Veröffentlicht: **Internat. Conference on OPTO / IRS2 / MTT, Erfurt, 09. - 11.05.2000**

Förderung: **Dieses Projekt wurde teilweise vom BMBF unter Nr. 01IL902R/3 gefördert.**

Imaging Laser Radar for 3-D Modelling of Real World Environments

Mettenleiter, M., Härtl, F., Fröhlich, C.

Zoller + Fröhlich (Z+F) GmbH, Simoniusstr. 22, D-88239 Wangen, Germany
Phone: +49-7522-9308-0 Fax: +49-7522-9308-52 email: info@zofre.de

Langer, D.

Z+F USA, Inc., 714 Maryland Ave., #3, Pittsburgh, PA15232, USA
Phone: +1-412-363-4143 Fax: +1-412-363-4143 email: langer@zf-usa.com

Abstract

This paper reports design details and applications of the developed visual laser radar. It presents experimental results from "inspection of tunnel tubes", modeling of a "car body welding cell" and a "car body gripper" in the automotive industry. The laser radar was developed at Z+F and is designed for high performance measurements with high robustness, suited for deployment in real industrial environments. A combination with different mechanical beam deflection units results in a visual laser radar for 3-D surveying of environments.

1. Introduction

The development of special, active physical sensor systems for the direct 3D measurement of environment geometry is gaining more and more importance, as it is the basis for realizing many applications in the area of automation technology. This is especially true for applications that require an on-line acquisition of geometric environment information, such as the guidance of autonomous robot vehicles, service robots or other assistance systems. In addition to these applications, the capture of the "As-Is" state of certain Objects or complete environments ("Digital Factory") is becoming more important in order to obtain further results for the realization, planning or simulation of certain operations, based on the actual state of the environment. Examples are the inspection and modeling of environmental objects, such as tunnel tubes, buildings or facades or complete industrial plants, such as chemical processing plants, nuclear power stations or single work cells in the area of automobile manufacturing. Here, it is important to guarantee a fast registration of the environment in order to avoid a long down-time of the plant while the measurements are in progress. The basis for the realization of such tasks is an image of the environment in 3-D, which as accurately as possible reflects the "As-Built" condition of the object or environment. For an inspection or surveying of real environments and additional modeling, the sole use of 3-D geometry is sufficient in many cases. Increasing requirements for the realization of ever more complex tasks as well as human interaction during a planning, simulation, optimization or execution phase require the measurement of a multitude of physical parameters (geometry, visual image, color, etc.) and their analysis and abstraction into the relevant information. A visual laser radar is used for a non-contact and accurate survey of an area which is completely measured in three dimensions and visually imaged within a few seconds. This information forms the basis for the generation of real models of the 3-D environment.

This contribution describes the design and function of the developed visual laser radar in detail, adapted to an environmental survey at medium ranges. The system is based on the transmission of two-frequency, modulated laser light in order to determine the distance between the sensor system and an object. In contrast to other laser radars, the system introduced here is designed for highly accurate and fast measurements, guaranteeing eyesafety at the same time. Robustness as well as a high absolute and relative accuracy enable the deployment in real industrial environments. Section 2 describes the principle of measurement and two basic modules of the measurement system; the spot laser sensor and the beam deflection unit. Currently two different deflection units are used with the spot laser measurement system. A single rotating deflection mirror is used for profile measurements within long stretches of tunnel tubes. A combination of simultaneously rotating and nodding deflection mirror is used for the survey of local environments and generation of corresponding single 3-D images. Results are demonstrated from the deployment of both variations of the visual laser radar, such as "tunnel inspection", survey and generation of a 3-D model of a "welding cell" and "car body gripper" in automobile manufacturing.

2. Visual Laser Radar

The developed visual laser radar is an optical measurement system and is based on the transmission of laser light. The environment is illuminated point by point and the light scattered back from the object is detected. The laser radar consists of a one-dimensional (1D) laser measurement system in combination with a mechanical beam deflection system for spatial measurements of the environment. Both components operate independently from each other and are connected via a common control and surveillance unit. Any difference from normal operation results in an automatic shut-down of the entire system.

2.1 Spot laser measurement system

In order to cover measurements at a medium range up to 60 m and simultaneously realize an absolute accuracy within mm-range, a phase difference method is used, based on the transmission of modulated laser light. The transmitted laser light P_E is intensity modulated with a sine signal (AMCW method). The light scattered back from the object PR is detected by a photo diode. The time of flight from sensor to object and back is directly proportional to a phase shift between transmitted signal and detected back scattered light, depending on modulation frequency and object range.

However, since phase shifts can only be measured modulo 2π, it is important to consider the required unambiguous measurement range and measurement accuracy. The use of an avalanche photodiode coupled with a signal amplifier guarantees the required dynamic range of the signal (Reflectivity: $X = P_R / P_E$).

