NEW APPLICATIONS WITH LIGHTWEIGHT 3D SENSORS

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Introduction

Applications for mobile robots or for sensors of mobile robots depend on several criteria, e.g., the price, the performance, the weight, or the size of the sensors and robots. Nowadays, 2D Laser scanners, e.g., Sick scanners, are very popular as robotic sensors because of their precision and wide scanning range. A few groups built 3D scanners on the base of such 2D laser scanners [1], [2], [3]. The main problems with these 3D scanners are their size and weight, e.g., the 3D scanner built by Fraunhofer AIS has a height of 25 cm and a weight of 7.5 kg. These sensors are oversized and too heavy for applications like sewer inspection or the inspection of small holes. Recently, Hokuyo offers a light 2D laser scanner (URG-X002), which comes to be very popular. Based on the Hokuyo scanner, AIS has built a lightweight 3D scanner for new applications of mobile robots. Furthermore, CSEM and PMD build 3D time-of-light cameras [7], [8], [9], [10]. We show, how such small and lightweight 3D sensors can be used for the inspection of pipes, holes and environments.

State of the art of 3D-sensors and environmental mapping with robots

The robotic mapping problem is that of acquiring a spatial model of a robot's environment. If the robot poses were known, all local sensor inputs of the robot, i.e., local maps, could be registered into a common coordinate system to create a map. Unfortunately, any mobile robot's self localization suffers from imprecision and therefore the structure of the local maps, e.g., of single scans, needs to be used to create a precise global map. Finally, robot poses in natural outdoor environments involve yaw, pitch, roll angles and elevation, turning pose estimation as well as scan registration into a problem in six mathematical dimensions. In previous works we already presented partially our 6D SLAM algorithm [14], [15], [16]. In [14] we use a global relaxation scan matching algorithm to create a model of an abandoned mine and in [16] we presented our first 3D model containing a closed loop. The measurements were made with a 3D scanner based on a heavy 2D Sick laser range finder (LMS 200, 4.5 kg).

Instead of using 3D scanners, which yield consistent 3D scans in the first place, some groups have attempted to build 3D volumetric representations of environments with 2D laser range finders. Thrun et al. [17], Früh et al. [18] and Zhao et al. [20] use two 2D laser scanners for acquiring 3D data. One laser scanner is mounted horizontally, the other vertically. The latter one grabs a vertical scan line, which is transformed into 3D points based on the current robot pose. Since the vertical scanner is not able to scan sides of objects, Zhao et al. use two additional, vertically mounted 2D scanners, shifted by 45°, to reduce occlusions [20]. The horizontal scanner is used to compute the robot pose. The precision of 3D data points depends on that pose and on the precision of the scanner.

A few other groups use highly accurate, expensive 3D laser scanners [21][22][23]. The RESOLV project aimed at modeling interiors for virtual reality and tele-presence [23]. They used a RIEGL laser range finder on robots and the ICP algorithm for scan matching. The AVENUE project develops a robot for modeling urban environments [21], using a CYRAX scanner and a feature-based scan matching approach for registering the 3D scans. Nevertheless, in their recent work they do not use data of the laser scanner in the robot control architecture for localization [22]. The group of M. Hebert has reconstructed environments using the Zoller+Fröhlich laser scanner and aims to build 3D models without initial position estimates, i.e., without odometry information [24]. Recently, different groups employ rotating SICK scanners for acquiring 3D data [25], [26]. Wulf et al. let the scanner rotate around the vertical axis. They acquire 3D data while moving, thus the quality of the resulting map crucially depends on the pose estimate that is given by inertial sensors, e.g., gyros [26]. In addition, their SLAM algorithms do not consider all six degrees of freedom.

