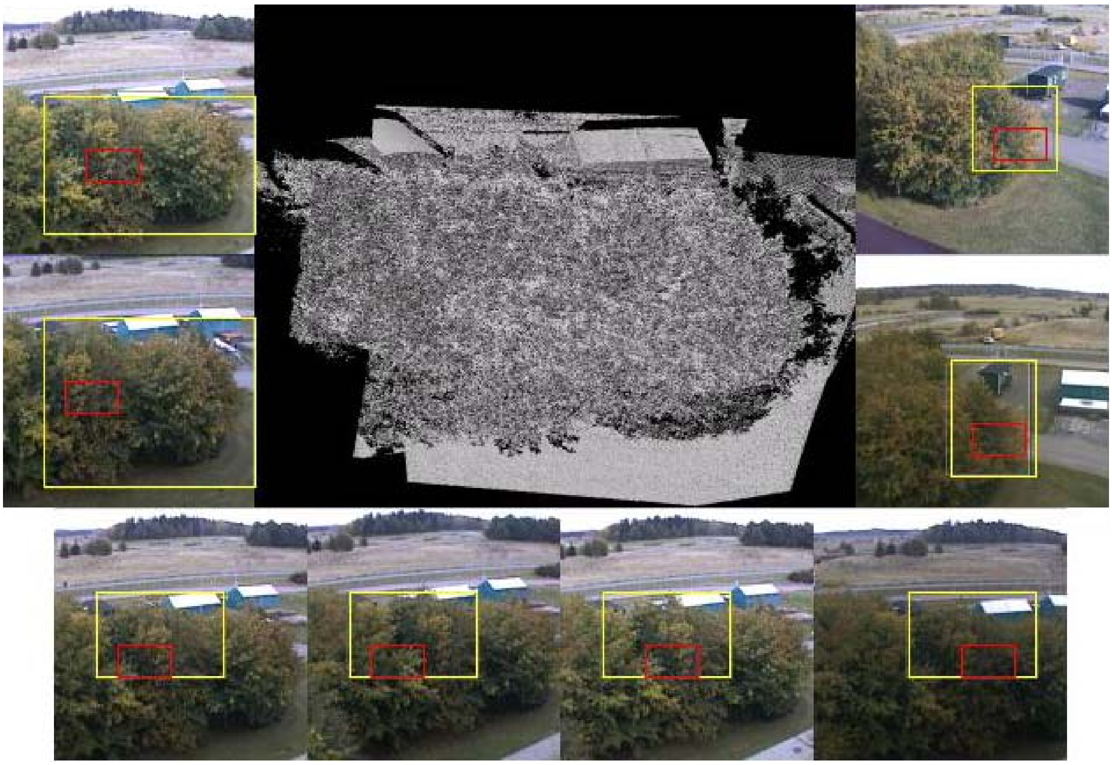

Figure 8. In the middle a 3-D laser radar image of a group of trees stitched together from eight different views. Around is a series of visual views taken from each individual imaging position of the laser scanner. The red rectangles indicate the location of the hidden car.

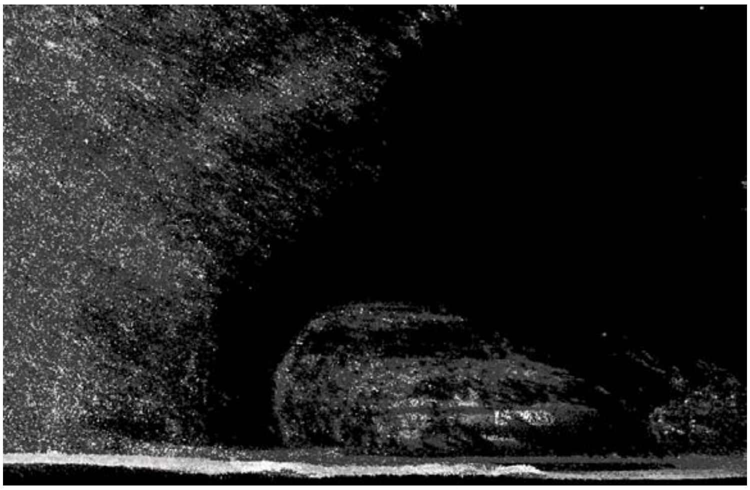

Figure 9. 3-D laser radar images from different viewing angles can be combined to give a well-resolved image of the target. This image, combined from eight views, is re-projected and shows a Volvo V40 hidden behind dense vegetation.