In order to achieve an extended measuring range as well as high accuracy, the transmitted signal is simultaneously intensity modulated with two different sinusoidal frequencies. The detected laser light contains the phase shifts for both modulation frequencies. The coarse channel component (LFS) is used for a coarse but unambiguous range value within the fixed maximum measuring range, whereas the fine channel component (LFS) delivers precise but ambiguous range measurements. Through frequency selective computation of the phase differences from both measurement channels, an unambiguous and precise range measurement can be obtained. Therefore the amplitude of the detected back scattered light is equivalent to the reflectivity value of the object for constant transmitter signal amplitudes.

Range and reflectance value are measured by the same receiver at the same time, so that they directly correspond to a single data point in space (pixel by pixel correspondence). The range value has a resolution of 15 bit and the reflectance value a resolution of 16 bit. Both measurement values are mostly independent from environmental influences (ambient light, etc.) due to the active illumination with laser light.

Table 1 shows an overview of currently available systems with different ambiguity intervals. Please note that by switching the measurement frequency of the coarse channel by software, one can achieve double the ambiguity interval while at the same time keeping the accuracies given by the fine channel. Thus the system LARA25200 can be operated with an ambiguity interval from 0.6 to 25.6 m and 0.6 to 13.1 m. The system LARA53500 can be operated from 0.6 to 54.1 m or 0.6 to 27.4 m. Accuracies remain the same.

Description	**LARA 25200**		**LARA 53500**	
Ambuiguity Interval: D_{max}	12,6 m	25,2 m	26,8 m	53,5 m
Range Resolution (mm/LSB)	0,38207713		0,817213123	
3σ range noise; f_s = 125kHz				
X = 95% at distance D	3 mm (D = 13m)		14 mm (D = 35m)	
X = 20% at distance D	8 mm (D = 13m)		36 mm (D = 35m)	
Linearity Error	< 3 mm		< 5 mm	
Laser Power P_E (CW)	13 mW		30 mW	
Modulation Frequency (HFS/LFS)	96 / 12 MHz	96 / 6 MHz	44,8 / 5,4 MHz	44,8 / 2,7 MHz
Data Sampling Rate (Points per Sec.)	≤ 625.000		≤ 500.000	

Tab. 1: Specifications of spot laser system

Thus the basic module for measurement of natural surfaces, from highly reflective to highly absorbing, has been implemented with the developed laser measurement system. It is suitable for industrial applications, where an accurate and fast registration of geometry and simultaneous visual imaging of objects is required.

An integration of the spot laser measurement system with different mechanical beam deflection units opens additional application areas, since only then a spatial survey of an extended scene in the environment can be achieved. Following, two currently implemented deflection units are described in more detail.

2.2. Beam Deflection Units

A spatial registration of an extended section of the environment (tunnel measurements, etc.) is realized by a 360° profile measurement while driving through the environment. Helix-shaped profiles are stacked to form an image. This method of registration has been proven to be better suited for a very large spatial coverage of an environment as compared to merging several single images. Local sections of the environment, however, can be easily surveyed by the combination of the spot laser measurement system with a 2-D beam deflection unit. Both systems are described in more detail as follows.

2.2.1 Profiling System

A 360° profile measurement is implemented through the combination of the spot laser measurement system with a one dimensional deflection unit. The rotation of the deflection mirror about the optical axis of the laser measurement system results in a 360° profile measurement. The revolutions of the mirror are set to 200rps, so that up to 200 profiles per second can be measured. Each of these 360° profiles consists of up to 3125 data points (range and reflectance), corresponding to a data sample rate of maximally 625 kHz of the laser measurement system. The achieved angular accuracy is directly based on the encoder fixed to the deflection mirror and is currently given by 0.02°. A large spatial coverage of an extended section of the environment (tunnel survey, etc.) is implemented by measurement of profiles perpendicular to the direction of motion, while driving through the environment. Spatially successive profiles (Helix) are stacked to form an image, where the lateral distance between two profiles can be varied depending on the speed of the carrier vehicle.

The range images obtained in this way show the geometric relationship between objects in the environment, whereas the reflectance images are used for identification and extraction of objects, visual inspection and also classification of object surface and documentation. Reflectance images are similar to video images, except that they are independent of ambient lighting conditions.

2.2.2. Imaging System

In order to implement a survey of a local 3-D section of the environment, a 2-D deflection unit is combined with the spot laser measurement system (Figure 2). The deflection unit enables imaging of 360° in azimuth (horizontally) and 60° in elevation (vertically). The deflection of the laser beam is achieved by a single rotating (azimuth deflection) and simultaneously nodding mirror (elevation deflection). The nodding rate and rotational speed of the mirror are set such that the range and reflectance image are measured in approximately 80 seconds. Both images consist respectively of 1400 rows (elevation) with 8000 data points (azimuth) per row. They correspond pixel by pixel. The achieved angular accuracy for this deflection unit after calibration is approximately 0.05 degrees (azimuth and elevation).

