1. Introduction

Active sensor systems which can directly measure 3-D environmental geometry are becoming widely accepted across a broad range of industries. They have become the basis for realizing many applications in the area of robotic automation technology. This is especially true for applications that require online acquisition of geometric environment information, such as the guidance of autonomous robot vehicles (Hancock, 1997; Schmidt, 1991; Langer et al., 1994; Fröhlich and Schmidt, 1991), service robots (Schmidt, 1991; Präfler et al., 1998; Schraft, 1994) or other assistance systems. In addition to these applications, the capture of the “as-is” state of certain objects (Dalton, 1998) or complete environments (“digital factory”) (Mettenleiter et al., 1997; Langer et al., 1998; Bailey and Fröhlich, 1999) 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 modelling of environmental objects, such as tunnel tubes, buildings or façades or complete industrial plants; chemical process plants; nuclear power stations or single work cells in the area of automobile manufacturing. Here, it is important to guarantee a fast capture of the environment in order to avoid lengthy down-times of the plant while the measurements are in progress. The basis for 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 the inspection or survey of most environments, the 3-D geometry is a sufficient basis from which to construct a realistic and representative 3-D CAD model. Conversion of laser derived point data into CAD models is performed with Light Form Modeller (LFM)[1] which has been developed by UK Robotics to work in conjunction with the Z+F laser system[2]. Requirements for the realization of ever more complex tasks as well as human interaction during a planning, simulation, optimization or execution phase may also require the measurement of a multitude of other physical parameters (visual image, colour, temperature, etc.) and their analysis and abstraction into the relevant information. The 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 paper describes the design and function of the visual laser radar in detail, adapted to perform environmental surveys at medium ranges (< 60 meters). 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 radar systems, the system introduced here is designed for highly accurate and fast measurements, guaranteeing eye safety at the same time. Robustness as well as a high absolute and relative accuracy enables the deployment into 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 a 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 and a model of a “chemical processing plant”. The contribution closes with an evaluation of the results and an outlook on future deployments of the visual laser radar in the area of virtual reality (VR) applications.

2. Visual laser radar

The 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 (1-D) 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 60m 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 PE (780nm) is intensity modulated with a sine signal. The light scattered back from the object PR is detected by a photodiode. 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 of sine signals are only ambiguous up to a maximum phase shift of $2\pi(360^\circ)$, 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: $X = P_R/P_E$) for measured objects from $X = 5$ per cent . . . 99 per cent across the entire measuring range.

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 (Figure 1). The detected laser light contains the phase shifts for both modulation frequencies. The coarse channel component (low frequency signal “LFS”) is used for a coarse but unambiguous range value within the fixed maximum measuring range, whereas the fine channel component (high frequency signal “HFS”) 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. Attenuation due to object range is proportional to $1/D^2$.

Range and reflectance values 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 I 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 accuracy given by the fine channel. Thus the system LARA25200 can be operated with an ambiguity interval from 0.6 to 25.6m and 0.6 to 13.1m. The system LARA53500 can be operated from 0.6 to 54.1m or 0.6 to 27.4m. Accuracy remains the same.

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 are required.

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

The short time of flight of the emitted laser beam to the object and back to the detector in combination with a comparatively slow mechanical scanner prevents cross-overs from previous measured directions to the actual one. Therefore, the actual measurement is not effected by the reflected beam caused by multiple reflections from a distant object back at the same time as from the actual one.

In the following sections 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 (Fröhlich et al., 1994), 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 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 (Figure 2). 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

<table>
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<td>Range resolution (mm/LSB)</td>
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Imaging laser radar for 3-D modelling of real world environments  
C. Fröhlich, M. Mettenleiter, F. Härzl, G. Dalton and D. Hines  
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profiles per second can be measured. Each of these 360° profiles consists of up to 3,125 data points (range and reflectance), corresponding to a data sample rate of maximally 625kHz 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.

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 3). 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 1,400 rows (elevation) with 8,000 data points (azimuth) per row. They correspond pixel by pixel. The achieved angular accuracy for this deflection unit after calibration is approximately 0.05° (azimuth and elevation).