Recent field tests conducted by FOI show that 3-D laser radar can penetrate camouflage nets and provide an image of concealed objects. An example is shown in Figure 10, where a man is standing under a camouflage shelter. In the 3-D laser radar image, with last echo setting, the man is clearly visible. The low reflectance of the face causes the man's head to disappear.

Figure 10. A photograph of a vehicle camouflage shelter to the left. To the right, a re-projected 3-D laser radar image (last echo) of the scene, also revealing a man standing in the middle of the shelter. Note the low reflection from the face. As the last echo is recorded, the pulse returns from the man under the net cause a “shadow” on the front of the net.

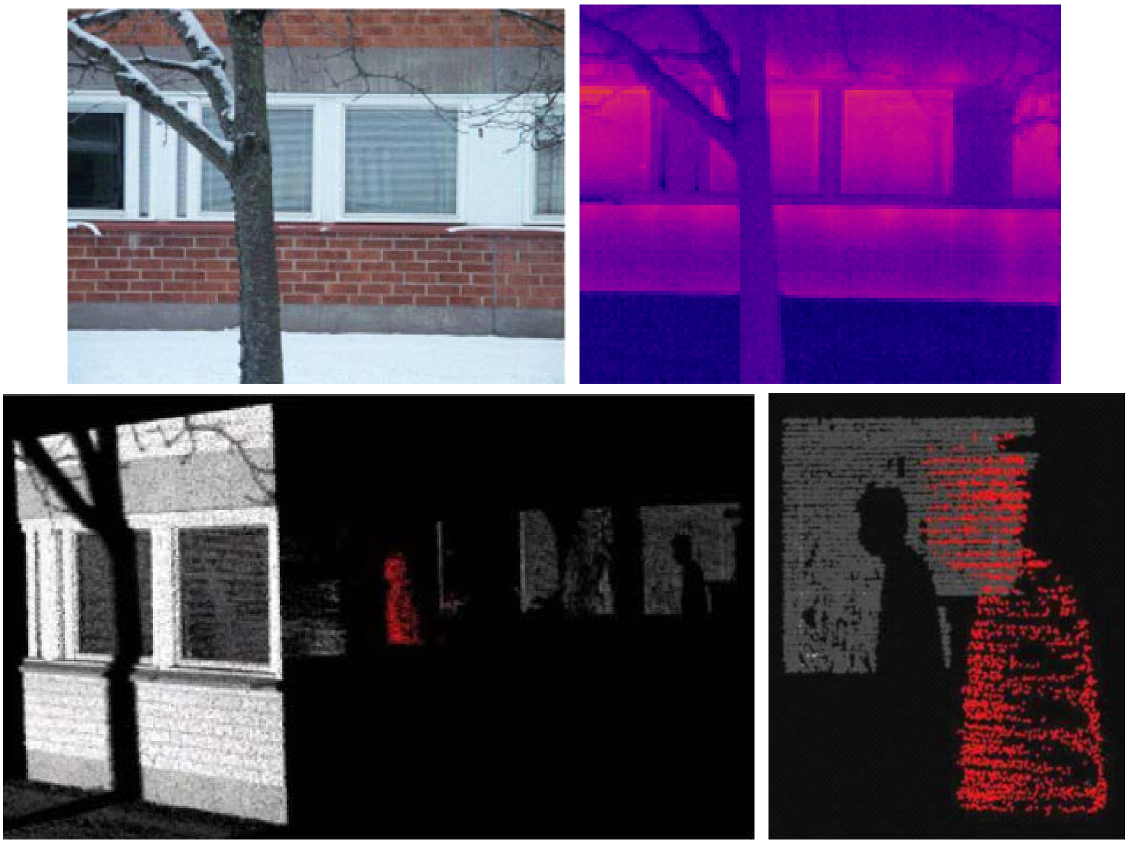

Figure 11. Top left shows a photo of a window with the Venetian blinds down (approx. 3 mm spacing), and top right shows an IR image of the same window. Bottom left shows a 3-D laser radar image (rotated 45 degrees with respect to the viewing angle) showing a man inside the room. Bottom right show a section of the3-D data point cloud (front view). The person is highlighted in red for clarity.