3. Applications

The unique characteristics of the laser radar support a large variety of different application areas. Next to the classic guidance of autonomous transport systems and service robots for the execution of locomotion and manipulation tasks, both variations of the visual laser radar are deployed in following applications:

3.1 Profiling Laser Radar

Several railway and road tunnels have been surveyed with a profiling laser radar (LARA25200, configured with 12.6 m). Here, the laser radar is mounted on a carrier vehicle, which moves with a speed of up to 30 km/h through the tunnel.

Figure 1 Subway tunnel in New York, USA

Figure 1 shows the result obtained from the survey of a subway tunnel in New York City. The subway tunnel has a width of 4.5 m and a height of 4 m and was surveyed longitudinally with the system (v = 15km/h). The laser radar was mounted in the middle of the carrier vehicle at a height of approximately 2.5 m above the ground. The single profiles measured in this way are stacked to form an image. The result of the tunnel tube survey is displayed in Figure 5 for a section (approx. 25 m) of the entire tunnel. The image clearly shows the rectangular cross-section of the tunnel tube with all the details on the walls (cables, holders, etc.), the rails and both footpaths to the left and right of the railroad. The obtained accuracies corresponds to the given accuracies for the spot laser system (refer Tab 1).

The digitized geometry of the tunnel tube is the basis for checking the free space profile of trains and cargos. Here, a specific profile size is checked for the entire tunnel, where narrow or potential collision areas are marked on a map. Using the available visual information, additional areas on the tunnel walls can be detected that show an especially high reflectivity. These are damaged areas on the tunnel walls, where water entered and resulted in a deposit of limestone. he result of the survey and post-processing of the data results in a map of the tunnel tube containing all geometric details. Furthermore, all potential narrow regions (below a given free space threshold) and damages on the tunnel walls (fissures, etc.) are localized. An inspection of the entire tunnel tube is thus completed successfully.

3.2 Imaging Laser Radar

An important application area of the visual laser radar is the generation of "as-built" 3-D models of industrial manufacturing environments. Current state of the art are models of manufacturing shops with production facilities from construction plans. Since these CAD models usually do not correspond with the real environment (changes in the environment, missing details, etc.), an accurate model corresponding to the actual environment needs to be generated for planing and optimization of certain tasks. Such models are generated by surveying the environment with the visual laser radar and further model generation using the software package "Light Form Modeler".

Following, results from three different application examples of the imaging laser radar (LARA25200 and LARA53500) are shown. Here, a survey with additional model generation was performed for a "welding cell" and "car body gripper" in an automobile manufacturing plant (high degree of dirt, partially metallic surfaces). The obtained "as-built" 3-D CAD models are presented.

Automobile Manufacturing Plant:

The "welding cell" and the "car body gripper" were surveyed with a LARA25200 (12.6 m) from several different viewpoints. The obtained images were then merged and used to generate 3-D models. The work cell shown in Figure 2 is used for spot welding a car body. On the left and right side of the images, you can recognize the pedestals for mounting the welding robots (cylinders on platform). The robots themselves were not modeled as they can be imported from a CAD library of the robot manufacturer. The pedestals were modeled in order to fix the exact position of the robots within the work cell. Similarly, the location of the welding tool tongs on the end-effectors is important and thus has been modeled as well. They appear in the background as if suspended in mid-air, since the accompanying robots are missing. By positioning the robot model, taken from the CAD library of the manufacturer, onto the pedestal and connecting the robot arm to its end-effector (welding tool), a complete model of the robot in its reference position can be generated. The blocks on the side of the cell contain the control electronics for the machinery. The conveyor belt for transporting car bodies between work cells has also been modeled only in parts, as the remainder (mostly moving parts) can be imported from libraries. All objects were modeled from measurement data of the visual laser radar and can be well recognized.

