On Qualitative Uncertainty in Range Measurements from 2D Laser Scanners

Received 16th July 2007; accepted 3rd October 2007

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Abstract:

This paper describes a research concerning recognition, classification, and correction of qualitative-nature errors in range measurements from 2D laser scanners. Nowadays, such scanners are commonly used on mobile robots for navigation. The main causes of qualitative uncertainty are the mixed measurements. This effect has been investigated experimentally for two different classes of the laser range sensors, and explained by analysing the physical phenomena underlying their operation. A local grid map has been proposed as an intermediate data structure, which enables to remove the erroneous range measurements, being either mixed measurements, or being caused by dynamic objects in the vicinity of the robot. A novel fuzzy-set-based algorithm has been employed to update evidence in the grid. The results of tests show, that this algorithm is superior to the common Bayesian approach, when qualitative errors in range measurements are present.

Keywords: *laser range sensors, uncertainty, qualitative errors, mixed measurements, mobile robots*

1. Introduction

Range sensors, such as ultrasonic range finders (sonars), laser range finders and laser scanners are today the most used exteroceptive sensors in mobile robotics. The navigation system of an autonomous mobile robot requires not only range readings, but also information about the uncertainty of these readings. This information enables the robot to decide if the given measurement is precise and reliable enough to support particular tasks, such as obstacle avoidance, map building and self-localization.

The statistical methods and tools used to investigate, analyse and describe the measurement uncertainty are well known from the literature [3]. However, the nature of a mobile robot tasks, that must be performed in real-time, often in a previously unknown, dynamic environment, makes it quite hard to ensure, which object in the environment caused the given range measurement. This is an uncertainty as to the origin of the measurement, which is usually neglected by the literature concerning measurement science and statistical data analysis, but is considered crucial in tasks related to tracking and navigation [2]. This uncertainty is of qualitative nature, i.e. it cannot be described in the usual terms of mean value and standard deviation. The measurements, that are corrupted by this type of uncertainty should be identified and eliminated from the further sensory data processing in the mobile robot, as they do not fit to the statistical measurement model, which is a basis for this processing, and they may cause erratic behaviour of the map-building and localization procedures [14].

Nowadays, 2D laser scanners are commonly used on autonomous mobile robots for navigation, in particular for environment mapping and self-localization. Laser scanners are active optical sensors that emit light waves and receive light reflected by surfaces of the objects to be detected. Laser scanners have many advantages over passive vision sensors. The most important advantages of the active optical sensors are: (i) independence from the natural lighting of the scene, (ii) direct measurement of distances, avoiding the time-consuming and error-prone image processing, which is required to obtain the scene depth information in passive camera-based systems.

Superiority of the laser range sensors to the still popular sonars stems directly from the properties of the measurement medium. The length of the light wave is very small, thus most of the observed surfaces produce diffuse reflections preventing the laser sensor from specular reflections that are the main source of spurious range readings in sonars. Shiny surfaces give sporadically erroneously long distance readings whenever a specular reflection occurs. Such reflections are possible if a highly reflective plane is inclined at a sharp angle to the laser beam axis. In practice, if a mobile robot equipped with a laser scanner is used in a typical indoor, office-like environment, the spurious measurements due to specular reflections are very rare. Only extremely reflective surfaces – mirrors and polished metal cause this effect. Moreover, specular reflections in laser scanners often result in maximum range measurements, which can be easily eliminated by fixed-value range tresholding.

Although the light-emitting range sensors exhibit much better properties than sonars as to the specular reflections, there are other physical phenomena that cause qualitative errors in readings of the laser scanners. Use of mobile robots in realistic indoor environments, that are often cluttered and populated, makes the laser scanner vulnerable to such qualitative errors as range readings corrupted by dynamic objects (e.g. people walking by the robot). However, particularly significant qualitative errors occur, when the laser beam hits simultaneously two objects at different distances or two surfaces having different reflective properties. Such errors are known in the literature as mixed pixels [5], mixed measurements [15], or discontinuous points [1]. We use the term "mixed measurements", because we are working with range readings from 2D scanners rather than with 3D images consisting of pixels.

In the reminder of this paper we experimentally characterize the mixed measurements for two different 2D laser scanners used on mobile robots at the Mobile Robotics Laboratory of the Institute of Control and Information Engineering (ICIE). The sensors used in experiments are based on different measurement principles, thus the characteristics of the qualitative errors occurring in the data obtained from these devices differ significantly. We analyse the physical background of the mixed measurement phenomenon in both sensor types, and draw conclusions as to the environmental conditions that cause this undesirable effect, and range of observability of the mixed measurements. On the basis of this analysis we develop a sensor and an application-independent method to filter out the qualitative errors from 2D range readings. This method is able to deal with both the mixed measurements and readings that are caused by dynamic objects.

2. Laser Scanners in Mobile Robot Navigation

2.1. Laser Range Measurement Techniques

Range measurements in laser scanners are accomplished either by determining the time of flight of an emitted laser pulse travelling to a target and then reflected back, or by determining the phase-shift between an emitted continuous wave and its reflection. There exist also other laser ranging techniques (e.g. triangulation), but currently their use in mobile robotics applications is marginal [6].

In the phase-shift-based ranging technique, the distance to a target is proportional to the difference of phase between the amplitude-modulated continuous wave (AMCW) of laser light, and a fraction of this wave reflected by the target surface back to the sensor. The range to the target object r is proportional to the measured relative phase shift ϕ_d:

$$r = \frac{c}{4\pi f_{AM}}\phi_d = \frac{1}{2}\lambda_{AM}\frac{\phi_d}{2\pi}, \qquad (1)$$

where f_{AM} is the modulation frequency, λ_{AM} is the wavelength of the modulation, and c is the speed of light. Since ϕ_d is determined modulo 2π, the range measurement is unambiguous only within the distance $r_u = ½\,\lambda_{AM}$ from the sensor. Laser scanners using this measurement method are known as AMCW sensors [6].