The ability to image objects that are partly concealed, e.g., by Venetian blinds, has been studied at FOI. Whereas thermal imagers can’t be used for imaging through windows, due to the wavelength dependent transmission of the glass, the laser radar illumination at 1.5 µm wavelength is transmitted through the window and can be used to image objects inside a building. This is illustrated in Figure 11, where a person is standing in a room with the Venetian blinds covering the window. Another example is shown in Figure 12 with an image from a flash 3-D laser radar.

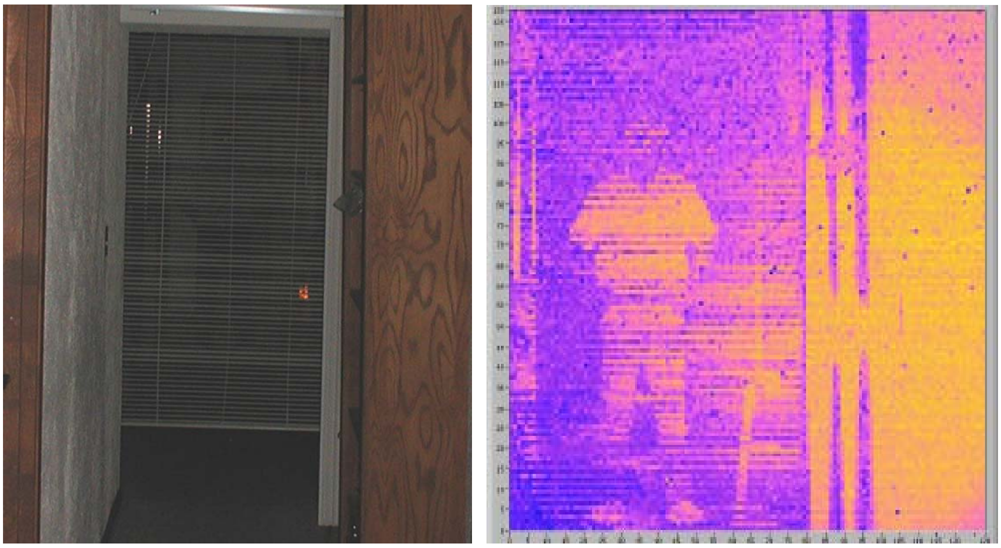

Figure 12. To the left a photograph of a scene with a man concealed behind Venetian blinds. A reflection of the camera flash can be seen in a reflector (placed on a stool next to the man). The flash 3-D laser radar image to the right reveals the man behind the blinds. (Courtesy: R. Richmond, AFRL, USA)

4.1.1 Reflection from human faces and clothes at 1.5 µm

The reflection from human faces at the eye-safe wavelength 1.5µm is obviously of interest for applications like detection of people in concealed environments and face recognition. An example from some initial experiments is shown in Figure 13 [5]. Bare skin seems to have lower reflectance than hair and clothes.

Figure 13. To the left a photograph and to the right a laser radar image (reflectance) at 1.5 µm wavelength. Note the high reflection from the clothes and hair compared with the reflection from the skin. Also note that the eyes were shut during the scan.

4.2 Urban modelling

Modelling of urban environments and specific scene elements is highly facilitated by 3-D data from a laser radar. An example of urban modelling is shown in Figure 14, which depicts the market place in "Old Linköping". The data was taken with one scan with a 3-D laser radar positioned at the centre of the market place.

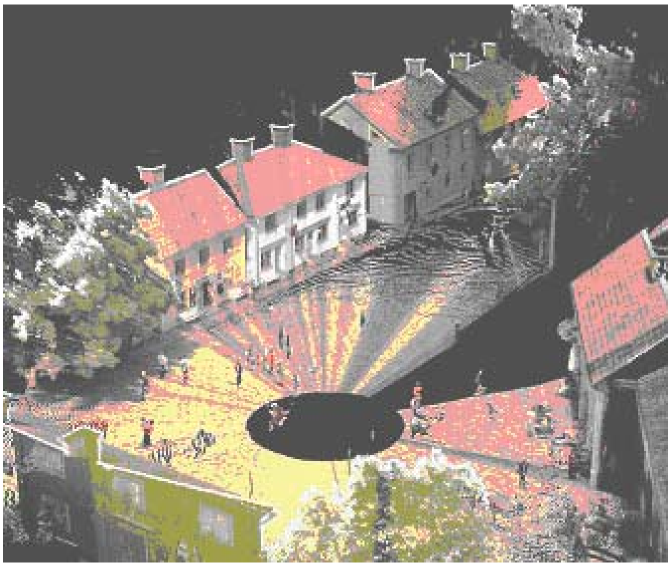

Figure 14. Data from one scan with a 3-D laser radar, showing the market place in "Old Linköping".

4.2.1 Recognition and classifications

Methods have been developed for processing airborne laser scanner data. The long term goal is to develop methods to automatically extract geographic information for supporting the construction of 3-D virtual environment models. The methods work on gridded data. First, the irregularly distributed laser points are resampled into regular grids ($0.25 \times 0.25 m^2$). Two grids are stored: one grid containing the highest elevation value in each cell (DSM_{max}) as shown in Figure 15, upper left, and one grid containing the lowest value (DSM_{min}).

The first class to be determined is the ground surface. The method to estimate the ground surface (DTM) works on DSM_{min} and is based on active contours [18]. The method is based on the theory of active shape models [19, 20]. The active contour can be seen as a net being pushed upwards from underneath the surface and attached the laser points.

The data points above the ground surface are then further classified. Classification of buildings starts by a segmentation using multiple return information. Multiple returns occur when different parts of a laser pulse "footprint" are reflected from different elevations. For example, at edges of buildings and within vegetation, the laser footprint is often split so one part is reflected from the top of the object and the other part is reflected from ground, see the middle image in Figure 15. Using this information of multiple returns, much of the vegetation can be removed or at least separated from buildings. Separate segments are defined for each group of pixels that are more than 2 meters above the ground surface. Each segment is then classified as building or non-building based on measures of curvature, maximum slope [21] and shape using an artificial neural network. Next, posts (e.g., lamp posts) are classified by detecting narrow, high objects. Remaining pixels which are more than 2 meters above the ground surface are classified as vegetation. Pixels classified as ground are further classified as "road" (roads, paths, other paved areas, etc) or "non-road" using the intensity of the returned pulses as shown in Figure 15, upper right.

The elevation data within each segment classified as buildings are used to construct 3-D models of buildings. First, planar roof faces are extracted using a clustering of surface normals. Next, topological points are inserted where each face's neighbour changes. Sections between these points separating the roof faces are defined as intersections, edges or both. In order to obtain building models with piecewise linear walls, straight lines are estimated along edge sections using the 2-D Hough transform. New points are inserted at the intersections of the estimated lines. Using this information, 3-D models of building are constructed.

Finally, single trees are extracted in the areas classified as vegetation [22]. For each extracted tree, the position, tree height and crown diameter are estimated using the elevation data and the area of the crown segment. The different layers of extracted information can be used to construct a 3-D virtual environment model as shown in Figure 16.

Figure 15. Left: Gridded height data (DSM_{max}). Middle: Multiple return image. Right: Classification results, buildings (black), vegetation (gray), roads (dark gray), posts (white).

Figure 16. 3-D virtual environment model, showing the ground surface with building and tree models.

4.2.2 Visualitation and surveillance

The availability of 3-D models of an urban area does not only allow visualisation of the modelled objects and buildings themselves but also of sensor data. This can drastically improve situation awareness in situations like surveillance, crisis management, and urban fighting situations.