Other approaches use information of CCD-cameras that provide a view of the robot's environment [27], [29]. Nevertheless, cameras are difficult to use in natural environments with changing light conditions. Camera-based approaches to 3D robot vision, e.g., stereo cameras and structure from motion, have difficulties providing reliable navigation and mapping information for a mobile robot in real-time. Thus some groups try to solve 3D modeling by using a planar scanner based SLAM method and cameras, e.g., in [27]. Weingarten et al. presented first approaches in robot navigation with an evaluation prototype of a Swiss Ranger SR-2 in [30]. It could be shown, that obstacle avoidance with the Swiss Ranger has a lot of advantages in contrast to use a 2D laser scanner, which cannot detect any obstacles that lie not at the same height as the scanning plane. They also pointed out, that camera calibration and preprocessing were necessary to get stable sensor information due to noise and inaccuracy. Gut focused on surveying and mapping tasks, where high precision is required [11]. He uncovered several erroneous effects based on environmental or sensorial influences.

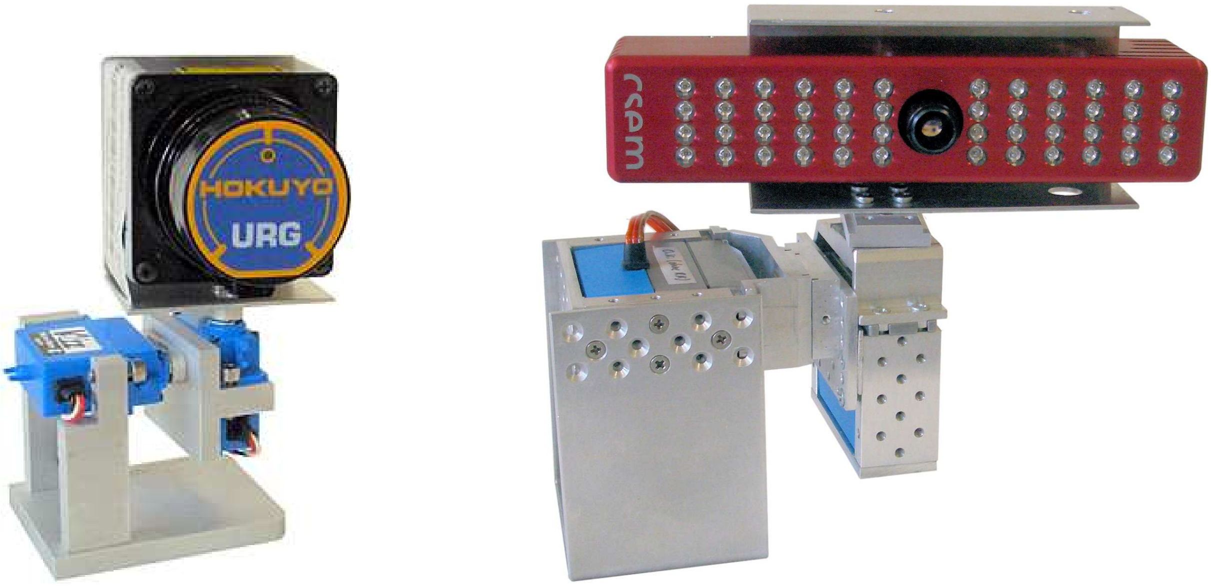

Figure 1: Lightweight Hokuyo laser scanner (left) and CSEM Swiss Ranger (right), both mounted on a pan and tilt unit

This paper presents a lightweight 3D scanner and a 3D camera (Fig. 1) together with possible new applications based on these 3D sensors. Their main advantages are the relative cheap price, the weight, the size and the low energy consumption and/or the data acquisition speed. With these sensors, a small mobile robot can analyze its environment in three dimensions, and that is done in real time. Within smallest space, the sensor can provide three-dimensional maps of its environment. A mobile robot equipped with the 3D scanner can autonomously recognize and avoid obstacles on its way - e.g., in narrow sewers or cavities with danger of collapse. 3D sensor systems are necessary for high-quality pictures and flexible movements of the robot in real time. However, these were so far so large and so heavy that they could be applied usually only on bigger robots and in larger environments (Fig. 2).