In the time-of-flight (TOF) ranging technique, the distance is determined by measuring the time interval between the transmitted and received light pulses. The range r is calculated from the equation:

$$r = \frac{1}{2}ct_{TOF}, \qquad (2)$$

where t_{TOF} is the elapsed time. As the emitted pulse propagates at the speed of light, to obtain a millimetre-level resolution of range measurements a TOF laser scanner requires a timing circuitry of picosecond accuracy. A review of the state-of-the-art with such precise time interval measurements is presented in [8]. Technological requirements of the sophisticated electronics make TOF laser range finders quite expensive. That was a major obstacle in a wider adaptation of the TOF-based lased scanners in mobile robotics, where high-resolution range measurements are desired. This situation has changed to a great extent with the introduction of commercially available 2D TOF laser scanners manufactured in quantities for industrial automation and civil engineering applications. Currently, time-of-flight laser scanners are commonly used on mobile robots for navigation.

2.2. Experimental Laser Scanner Based on the AMCW Principle

The experimental laser scanner for mobile robotics applications developed at the ICIE is based on a commercial AMCW range finder manufactured by *Pepperl & Fuchs GmbH*, what makes it to be unconditionally eye-safe and inexpensive (Fig. 1A). The carrier signal from a near-infrared (880 nm) emitter diode is modulated with the sinusoid of f_{AM} = 8 MHz frequency, what makes it possible to unambiguously measure distances up to 18.75 m. However, due to the limited power of the transmitter and receiver sensitivity, the practical range of measurements of the distance is limited to 5 m for target surfaces with reflectance of about 90%. The sensor has the range measurement resolution of 10 mm and produces 280 measurements per revolution within the angular range of 360°(Fig. 1B). The interested reader will find more details of the scanner construction in [7].

(A) (B)

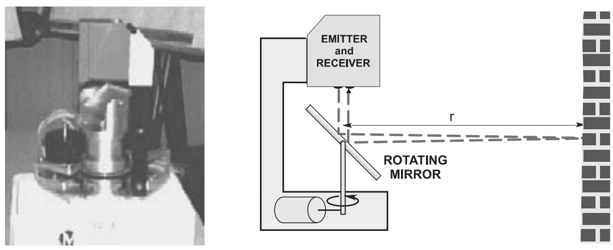

Fig. 1. ICIE laser scanner (A), and its simplified block diagram (B).

The used commercial range finder based on the AMCW principle is characterized by a strong coupling between the measured range and the received signal intensity. This coupling, typical to the AMCW ranging technique and recognized in early papers as range-intensity cross-talk [5], introduces important systematic uncertainty into the range measurements. This uncertainty can be effectively compensated by a proper calibration procedure [1]. Unfortunately, the low-cost range finder device used in the ICIE AMCW scanner does not have the intensity measurement channel, what makes impossible to implement such a calibration as the one described in [1]. It is also not possible to estimate the standard deviation of the range measurements on the basis of the received signal intensity. To remedy this problem a range measurement correction procedure has been developed, which couples the range error and the standard deviation of range measurement calculated upon a series of measurements. This procedure corrects most of the systematic errors, however it is done at the expense of the time used to collect a series of measurements [7].

2.3. LMS 200 Laser Scanner Based on the TOF Principle

The LMS 200-30106 manufactured by Sick AG is a commercial 2D laser scanner based on the TOF measurement principle (Fig. 2A). The Sick LMS and the older PLS series are currently the most commonly used 2D laser scanners in mobile robotics.

(A) (B)

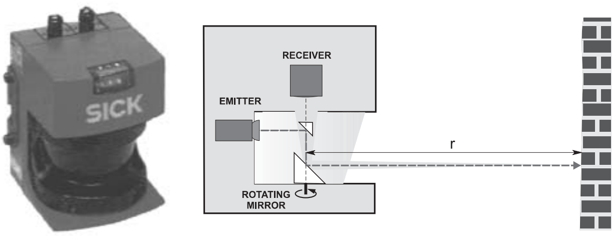

Fig. 2. Sick LMS 200 laser scanner (A), and its simplified block diagram (B).

The laser beam is deflected by a rotating mirror in the range from 0° to 180° (Fig. 2B). The angular resolution of the LMS scanner is selected by software. We limit our study to the 0.5° resolution mode. In this mode a single scan contains 361 range measurements. The LMS 200 scanner can measure ranges up to 8 m with the systematic error below 20 mm, and the standard deviation of 5 mm. In comparison to the AMCW scanner, the quantitative uncertainty of the range measurements obtained with the LMS 200 depends to a much smaller extent on the optical properties of the target surface [16].

In this scanner a near-infrared (905 nm) laser pulse of 3.5 ns duration is emitted and reflected from the target surface. At the moment of pulse emission a time counter is started. The returned pulse is received by a photo detector. The resulting output signal is compared to the average noise level of the photo detector. When the detected signal is larger than a given threshold value, the counter is stopped, and the measured range is calculated from equation (2). Laser pulses reflected by objects with different optical properties, and located at different distances from the sensor have different light intensities. Thus, they produce on the photo detector signals with different rise times. A difference in the signal rise time may cause a significant error in determination of the pulse return time, what in turn causes an error in the measured distance. In the LMS/PLS scanners the time of flight is roughly compensated for the rise time error by the internal electronics, which discriminates between several levels of the signal strength [4]. Unfortunately, the manufacturer does not provide detailed description of the internal scanner electronics, in particular the method employed for detecting the exact timing point is unknown, what makes unambiguous interpretation of the experimental results obtained with this sensor harder.

3. