Laser-Radar Based Obstacle Avoidance System for Helicopters

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Abstract

Helicopters in low-level flight are endangered by power lines or telephone wires, especially when flighing at night and under poor visibility conditions. Existing night vision equipment cannot provide safe detection of these dangerous objects. From this reason there has been a widely accepted need for a reliable means of detecting such obstacles under all possible conditions for some time.

Solutions to this problem have been proposed based on millimeter wave technology and other types of active systems. As an alternative to these systems, Dornier Luftfahrt GmbH has developed a Laser Radar Sensor which has shown good capabilities to solve this task without many of the shortcomings of other radar systems.

After a short technology overview, this paper presents the operating concept of the new sensor system together with ground test results which have been achieved so far. System and integration concepts for display and warning functions are discussed which take into consideration the different requirements for various military and civil operations.

Introduction

Helicopters in low-level flight are endangered by obstacles, particularly in NOE (Nap-of-the-earth) missions. The most crtitical problem exists during night and bad weather operations with night vision equipment. The most dangerous objects under these conditions are overhead wires of all categories , which can hardly be seen with night vision goggles or FLIR sensors.

Flight safety of helicopters used for SAR (search and rescue), by police and special forces would also be increased by a reliable obstacle warning system. Requirements, however, are not exactly the same. While helicopters performing military missions have requirements for low detectability and an extrem high level of performance, the design of an obstacle avoidance system for civil use would probably be driven primarily by cost, size and weight considerations. In any case, an obstacle warning system must be able to alert the pilot in time to allow evasive maneuvers. This means,that both sensor performance and data processing must meet certain time requirements. The false alarm rate of the system must be kept as low as possible, since numerous false alarms are inacceptable. On the other hand, the system must exhibit 100% performance under all conditions under which the helicopter would be flown without an obstacle avoidance system.

Dornier suggests the usage of its proprietary Laser Radar (LADAR) technology as solution to the helicopter obstacle avoidance problem. The sensor and system concepts will be discussed, following a short overview of technology alternatives. A video tape showing some test results achieved so far is presented during the symposium.

Technologies for Obstacle Avoidance Sensors

The problem of detecting small obstacles like wires, antennas, poles etc. has been approached in the past mainly with millimeter wave radar technologies [1], [2], [3]. In the millimeter wave region of the electromagnetic spectrum back-scatter cross sections of wire-like obstacles is sufficient for detection. However, this is true only if beam propagation is nearly perpendicular to the wire [4]. In addition, wire diameter will cause variations in cross sections [4]. For obstacle location a certain minimal angular resolution is required. From the diffraction limit ($1.22 \cdot \lambda/D$ with D = aperture diameter and λ = wavelength) follows the maximum angular resolution for a given aperture at a particular wavelength (e.g.: for an aperture diameter of 0,42 m and a wavelength of 3 mm (90 GHz), an angular resolution of about $0{,}5^\circ$ can be obtained). This angular resolution is sufficient to fulfill the requirement of obstacle detection. Experimental obstacle avoidance demonstrator developments are being pursued at 94 GHz and at around 60 GHz of the millimeter wave region in the electromagnetic spectrum. Both technologies, Frequency Modulated Continuous Wave (FMCW) [4] and pulsed radars [5] are under consideration. The advantage of millimeter wave technology is its enhanced performance under poor visibility weather conditions, in particular fog. A disadvantage, on the other hand, is its poor angular resolution even at relative large apertures (i.e.: example of diffraction limit at 90 GHz shown above). Small diameter apertures and high angular resolution however are prerequisits for fast scanning obstacle avoidance sensors.

To detect all obstacles some form of field of view (FOV) scan must be performed. This scanning procedure, however it is carried out, must be such that small obstacles like thin wires are detected while maintaining sufficiently high angular resolution for obstacle location. Furthermore, this FOV scan must be repeated several times per second (depending on flight speed of the helicopter) to give sufficiently early warning of obstacles in the flight path. For large aperture systems it is difficult to perform scans with frame rates > 1 Hz. Increased weight and volume caused by large apertures are additional factors which ultimately limit the performance of millimetric wave obstacle avoidance sensor systems.