The most common way of analyzing data from (multiple) surveillance cameras is basically to sit and watch the monitors. One of the problems with such an approach is that although it is easy to notice when an extraordinary event occurs, it is still difficult to perceive what is actually happening. Imagine some form of urban crisis, e.g., riots, panic, or fighting. People (and groups of people) and vehicles move into and out of the fields-of-view of the cameras. It is not an easy task for a manual operator to connect all these micro-events and see the larger picture.

A solution is to visualize the 3-D model of the area, and project the recorded video on the model. In the synthetic world, the cameras are replaced by video projectors, projecting what the cameras in the real world sees [23]. There are several advantages of this approach:

- It gives an overview of the area and shows the various camera recordings in the same view at the same time.
- It becomes obvious how the different recordings are related in time and space.
- Other sensor data, like intruder detectors, acoustic or seismic tracking and detection, can easily be integrated in the same view. For example, if a threat is detected outside the field of view of all cameras, it can still be marked in the synthetic 3-D environment and directly related to visual (model and video) data. Moreover, assume that a shooter is located using an acoustic sensor network [24], not only the shooter can immediately be marked in the 3-D model but also the entire area within his field of view, i.e., the current risk area.

4.3 Recognition

4.3.1 Recognition of humans, human activity and objects

Computer-based image processing can on a high level be divided into two groups; image enhancement and automatic analysis. The purpose of both approaches is to clarify the contents in the image(s) to support an operator. In image enhancement the over-all intensity (or range data) in the image is improved but the decisions of what parts of the image that are interesting, and what they contain, need to be made by the operator. In some cases this is a satisfactory solution. In other cases, for example when large image (or 3-D data) sets have to be analyzed in a short time frame, automation of parts of the processing can support the operator. Examples are cueing to interesting parts of the image and selection of image frames (or range frames) where interesting objects are present. Furthermore, post processing of data can support the operator in interpreting images of partly occluded objects, for example objects or humans that are located behind camouflage nets, terrain foliage, Venetian blinds or glass in buildings and vehicles.

Image enhancement of gated viewing images has been shown in [25]. In gated viewing the images are subject to noise and disturbance mainly originating from target reflections, atmospheric disturbances (turbulence, speckle noise), camera and laser performance. Further, the platform may be in motion. By tracking the translation and rotation of sharp lines and edges in the image during the turbulence and platform/camera motions, it is possible to apply temporal smoothing to reduce the effects of (random) illumination variances. Using this kind of image enhancement human activities at km-distances, e.g., people in a vehicle, can be enhanced and possible to detect and interpret by an operator, see Figure 17.

Laser illumination causes intense reflections in optics, for example in headlight reflectors and other reflective materials on vehicles. This has been used to detect vehicles hidden behind camouflage nets and terrain foliage [26]. In this work, “hot spots” originating from highly reflective areas on the target were detected using a statistical approach.

Some short range GV systems have enough resolution to resolve a human face for visual recognition. There are also biometric measures that can be used for recognition of motion patterns [25]. Biometrical measures discussed are the 15 main parts of the human body (head, neck, torso, upper arm, forearm, hand, hip, calf, foot). By tracking the body parts, and their interrelations, patterns that are specific for each individual can be extracted.

Figure 17. Image from a gated viewing system at night, showing two soldiers in the front seat of a command vehicle, both holding up their arms to cover a lamp. Notice the reflection in the headlights and the clearly visible antenna on the roof. For comparison, a similar vehicle is shown in the right photograph.

In military applications, laser radar have been used for some decades for semiautomatic or automatic detection and recognition of military targets, like vehicles, see [27] for a recent overview. Traditionally, 3-D laser radar have been used, but since a sequence of GV images can be transformed to a 3-D volume [28], some algorithms from military applications can be used for this kind of data as well.

4.3.2 3-D imaging using range gated viewing

With appropriate gate control, we can use multiple images from a gated viewing system for making a 3-D reconstruction of an imaged scene. The first algorithm for this purpose developed at FOI [29] was applied to data acquired with an experimental long-range gated viewing system at a range of 7 km from the target scene. Developments of the original algorithm have lately provided significantly increased efficiency in data collection requirements and improved range resolution. A related technique for high accuracy 3-D reconstruction at shorter ranges has recently been reported by Busck et al. [30].

4.3.2.1 Basic Principles of 3-D Reconstruction

Successively moving the gate over a scene in steps along the range axis produces an intensity variation in each individual image pixel. This intensity profile provides the basis for a 3-D reconstruction from gated viewing. In principle, we can measure the range value of an image pixel by determining at what gate range setting it lights up or turns dark as the gate range is successively shifted onto or off the target scene. Separate treatment of each pixel is necessary for accurate reconstruction, due to the non-uniform properties of the laser beam, target scene, and atmosphere when regarded over the image surface. Figure 18 shows an example of images from a sequence collected when sliding the gate over a scene containing a military vehicle.

When collecting successive images while shifting the range gate offset, the resulting pixel intensity values for any given delay time is proportional to the convolution of the camera gain and the mirrored return laser pulse shape. Hence any measured pixel intensity value will be a noisy sample from this curve. The displacement of the curve along the time axis corresponds to the range to the target, so the problem of range imaging becomes one of estimating properties of this function for every pixel from a set of noisy measurements, using signal processing methods.

Figure 18. Left: A visual photograph of the scene used for gated viewing experiments. Right: Gated viewing images, captured using four different settings of the gate delay time. This results in the laser reflections from the front, entire, back, and background of the vehicle being imaged in the four frames. The range to the target is 0.9 km and the gate width 40 ns, corresponding to a physical depth of about 6 m.

An example of a 3-D imaging result is shown in Figure 19, where the algorithm has been applied to the set of images previously presented in Figure 18. The strength of gated viewing for 3-D reconstruction compared to other present techniques is the combination of high lateral and range resolutions as well as long range capability.

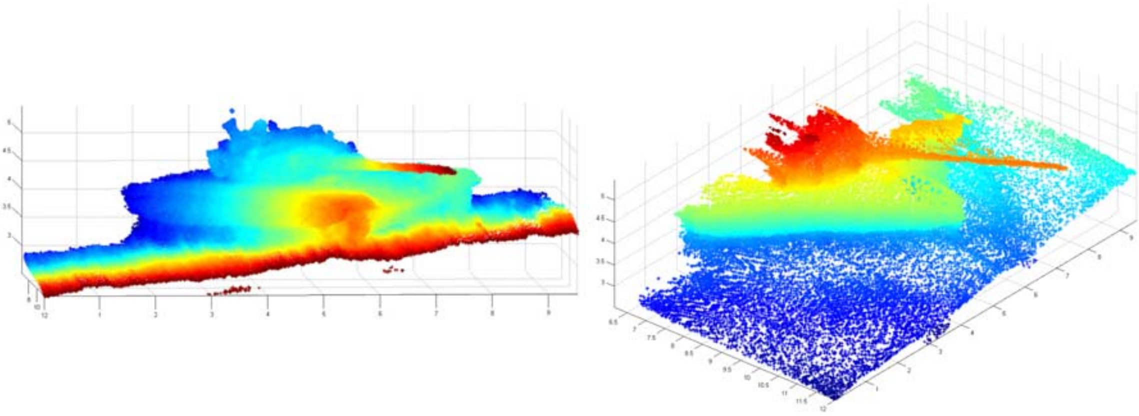

Figure 19. Two different views of a military vehicle reconstructed from gated viewing measurements. Left: Range coded colour scale as seen from the point of observation. Right: Height coded colour scale with the 3-D reconstruction rotated into a different viewing angle.

5.0 CONCLUSIONS

We have described the technology and potential use of 3-D laser radar systems. With this active sensor it is possible to accurately and remotely measure range and 3-D shape of objects, such as vehicles and humans. A full 3-D scan can be used to accurately model a scene, whether it is an urban scene, the scene of a crime, or individual objects (vehicles, people, etc.). Furthermore, with 3-D laser radar it is possible to penetrate for instance vegetation, Venetian blinds, camouflage nets, and create an image of what is behind. This illustrates the strength of the 3-D laser radar to uncover (partly) hidden objects, and to observe possible activity, e.g., through the windows of a building.

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