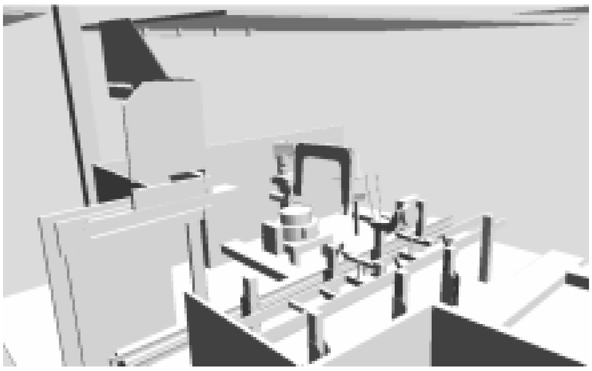

Figure 2: View of a "welding cell", including welding robots

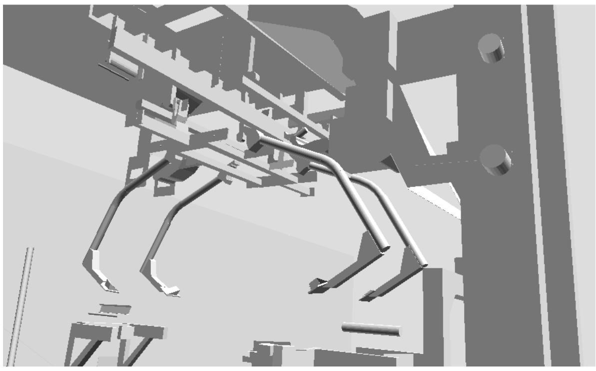

Figure 3: Model of a "car body gripper"

Figure 3 shows the 3-D model of a car body gripper. The tongs grab the inside of the car body and move it along. The structure then glides on rollers on a rail suspended from the ceiling. A small section of this guiding rail and a support column were modeled. The car body will be placed on the partially modeled support structure and lifted from there again. Walls and floor are just modeled as simple planes since the user is only interested in the free space within this cell.

With the help of geometric models like these and a CAD library of known parts and machines, entire production runs can be simulated and optimized.

4. Summary and Outlook

With the developed visual laser radar, an active measurement system is available that is suitable for industrial surveying tasks. The two beam deflection units that were introduced cover a large area of possible applications in a real environment. The deciding advantages of the developed laser radar compared to other systems can be summarized as follows:

- Acquisition of pixel by pixel corresponding range and reflectance images, without the use of artificial markers.
- High measurement data rate (up to 625,000 pixels per second)
- Absolute and relative accuracies in the mm-range within an unambiguous maximum range up to 53.4 metres.
- Very high resolution images (8,000 x 1,400 pixels, i.e. 11.2E6. pixels for a 360° x 70° image)

The developed laser radar offers high accuracy measurements in conjunction with a high sampling rate and large dynamic range in reflective properties of object surfaces (highly reflective to absorbing). It is currently available with two different ambiguity intervals. The obtained measurement results across the entire measuring range are currently unique among all known optical distance measuring systems. The technical specifications in conjunction with the attained robustness fulfill the requirements for deployment in industrial environments, for interior as well as exterior applications. This has been demonstrated by the described deployments of the system for "tunnel inspection", survey of a "welding cell" and "car body gripper". Due to the high sampling rate and corresponding high spatial resolution, the visual laser radar can be deployed during normal production runs in a manufacturing facility without interruption of the production process. Thus an additional spectrum of possible application areas is given by for e.g. inspection, reverse engineering, documentation or mapping. For VR-applications (movies etc.), the generated CAD models are post-processed in order to apply realistic or virtual surfaces to the objects. Using appropriate software, the objects are first transformed into polygonal surfaces with applied shadow and lighting effects for a 3D impression ("rendering"). For an even more realistic impression, the objects are then texture-mapped using digital color pictures or fake textures from special libraries. Finally, ambient lighting conditions and mirror effects can be simulated by applying a raytracing process, where the course of single lightrays in the image is recomputed.

Acknowledgements

Thanks to all involved companies, but especially the ground work by the "Lehrstuhl für Steuerungs- und Regelungstechnik der TU München, Prof. Dr.-Ing. Dr.-Ing. E.h. G. Schmidt", an international cooperation evolved which enabled a general application in the area of "virtual engineering – from survey to simulation".

References

[1] Besl, P.; McKay, N.D.: “A method for registration of 3D shapes“, IEEE Pattern Analysis and Machine Intelligence PAMI 14, (1992).

[2] Bishop, J. R. "Intelligent Travel: The Automated Highway System." Proceedings of the International Conference on Intelligent Autonomous Systems (IAS-3), 1993.

[3] Hancock, J. High-Speed Obstacle Detection for Automated Highway Applications. Thesis proposal. Carnegie Mellon Tech. Report, CMU-RI-TR-97-17, (1997).

[4] Hebert, M. and E. Krotkov. "3D Measurements from Imaging Laser Radars: How Good Are They?" Image and Vision Computing, vol. 10, no. 3, (1992).

[5] Schmidt, G.: "Towards Integration of Autonomous Subsystems for Assembly and Mobility into Flexible Manufacturing". Proc. of Internat. Workshop on Information Processing in Autonomous Mobile Robots, München, (1991), pp. 3 - 20

[6] Langer, D.; Hancock, J.; Martial Hebert, M.; Hoffmann, E.; Mettenleiter, M.; Froehlich, C.: “Active Laser Radar for High-performance measurements“. IEEE Robotics and Automation, ICRA Leuven, May 16-21, (1998)