At higher frequencies of the electromagnetic spectrum (i.e.: infrared region), an increased performance can be obtained, even though performance is reduced under poor visibility conditions. In the infrared region, differing obstacle avoidance approaches are being pursued. The most promising approaches aside from mmW radar are [1]:

- Carbon dioxide laser radar
- Near-infrared laser radar
- Range-gated active television or gated viewing

With all of these system approaches obstacles can be located by range and angular coordinates. They can achieve high frame rates due to their small apertures.

CO_2 Laser Radar The CO_2 Laser radar technology has been under investigation for obstacle avoidance systems for quite a number of years, going back as far as 1969 [6]. In this spectral region (10,6 μm), most object surfaces exhibit enhanced emission and reduced reflection. Thus, to get sufficient detection probability, heterodyne or homodyne laser radar technology must be implemented. This can be achieved with continuous-wave (CW) or pulsed type technology. Both technology types have been implemented for wire detection in obstacle avoidance systems in the past (e.g.: LOWTAS [6]).

Atmospheric transmission in the 10 μm region is better than in the millimeter wave region; but in the fog attenuation will increase by almost two orders of magnitude. Good angular resolution can be achieved at 10 μm with small apertures (e.g.: for $D = 10$ cm an angular resolution of about $0{,}06^\circ$ can be obtained at 10μm). Furthermore, because of its coherence properties hetero- and homodyne technology allow velocity determination via the Doppler effect.

Near-infrared Laser Radar In this spectral region laser radar technology is quite well developed. Compared to the 10 μm region there is also enhanced reflectivity for natural objects and others. Due to the shorter wavelength cables and wire surfaces appear rough and they back-scatter not only at 90° incident, but also at oblique angles. This makes the near-infrared region ideal for wire detection.

Laser radars in the near-infrared region do not have to employ coherent detection schemes, but achieve high sensitivities with direct detection [7]. The application of this simpler detection scheme is particularly due to the availability of large gain detectors. For wavelengths ranging from 0,8 μm to about 1 μm there are also laser diodes commercially available for transmitter sources.

Analysis of this technology show that low-cost, lightweight obstacle avoidance sensors can be provided with good detection capabilities even for wet cables and wires at oblique angles [1]

Gated Viewing Range-gated television is an active range dependent imaging principle. It employs an image intensifier to detect returns from the scene which is illuminated by short light pulses from a laser or other light source. An enhanced image of the target is obtained by turning on the image intensifier just as the light pulse from the target (e.g.: cable or wire) arrives at the image intensifier. To search for obstacles, a series of light pulses has to be sent out to step through the various ranges. From the time difference between pulse transmission and reception at the image intensifier, the target range can be deduced.

Selection of Laser Radar from Operational Application

In the previous section a general discussion of technologies applicable to obstacle avoidance sensor systems was given. This discussion included physical arguments on obstacle type, clutter and obstacle reflectivities as they relate to wavelength. Image generation and aperture size, as they relate to angular resolution, have also been considered. These aspects together with technology considerations and oeprational requirements for helicopter use are the basis for developmental parameters of the following obstacle avoidance sensor concept.

By arguments of performance, state of technology, complexity, weight and cost he near-infrared laser radar, operating at 0,9 μm, presently is tthe optimal obstacle avoidance sensor for helicopter applications.

A near-infrared laser radar is selected due to the following basic operational requirements:

Operational Conditions:	Day/Night operation under all environmental conditions acceptable for low level flight
Obstacle Detection Ranges:	600 m for extended objects 400 m for single wires of 25 mm diameter 300 m for single wires of 12 mm diameter
Obstacle Conditions:	Wet, dry or snow covered
Obstacle Warning Info:	Range and direction of obstacle in field of view, presented in a manner to be determined

Basic obstacle avoidance LADAR (laser radar) developmental parameters are formulated in view of geometric and kinematic operational requirements.

The dimensions of the field of view (FOV) to be scanned are based on the requirement that all obstacles within a corridor of about three times the diameter of the rotor must be detected. This means that for a helicopter rotor of 10 m in diameter the scanned FOV should be at least 20° x 20°. Actually the FOV should be twice that size due to the fact that the direction of travel does not always coinside with the helicopter axis; it can be off by as much as 30° - 40°. Furthermore, obstacles must also be detected sufficiently early for turns to be executed.

Obstacle detection range will be defined by the helicopter speed and manoeuvres to be executed. It has been shown that for speeds up to 50 m/s there is sufficient time to execute avoidance maneuvers for obstacle detection ranges of 300 - 400 m.