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.

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 (Hancock, 1997; Schmidt, 1991; Fröhlich and Schmidt, 1991; Fröhlich, 1996) and service robots (Praßler et al., 1998; Schraft, 1994) for the execution of locomotion and manipulation tasks, both variations of the visual laser radar are deployed in the following applications:

- Survey and documentation of building façades and historic monuments for preservation purposes and long-term surveillance of endangered objects.
- Inspection of dangerous areas which are off-limits to humans (nuclear power stations (Dalton, 1998; Bailey and Fröhlich, 1999), contaminated environments, etc.).
- Inspection of tubes (tunnels (Fröhlich et al., 1994), channels, sewers, etc.).
- Survey and modelling (CAD model) of miscellaneous objects such as machine
parts, production facilities (Dalton et al., 1997), industrial plants (Bailey and Fröhlich, 1999), airplanes, ship plates.

• VR applications in the area of movies, planning of interior building design up to the virtual visit of museums, etc., via the Internet.

The following results which were obtained are discussed for three different applications. Different techniques are used for the visualization of the results:

1) Display of reflectance images. Reflectance images are always displayed as grey-level images, where dark areas (low reflectivity $X = 0$ per cent ... 2 per cent) appear as black and light areas (high reflectivity $X < 99$ per cent) appear as white. This type of gray-level coding is very familiar to the human eye and enables a direct evaluation of the measurement results without any further processing.

2) Display of range images. A range image can also be displayed as a grey-level image, where each range value is assigned to a corresponding grey-level; objects at close distance appear dark and those at large distance appear white. Mostly, however, range images are displayed as a 3-D animation within a Cartesian space. The necessary coordinate transformation (Fröhlich, 1996) is performed according to an internal sensor model.

3) Display of both images superimposed. A superimposition of reflectance and range image is especially suited for display purposes as it conveys a spatial impression as in reality. This display results from a 3-D animation, where each data point is transformed into cartesian coordinates and then imaged with a grey-level value corresponding to its reflectivity.

Only 256 grey-levels are available for visualization of the data as a grey-level image. In order to visualize the dynamic range of the measurement system (16-bit reflectance and 15-bit range) only the relevant section of the image is imaged on to the entire grey-level map. This range is freely configurable.

3.1 Profiling laser radar
Several railway and road tunnels have been surveyed with a profiling laser radar (LARA25200, configured with $D_{\text{max}} = 12.6$m). Here, the laser radar is mounted on a carrier vehicle, which moves with a speed of up to 30km/h through the tunnel tubes.

Figure 4 shows the result obtained from the survey of a subway tunnel in London. The subway tunnel has a width of 4.5m and a height of 4m and was surveyed longitudinally with the system ($v = 15$km/h). The laser radar was mounted in the middle of the carrier vehicle at a height of approximately 2.5m 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 4 for a section (approximately 25m) 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 accuracy with respect to the geometric imaging of all objects in the tunnel corresponds to the given accuracy for the spot laser system (refer to Table I).

The digitized geometry of the tunnel tube is the basis for checking the free space profile of trains and cargoes. Here, a specific desired 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.

The 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. Currently 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 planning 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 Modeller” (Dalton, 1998; Dalton et al., 1997; Bailey and Fröhlich, 1999).

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) and a model of a “chemical processing plant” (thin pipes, vessels, metallic surfaces mostly covered by patina). The obtained “as-built” 3-D CAD models are presented as a result.

3.2.1 Automobile manufacturing plant

The “welding cell” and the “car body gripper” were surveyed with a LARA25200 ($D_{max} = 12.6m$) from several different viewpoints. The obtained images were then merged and used to generate 3-D models. The work cell shown in Figures 5 and 6 is used for spot welding a car body. On the left-hand and right-hand side of the images, you can recognize the pedestals for mounting the welding robots (cylinders on platform). The robots themselves were not modelled as they can be imported from a CAD library of the robot manufacturer. The CAD robot model supplied by the robot manufacturer also contains the complete kinematics of the robot, which cannot be captured by the laser radar. If necessary, though, the robot could also be modelled from the measurement data. The robot was positioned into its reference position before the start of the measurements. However, the pedestals were modelled 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 modelled 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, on to 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 modelled from measurement data of the visual laser radar and can be well recognized in Figure 6.