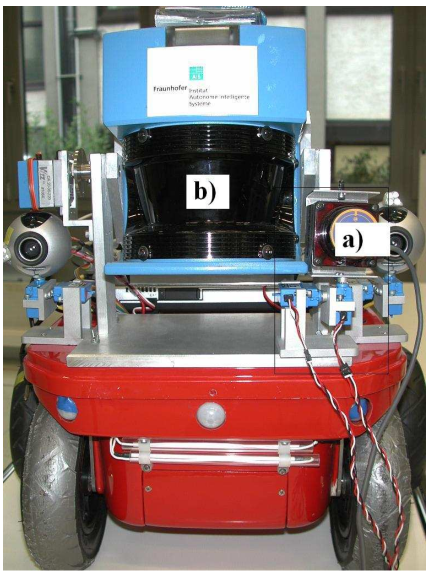

Figure 2: Comparison of the lightweight 3D scanner a) with the bulky 3D-scanner b) as used in RoboCup Rescue on the mobile robot KURT3D.

Lightweight 3D laser scanner

The new 3D laser system is significant lighter than its predecessor model and can survey areas with a diameter of up to 8 meters in 3 dimensions in one shot. With a size of scarcely 10 cm, it weighs only a tenth, namely instead of 7.5 kg only 0.5 kg (Fig. 1 and Fig. 2). To acquire the 3D data, the 2D scanner is mounted on a pan and tilt unit. The advantage is that the 3D scanner can be moved or nodded vertically and horizontally over a range of 170 degree to get the 3D data. Both scan methods can be used to build 3D maps, but horizontal scan acquisition has advantages in dynamic environments and with faster robots. Obstacles can be observed in a cycle less than 90 ms with a resolution of 0.36 degree over a range of [-120°, 120°] (Fig. 3).

The laser scanner detects lots of points in the environment and acquires distance information between each point and the center of scanner. Laser beams are sent out counterclockwise every 0.36°, this angle can be changed twice or more times. In that case, it takes the smallest value as the distance. The URG-X002 series considers the data returned from gesture 44 to gesture 725 as valid, that angular range equals 240°:

$$\alpha' = \frac{240^\circ}{725-44} \times (n-384),\ \alpha' \in [-120^\circ, 120^\circ]$$

Vertical scanning reduces the scan matching costs since a robot observes its front and back environment simultaneously over a range of 320 degree. This improves the scan matching especially when a robot enters a room where its front environment changes quickly and only front 3D scans have less overlap to previous 3D scans. 320° x 240° 3D point clouds with a 1 x 0.36 degree resolution can be acquired in 14 seconds (Fig. 3).

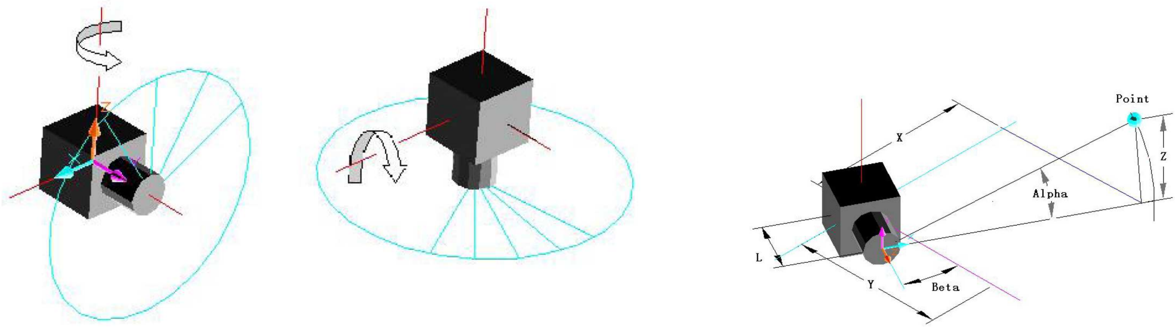

Figure 3: Left: Scanning around the vertical axis to obtain 340° scans of the environment. Middle: Scanning around the horizontal axis to get 3D data in front of a robot. Right: Calculation of the 3D data while turning with the pan/tilt unit.

Instead of using the robot with the 3D scanner in a stop and go fashion, which yields to consistent 3D scans, it is also possible to nod the scanner continuously. Precise inertial sensors are necessary to acquire a precise robot pose and to transform the scan points into 3D data points. The overall robot behavior seems more natural and the mapping is quite faster.

Instead of using the URG scanner as 3D scanners with the pan and tilt unit, which yields to consistent 3D scans in the first place, some applications, e.g. sewer inspection, attempt to build 3D volumetric representations of environments with only the 2D laser range finders. The laser scanner is mounted vertically (Fig. 3, left). It grabs a vertical scan line while moving the robot through the pipe mainly with a constant speed to ensure 3D data quality. So, the acquired points are transformed into 3D points based on the current robot pose. The precision of 3D data points depends on that pose, which is calculated on the basis of wheel encoders and a gyro. A smaller robot size, less weight and less power consumption are the advantages of this approach.

3D time-of-flight cameras for robotic issues

The development of 3D cameras constitutes important advances in visual sensing. The usability for robotic issues has been already identified. An outstanding asset of these cameras is the capability to deliver complete 3D scenes in fractions of a second (e.g. with 25 Hz), but it has to be balanced with fragility of accuracy. In contrast to the 3D laser, the fast acquisition yields to consistent 3D point clouds and a stop and go robot behavior to acquire the 3D point cloud can be avoided. Several erroneous influences have been examined yet, but the process to identify erroneous data during runtime remains to be an important task. This implies the usages of real-time capable filter algorithms. Both are implemented for the AIS 3D camera system and will be published in a later paper.

Our experimental setup consisted of a Swiss Ranger SR-2 device (Fig. 1) connected via the USB 2.0 interface to a workstation running SuSE Linux 9.3. The Swiss Ranger device was mounted on a pan and tilt unit with servo motors, which were used to adjust the device to several positions. Concatenating images while pivoting, the device enables a virtual 180° view. The camera belongs to the group of active sensors. It uses the phase-shift principle to determine distances. While the environment is being illuminated with infrared flashes, a CCD/CMOS sensor measures the reflected light. It provides amplitude data, intensity data and distance data, which are weakly addicted to each other. Amplitude data represent the incoming wave amplitude, intensity its offset and distance its phase shift. For a detailed description of the measurement principle, please refer to [30]. The camera comes with a resolution of 124x160 pixels. All measurements are being organized by a FPGA, which provides an USB interface to access the data values. The FPGA can be configured setting one or more of its eleven registers. One important register concerns the adjustment of integration time. It has a range from 1 to 255, which are multiples of 255 μs.

First of all, a per-pixel calibration is necessary to enlarge accuracy. The camera has to be mounted in a defined distance towards a white smooth wall. Some captures have to be taken to ensure the camera to be at the right running temperature. The calibration run needs an optimal adjusted integration time. Over saturation will falsify measurements. The distance offset register is set to 0 during calibration. We propose to determine a calibration matrix in polar coordinates to simplify measurement corrections. This matrix is used later for distance corrections by subtracting related measurement values. Because of the cameras phase-shift principle, it runs into a “modulo 2π problem”. To avoid negative values, which will appear after calibration matrix subtraction, we propose the following correction method:

$$d_p = (d_s - o + r_e) \bmod r_e$$

where d_p is the corrected polar distance, d_s the measured polar distance, o the related offset value and r_e the effective range of sensor.

Weingarten et al. used an empirically found solution to suppress noise by decomposing the space into cells [30]. A cell with a minimum number of data points is to be considered occupied. This simplification fits well for navigation tasks but will lack for mapping and dynamic issues. First, we analyzed inaccurate data points to verify the conditions under which they appear. The examination of Gut [11] provides an informative basis. It focuses surveying and mapping tasks, where high precision is required. The most interesting but irritating effect is that of scattering light on near objects. As already mentioned above, the provided data values are weakly addicted to each other. Intensity information of an object, for example, depends on its distance, its alignment in relation to the sensor and its surface properties, like color and texture. Amplitude and intensity values allow us to predict the accuracy of distance values. Some test scenarios should represent common environments a robot will typically act in and therefore include different compositions of objects to demonstrate their influences (see Fig. 4).

To get appropriated measurements the integration time has to be set up. This is one of the most important parameters to get stable data. It has to be adjusted in relation to each scene; otherwise too high saturation could cause erroneous effects.

Supposing that the photonic interference is the main reason for inaccuracy, it has to be minimized to get stable data. The physical law of inaccuracy considering photonic interference is defined formally as [8]:

$$\Delta L = \frac{L}{\sqrt{8}} * \frac{\sqrt{I}}{2 * A}$$

where ΔL represents the inaccuracy, L the maximum distance, A the amplitude value and I the intensity value. The maximum distance is defined as:

$$L = \frac{c}{2 * f_{mod}}$$

where c is the speed of light and f_{mod} the modulation frequency. The Swiss Ranger device uses a frequency of 20 MHz. That’s why it has an effective range of 7.5 meters.

Oggier et al. already reported the development of an algorithm to automatically select the best integration times for the image acquisition [9]. It uses the reflectivity and the distance data of a measured object to determine the most appropriate exposure time needed to obtain the best distance accuracies. Robotic issues require different modalities, so that the question of determining the best integration time can only be answered, if the boundary conditions are known. If you want to focus a single object, the best way to determine the integration time will be to suppress background information and other objects located in the scene. In most cases robots are situated in complex and often changing scenes. A controller is used to adapt the integration time on different lighting conditions. On the basis of the current picture, the integration time for the next picture is calculated. Changing lighting conditions produce bad pictures with some 3D errors. A precision filter eliminates the errors and the integration time calculation determines the integration time for the changed lighting conditions in the next picture.

Fig. 4 shows an example of the 3D data provided by the Swiss Ranger and our implemented adaptation algorithms. The 3D camera was mounted on the arm of a TeleMax robot while moving through our robotic lab. The weight of the 3D camera including the pan and tilde unit is 650 g.

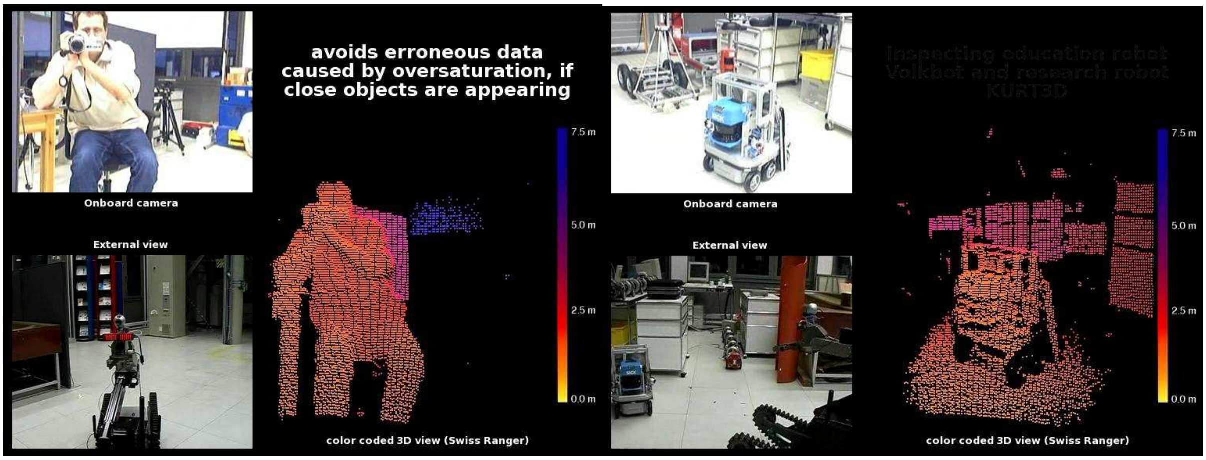

Figure 4: 3D information provided by the Swiss Ranger camera based on the camera calibration and online integration time adaptation / filtering.[1] *To illustrate 3D data in this paper, we choose a false color representation using the HSV model starting at 60º in reverse order to 240º. Near objects will appear yellow, far objects blue. Objects with medium distances appear red or magenta.*

Sample applications for 3D sensor systems

The systems described here are going to be applied as part of the Rescue robot control software, in which the lightweight 3D sensor systems are embedded. The control software has been used in the RoboCup events 2004 and 2005. In 2004, KURT3D won the second place at the RoboCup Rescue world championship and in 2005 the autonomy award at the German Open. Rescue robots had to discover fictitious earthquake victims in an artificial rubble field - at Lisbon in the year 2004 AIS participated with their mobile robot KURT3D, at that time equipped with a bulky 3D-scanner with a height of 25 cm and a weight of 7.5 kg. The AIS team was the first, which could show that robots can build three-dimensional maps in real time on realistic match conditions, which is a qualitative jump in relation to the bare lab tests [4], [5].

Furthermore, with the new small 3D scanner completely new application fields for the so-called "non destructive testing methods" are opened. E.g., small cavities develop frequently under underground pits or road courses and can become larger with the time. There is then the danger that the soil lying over it sags. So far these cavities must be drilled out more or less wide - with high costs. With the new lightweight 3D scanner civil engineers can work minimally invasive. They drill a small hole with a diameter of approximately 10 cm and sink the scanner, in order to estimate the danger caused by the cavity. Depending on the results, further necessary measures may be initiated.

In addition, a lightweight 3D-scanner can be useful in narrow sewers. In Germany, sewers with an overall length of 450.000 km lead the waste water in purification plants. Parts of this sewer labyrinth still originate from the 19th century. The law prescribes the regular examination of all public sewers, to detect leakages promptly. Since a majority of the pipes is not accessible, at present remote-controlled sewer robots help with the inspection. These are four-wheeled, rigid carriages, which are connected by cables with an aboveground control station, which is accommodated in a small van. The cable supplies the sewer robot with energy and transmits its video signals to the operator at the control station. From there, he also steers the carriage through the sewer. Their range of action is very much limited because of the cable; it has to be lifted again and again, and at the next manhole be sagged again. On one hand a lightweight 3D scanner improves the inspection quality of teleported robots and on the other hand it enables autonomous mobile robots without any cables.

[1] Videos of the small 3D sensor can be found at http://www.ais.fraunhofer.de/~surmann/videos.html

Beside sensors for the collection of the environment data, sewer robots have in addition a computer on board. The computer evaluates the gathered data immediately and uses them, in order to achieve certain tasks. Such a task could be: "Drive from pit 7 to pit 12 and take waste water samples at all inlets on this distance!" Only the basic data from the maps of the sewer net are known for such inspection travels. The sewer robot drives autonomously the distance within the tubing system. Therefore, it must localize its own position, recognize inlets and pits pass branches and different heights, and finally take samples of waste water at the correct locations. It must also deal with unexpected difficulties without any human assistance, e.g. if in-grown tree roots block its way.

Figure 5: Left: A jointed part of two sewers at Fraunhofer Campus Birlinghoven. Right: Scanning result displayed by 3D viewer.

The new 3D sensor system supports these tasks. Contrary to conventional 2D distance measuring, it can also recognize over-hanging obstacles. With its laser beam the scanner measures the distance to the object. The sensor system includes new software developed at the AIS as the most important part. The software measures and builds models of complete surfaces in the form of 3-dimensional point clouds with the help of different real time algorithms. The real time capability is the largest problem, which had to be solved. From the large amount of possible algorithms only very few could be used. Most were either not real time capable or not able to deal with complex environment information. If there is a lack of time on-site, the software in the on-board computer can process different tasks also still after the employment: for example the precise segmentation and recognition of objects as well as the generation of detailed maps.

Figure 6: Left: Sewer pipe network at Fraunhofer Campus Birlinghoven. Right: Scanning result displayed by 3D viewer.

In [14], an application for a 3D sensor system on a mobile robot is described in detail, where the task was to explore the state of an abandoned mine. A research team of the CMU collected 3D point clouds in the Mathies mine near Pittsburgh, USA, by means of the mobile robot Groundhog. They let the robot drive autonomously through the mine, which is closed for humans due to safety reasons. After 250 m the robot detected a broken ceiling, which blocked its further way, and the control software made the correct decision to go back. From the data that the robot had collected until then, it was possible to construct a coherent 3D model of this inaccessible area (Fig. 7). A smaller robot than Groundhog, which has the size of a jeep, perhaps would have been able to find a hole in the obstacle and continue its exploration. Of course, it would also be possible to collect data in narrower tunnels, if the mobile sensor platform is of a smaller size.

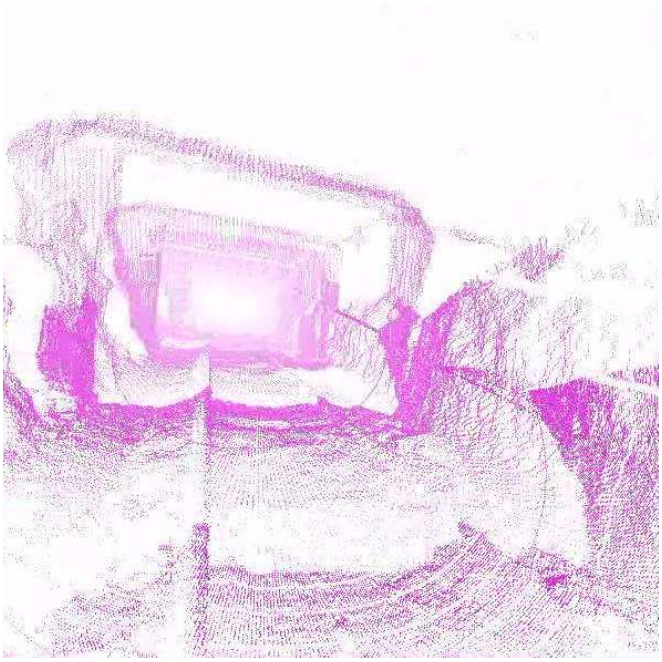

Figure 7: 3D Visualization of the Mathies Mine near Pittsburgh, USA.

Beside these outdoor applications, a 3D sensor system on a mobile robot is useful in buildings, too. While driving through the corridors, the system scans its environment and is able to detect floors, walls, and ceilings. A 3D model is generated from the collected data. A viewer, which projects the 3D scene on the screen, is available for the visualization of this model (Fig. 8). In this case, the size is not the main reason for the preference of a lightweight 3D sensor, but the price and the lower energy consumption, which means that the robot can drive for a longer period.

Figure 8: Left: Corridor at Fraunhofer AIS. Right: Scanning result displayed by 3D viewer.

Mapping and re-localization

Multiple 3D scans are necessary to digitalize environments without occlusions. To create a correct and consistent model, the scans have to be merged into one coordinate system. This process is called registration. If the robot carrying the 3D scanner were precisely localized, the registration could be done directly based on the robot pose. However, due to the imprecise robot sensors, self-localization is erroneous, so the geometric structure of overlapping 3D scans has to be considered for registration. As a by-product, successful registration of 3D scans re-localizes the robot in 6D, by providing the transformation to be applied to the robot pose estimation at the recent scan point.

The following method registers point sets in a common coordinate system. It is called Iterative Closest Points (ICP) algorithm [13]. Given two independently acquired sets of 3D points, M (model set, $|M| = N_m$) and D (data set, $|D| = N_d$) which correspond to a single shape, we aim to find the transformation consisting of a rotation $\boldsymbol{R}$ and a translation $\boldsymbol{t}$ which minimizes the following cost function:

$$E(\boldsymbol{R}, \boldsymbol{t}) = \sum_{i=1}^{N_m} \sum_{j=1}^{N_d} w_{i,j} \, ||\boldsymbol{m}_i - (\boldsymbol{R}\boldsymbol{d}_j + \boldsymbol{t})||^2 \, .$$

$w_{i,j}$ is assigned 1 if the i-th point of M describes the same point in space as the j-th point of D. Otherwise $w_{i,j}$ is 0. Two things have to be calculated: First, the corresponding points, and second, the transformation ($\boldsymbol{R}, \boldsymbol{t}$) that minimizes $E(\boldsymbol{R}, \boldsymbol{t})$ on the base of the corresponding points. The ICP algorithm calculates iteratively the point correspondences. In each iteration step, the algorithm selects the closest points as correspondences and calculates the transformation (R; t) for minimizing equation (1). The assumption is that in the last iteration step the point correspondences are correct. Besl et al. prove that the method terminates in a minimum [13]. However, this theorem does not hold in our case, since we use a maximum tolerable distance $d_{\max}$ for associating the scan data. Such a threshold is required though, given that 3D scans overlap only partially. Here $d_{\max}$ is set to 15 cm for the first 15 iterations and then this threshold is lowered to 5 cm. Fig. 9 (left) shows two 3D scans aligned only according to the error-prone odometry-based pose estimation. Matching point pairs are marked with a line.

At each iteration, the optimal transformation ($\boldsymbol{R}, \boldsymbol{t}$) has to be computed. In earlier work [14], we used a quaternion-based method [13], but now we are using a method based on singular value decomposition (SVD), because it is robust and easy to implement. It was first published by Arun, Huang and Blostein [19] in 1987. A more detailed description of our implementation can be found in [6].

The time complexity of the algorithm described above is dominated by the time for determining the point pairs (brute force search $O(n^2)$ for 3D scans of n points). We have implemented kd-trees as proposed by Friedmann et al., using the optimized kd-tree version, i.e., the expected number of visited leafs is kept to a minimum [28].

Since the ICP algorithm extensively computes nearest neighbors, we have proposed a point reduction to reduce the number of nearest neighbor queries and the computing time spend on it. During scanning, surfaces close to the scanner are sampled with more data points. These areas are sub-sampled using a median and reduction filter. Details of the algorithm can be found in [16].

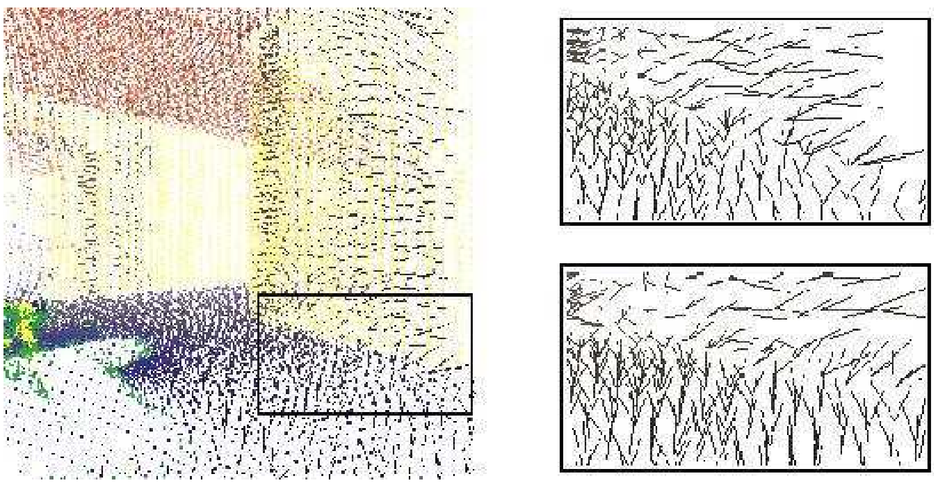

Figure 9: Point pairs for the ICP scan matching algorithm. The left image shows parts of two 3D scans and the closest point pairs as black lines. The right images show the point pairs in case of semantically based matching (top) whereas the bottom part shows the distribution with closest points without taking the semantic point type into account.

In [6] we presented a method, which utilizes semantic knowledge to speed up the ICP matching algorithm and yields to a more robust scan matching. Therefore a forest of kd-trees is used to search the point correspondences. For every semantic label a separate search kd-tree is created. The algorithm computes point correspondences according to the label. For example, points that belong to the wall are paired with wall points of previous 3D scans. Using semantic information helps to identify the correct correspondences, thus the number of ICP iterations for reaching a minimum is reduced. In addition, maximizing the number of correct point pairs guides the ICP algorithm to the correct (local) minimum leading to a more robust algorithm.

Conclusion

The new lightweight systems are versatile, precise and very fast sensors for autonomous mobile robots. No 3D sensor system is known, that is so efficient in the evaluation and at the same time so small, cheap and lightweight. In addition it is also less expensive than its predecessors, so users profit everywhere, where 3-dimensional measurements or 3D-models have to be provided in static or dynamic environments that are difficult to access.

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