Range resolution must be sufficient to detect wires which run 20 m or more in front of a row of trees. Angular resolution will be determined by the requirement that wires must be detected at a range of 450 m and heights of 7 m above the ground.

The image refreshing or frame rate is determined by the helicopter flight speed. This value depends on the questions at what rate the obstacle map should be updated. We believe no more than every 10 meters of travel. This translates into a frame rate of 5 Hz for a flight speed of 50 m/s. The selection of this frame rate guarantees a high probability of obstacle detection to provide the necessary flight safety.

Obstacle Warning LADAR (OWL)

From these operational considerations follow the basic Obstacle Warning LADAR parameters:

LADAR type:	Pulse time-of-flight 3 D imaging at $\lambda = 0{,}9\ \mu$m
FOV:	30° x 40° (vertical x horizontal)
Range image:	64 pixel horizontal 320 pixel vertical
Frame rate:	5 Hz
Range resolution:	2 m

The implementation of the Obstacle Warning LADAR with these parameters will be achieved with Dornier's proprietary ladar technology. OWL is eye safe at 0,9 μm.

In the first step of the development, a functional unit has been implemented with reduced parameters to demonstrate LADAR technology for obstacle detection (fig. 1). The basic wire detection function can be demonstrated with this unit, although at reduced range and frame rate and also with a slight reduction in the horizontal FOV (about 10°). The unit's obstacle detection capabilities, in particular of wires and cables, has been demonstrated during ground trials with the unit mounted on a moving platform, in advance to helicopter trials. Detection ranges were measured in day time with the platform stationary and moving. Range data was collected in form of digital range images, approximately one image every second. The data was displayed in real time on a monitor, by coding range on a gray and color scale. No data processing like geometric correction, filtering etc. was carried out. These so called range images represent the raw data. An example of such a range image is shown in figure 2 together with a reference photograph.

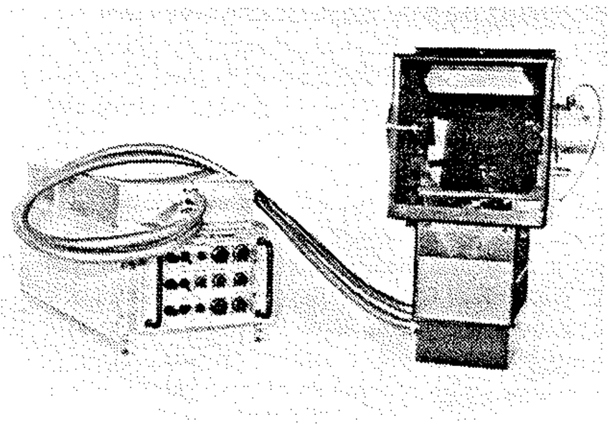


Fig. 1: Functional unit for proof of principle

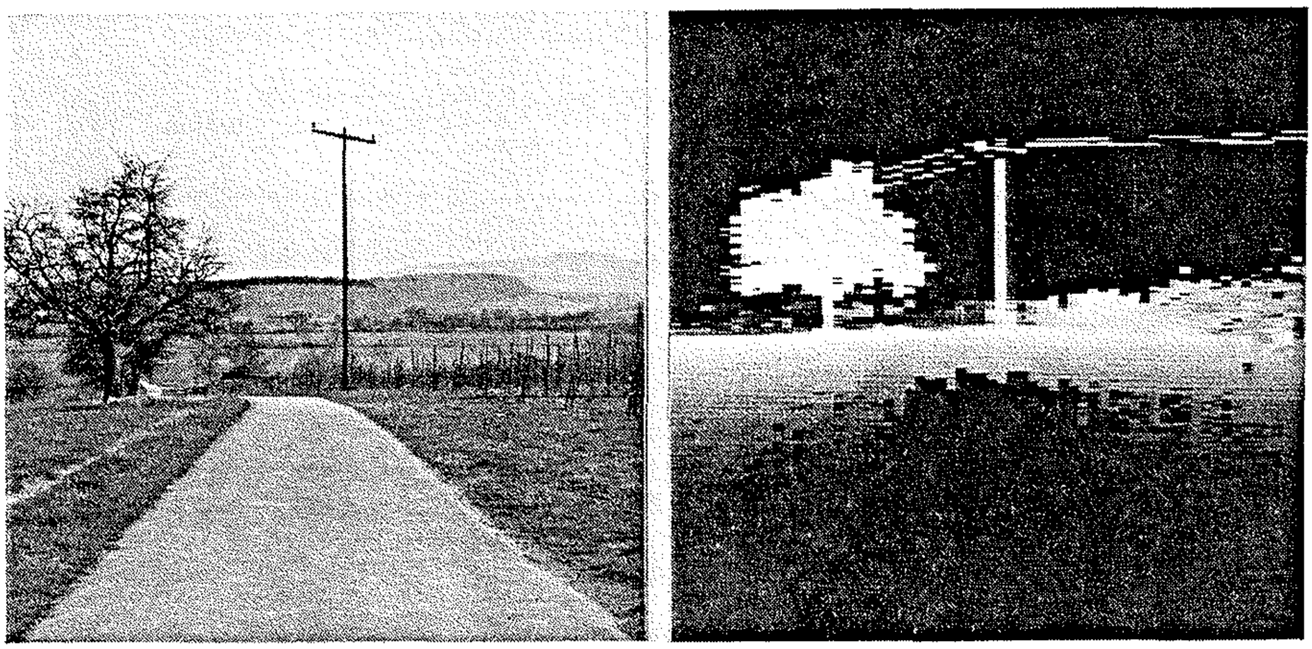
Test Results

Analysis of the functional unit ground trials yielded the following results. Detection ranges for extended objects of 240 m - 300 m, and detection ranges for wires against sky background of 100 m - 120 m, almost independent of wire diameter (i.e.: for wires of about 10mm - 25 mm diameter). No variation in the detection probabilities could be found between measurements from stationary and moving platforms. These ground trials define the operational parameters for the helicopter trials.

Real time generation of obstacle maps was also performed with this range data from ground trials. Details are described in the processing section of this paper.

Obstacle Warning LADAR Prototype

In the second step of the OWL development full scale prototype development is carried out. The specification for this prototype is obtained from the OWL parameters stated above.



Reference Photograph | Range Image

Fig. 2: Wire detection capability of the functional unit

The implementation of Dornier's proprietary ladar technology in the OWL prototype can be state briefly in term the following feature listing:

2-Axis Scan:	Line scan is performed electronically and column scan mechanically
Laser Source:	Laser diode line array in focal plane for fast line scans and high pulse repetition rates
Detector/Receiver:	Photo diode line array in focal plane with matched instantaneous FOV's, fast multiplexing and high gain photo diodes
2nd Axis Scan (Column):	Column scan is performed mechanically with oscillating mirror featuring line-of-sight (LOS) elevation adaption
Pulse Processing:	Digital pulse processing for high detection probability at low S/N (signal to noise ratio)

Most components of this prototype system have already been implemented and flight tested. The required high scanning rates, obstacle detection ranges and probabilities can be obtained with this concept and are demonstratable with the prototype. The simplicity of the OWL design is shown in fig. 3.

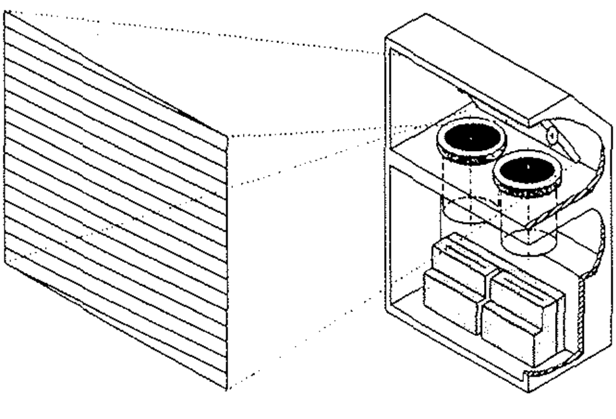


Fig. 3: OWL Prototype concept with schematic representation of FOV-scan

A very important feature inherent in the OWL concept is the achievable low weight and volume. The design goal for the weight is < 15 kg and about 27 liters for the total volume.

OWL's low weight and volume makes retrofit into already commissioned helicopters possible. An integration in the helicopter at the most effective position is feasible, with little change to the rest of the system.

The retrofit helicopter integration concept is shown in figure 4, indicating the position of the Obstacle Warning LADAR in the helicopter together with the obstacle detection configuration.