Figure 7 shows the 3-D model of a car body gripper. The tongs grab the inside of the car body and move it along. The entire structure then glides on rollers on a rail suspended from the ceiling. A small section of this guiding rail and a support column were modelled. The car body will be placed on the partially modeled support structure and lifted from there again. Walls and floor are just modelled 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. For this purpose, the software package “RobCad” from Tecnomatix is used which already contains a direct interface for importing these data.

Model of a chemical processing plant. The following chemical processing plant (“NSQ model”) was surveyed with a LARA25200 and then modelled in 3-D. The images show the result from the modelling based on the laser radar images. Different scans were surveyed from multiple viewpoints in order to acquire all details and remove shadow effects and other effects due to cross-overs from many pipelines. The individual images then were matched based on the same objects which were registered in single images. The resulting accuracy corresponds to those of the spot laser measurement system and the accuracy of the deflection system combined. The resulting as-build model depends on the details which are modelled and also depends on the capability of the software for measurements and modelling. In the resulting NSQ model, all pipelines and cross-connections between different parts of the model are completely modelled due to as-build dimensions. Some standardized objects, like intersections and vessels could also be imported from a library of predefined objects, if as-build details are not required in the model for these objects.

The generated CAD data are given as a wire-frame model and shown here as coloured surfaces for better visualization. Figure 8 shows the resulting model. Walls, floor and ceiling of the room are not displayed in the model. The cut ends of pipelines, however, show the breaks through the walls to the next.

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 (Hebert and Krotkov, 1992; Kweon et al., 1991; Environmental Research Institute, 1987; Schroeder et al., 1997) can be summarized as follows:

(1) Acquisition of pixel by pixel corresponding range and reflectance images, without the use of artificial markers.

(2) High measurement data rate (up to 625,000 pixels per second).
(3) Absolute and relative accuracy in the mm-range within an unambiguous maximum range up to 53.5m.

(4) Very high resolution images (8,000 × 1,400 pixels, i.e. 11.2E6 pixels for a 360° × 70° image).

(5) Cost savings for surveys due to a reduction of:
   - surveying time on location;
   - number of images required, as a continuous data acquisition in a horizontal direction is available within one image;
   - number of images required, as no detailed images are necessary (accuracy is maintained across the entire measuring range).

(6) Cost savings when modelling by automatic generation of CAD models offline at the office (all objects are covered in detail by the survey).

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 (Hebert and Krotkov, 1992; Kweon et al., 1991; Environmental Research Institute, 1987; Schroeder et al., 1997). 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”, as well as a “chemical processing plant”. Owing 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 example, 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 3-D impression (“rendering”). For an even more realistic impression, the objects are then texture-mapped using digital colour pictures or fake textures from special libraries. Finally, ambient lighting conditions and mirror effects can be simulated by applying a ray-tracing process, where the course of single light-rays in the image is recomputed. The current research focus at Z+F is in the area of VR applications of the visual laser radar as well as the development of a semi-automatic generation of CAD models from range and reflectance images.

Notes

1 The company UK Robotics, England (Dalton et al., 1997; Fröhlich and Schmidt, 1991), specifically developed the software “Light Form Modeller” for this type of visual laser radar, which realizes the generation of 3-D models from the measurement results given by range and reflectance images. A simulation is also supported on the basis of these generated “as-built” CAD models. For this application, specific interfaces were developed to directly import the models into the simulation software “RobCad” from Tecnomatix, Israel.

2 The implementation of the visual laser radar demonstrates an impressive system from theory up to a ready industrial high technology product. The two beam deflection units were designed and realized for industrial applications in close cooperation with two companies as well as Carnegie Mellon University (Hancock, 1997; Schroeder et al., 1997; Mettenleiter et al., 1997) and K2T, USA. The further developed visual laser radar from Z+F was awarded the “Dr Rudolf-Eberle Preis “Innovationen in Baden-Württemberg” in December 1998.

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