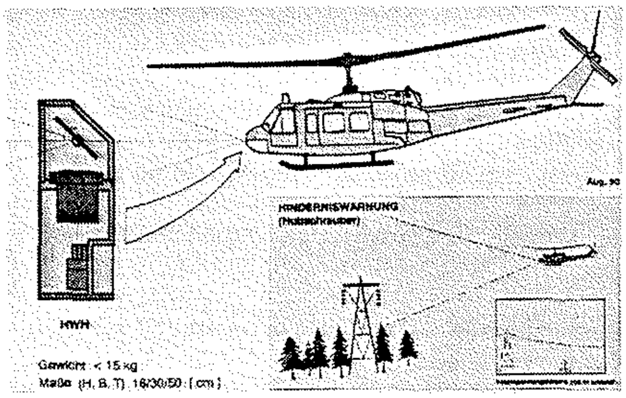


Fig. 4: OWL retrofit and obstacle detection configuration

System Concept Alternatives

A generic system structure of a laser radar based obstacle avoidance system consists of the LADAR sensor, a data processing unit together with display and acoustical/optical warning devices (fig. 5). Depending on the specific application, there exist several options in the implementation of these components.

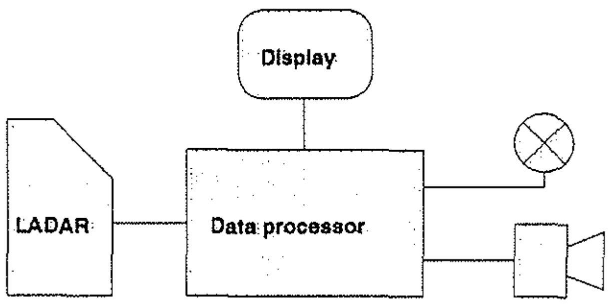


Fig. 5: Generic System Structure

System Concept Alternatives

Three different system alternatives are currently being considered:

- a low-cost system for applications like civil (SAR) helicopters, military training and transport helicopters, etc.

- a system solution for integration into existing avionics structures as a safety amendment for night and bad weather operation

- a highly integrated system for new avionics designs to support functions like semi-automatic NOE flight and intelligent ground proximity and obstacle warning.

The basic system is characterized by the following features:

- Fixed installation of the LADAR in the front section of the helicopter.

- Integrated data processing capability for obstacle detection and simple obstacle classification (Wires vs. trees and other vertical obstructions).

- Simple display showing rough direction, range and class of obstacle using a number of indicators.

- Operator's console for basic functions (On/off, initiate self test procedure) and selection of operation modes (i.e. wire alarm only, alarm on all obstacles, warning range, acoustical alarm on/off)

- acoustical alarm (buzzer)

Such a system could be available as an off-the shelf product in the mid-90s. It will be designed as a modification kit for commonly used helicopters like the BO-105.

The basic solution for military helicopters would also use a fixed-mounted LADAR, probably with a wider field of view. The operating wavelength of the LADAR would probably be shifted into the 1.5μ-region to reduce detectability and to increase detection range without sacrificing eye safety. In addition to the functions mentioned above, this system should have the capability to merge a processed range image with other sensor sight systems. By highlighting obstacles in the pilots vision system, the pilot could get better support for evasive maneuvers in critical situations.

The fully integrated system solution could become part of new battlefield helicopters like the TIGER or the COMANCHE. It provides:

- a lightweight frontend to be mounted in a turret together with other sensors, coupled to the electronics via digital links.

- a signal and data processing unit with an interface to the integrated avionics suite including displays, controls (via multi-function display/control elements) as well as vision and flight control elements.

The functions achieved by this system should include intelligent ground proximity and obstacle warning by analyzing the possible flight path. Since the LADAR produces high quality information on terrain and topography ahead of the helicopter, it can act as the primary sensor for semi-automatic NOE flight, allowing the pilot to control his flight in the xy-plane, while the system could automatically control the z-axis. The pilots action could be limited by the FCS (Flight Control System) to sectors scanned previously by the sensor.

Data Processing Basics

Introduction

It has been demonstrated that OWL is physically capable of detecting hazardous obstacles such as power lines and wires. In this section, we consider the subsequent system task of bringing the sensed obstacles to the pilot's attention.

The simplest way of doing this would be to generate a real-time display of the sensed range data, producing a gray-scaled coded range image like the one shown in figure 6. The corresponding reference scene is shown in figure 7. In the range image of a scene, the pilot will spot lines and wires more easily than with the unaided eye or with standard night vision equipment. The distance to a power line, for example, is smaller than the distance to the background; therefore, in a gray-scale representation of range, a power line contrasts clearly against the background, no matter what its individual reflectance properties are or what the existing exterior lighting conditions are.

The present concepts, however, go beyond merely displaying range images to the pilot. It is desired to aid the pilot in detecting obstacles. For this reason, automatic obstacle detection from range images will be discussed in the following section. Once obstacle detection is achieved automatically, display concepts alternative to the generation of range images may be considered (section "Display Concepts").

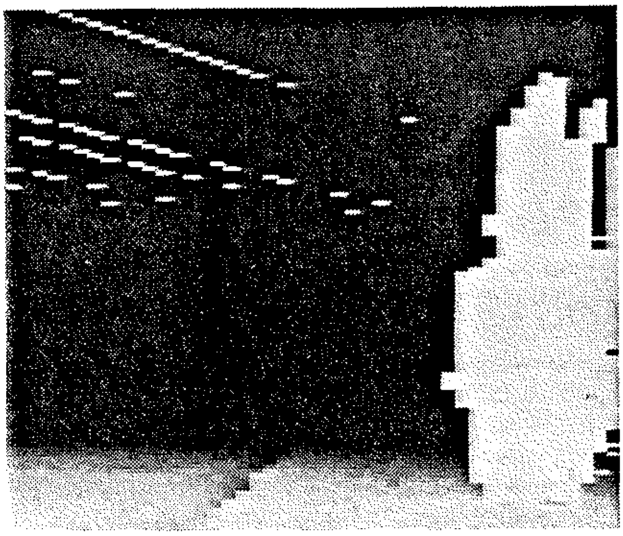


Fig. 7: Gray-scale coded range image taken with the functional laser radar described in the section "Obstacle Warning LADAR (OWL)"

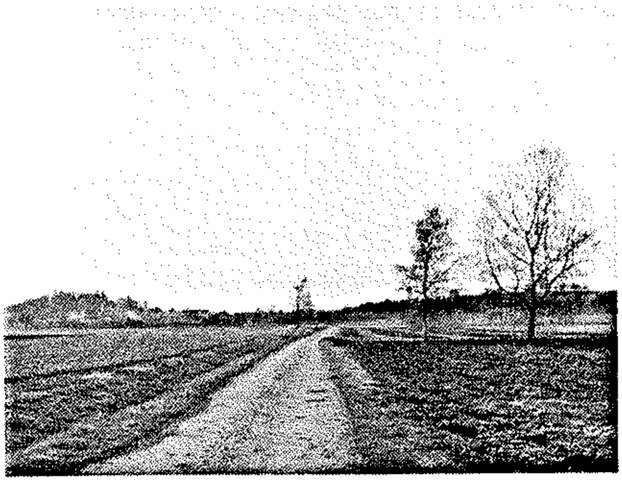


Fig. 6: Scene with power lines and trees; for reference with the range image of figure 6

Automatic Obstacle Detection from Range Images

The general scene sensed at low altitudes consists of 1) terrain and 2) various objects on or above the terrain. In this context, terrain should not be considered an obstacle; the pilot is aware that he is flying close to the ground and should not be warned of its presence. Any significantly protruding object is a potential obstacle for a low-flying helicopter. However, it must be taken into account that the pilot is aware of all massive objects and that he should therefore only be warned of certain poorly visible objects - such as lines and wires. Hence what is required presently is an algorithm which is capable of distinguishing the desired class of "thin" objects from terrain and other "massive" objects appearing in the image.

Lines and wires are uniquely characterized by their linear geometry. Digital range images are well suited to processing methods based on geometrical criteria, as range data is purely geometrical data. Hence in a range image, lines and wires are relatively simple to sample out. For this reason, range imaging is considered an appropriate technology for the selective obstacle detection required in this context.

The authors have been engaged in the development of a computer vision system for obstacle detection of a robotic vehicle [8,9]. The system consists of a 2-d imaging laser scanner (resolution 64 x 128 pixels) and an on-line processing unit incorporating three standard processors (M68020). Such hardware suffices to generate a map of obstacles from the sensor image at the frame rate of the sensor ($\approx$1 Hz). The algorithm which has been implemented in this system is described in detail in [8].

It has been verified that digital range images lend themselves to robust, fast, and relatively simple obstacle detection processing. From a range image, the 3-d geometry of the scene that has been sensed is directly obtainable. Applying geometric criteria in processing the 3-d representation of a scene quickly exposes obstacles. Another important feature of range images is the invariance property: If the geometry of a scene does not change, the corresponding digital range image remains constant, even if exterior lighting conditions, temperatures or surface reflectance properties of objects do. The intensity images obtained with video cameras or IR sensors lack this invariance property, and they are therefore more difficult to process for geometrical features.

An application of the obstacle detection algorithm for off-road vehicles to the range image of figure 6 yields the map of obstacles shown in figure 8. In a view from above, this map shows the relative position of the aircraft (represented by the small box located at the bottom of the image), the triangular field-of-view of the sensor, and the relative position of obstacles. This algorithm simply detects any strongly protruding object. The map of obstacles shows the power lines running across the scene and the couple of trees on the right. In a version of the algorithm for the helicopter application, only the power lines would be entered into the map of obstacles. The map of obstacles is considered to be just one possible display interface to the pilot.

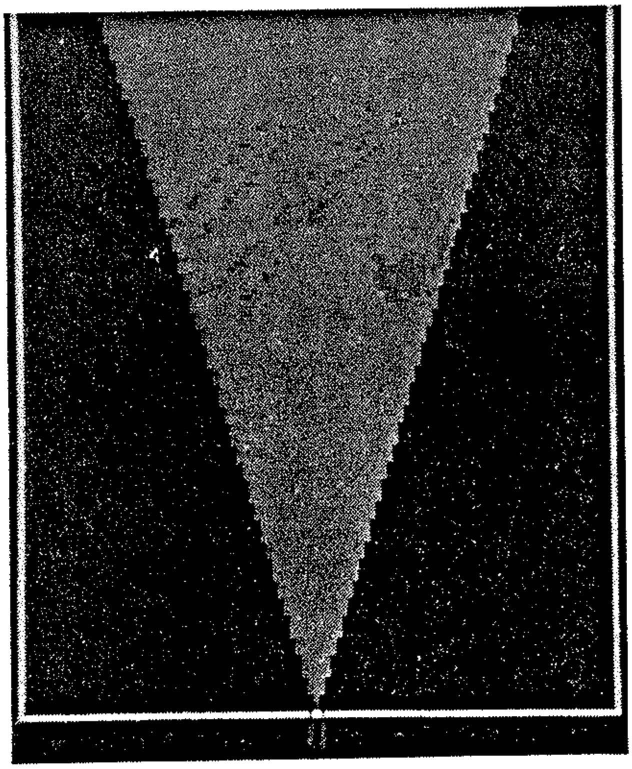


Fig. 8: Map of obstacles computed in real time from the range image of figure 6

Display Concepts

It has been said earlier that the existence of robust real-time algorithms for the detection of restricted classes of obstacles from range images will allow the development of an optimised obstacle display. Displaying the raw range image to the pilot is a display concept which is easy to realize but which may unduely increase the pilot's workload. The pilot should be warned only of obstacles he is not already aware of. The following is a list of alternative display concepts:

1. symbolic indication of obstacle size and distance
2. display of obstacles over a digital map
3. synthetic perspective display of obstacles
4. enhanced display of obstacles on a video display by colored or blinking pixels

In addition to each of these display, the sudden approach of an obstacle is brought to the pilot's attention by means of an acoustical warning. The pilot must then be able to recognize the extent and location of the obstacle as quickly as possible by glancing at one of the above displays.

Conclusion

For the safe detection of dangerous helicopter obstacles such as power lines and telephone wires, infrared laser radar (LADAR) sensors for physical reasons are superior to, commercial available, active sensors of greater wavelength. Operational requirements for an obstacle detection system for low-flying helicopters have been formulated. From these requirements, system parameters for an obstacle warning ladar (OWL) have been derived. A functional unit for the OWL development has been completed, realizing slightly reduced system parameters. Trials with this unit have proven good wire detection capabilities of laser-based Systems. An OWL prototype design has been presented. Due to the light weight and small volume of this design, it may be incorporated into different system concepts: low cost systems for military and civil helicopters as well as integrated systems for existing or new avionic designs. Finally, the range images generated by OWL can be processed for automatic obstacle detection in real time. This feature allows the design of an optimized man-machine-interface.

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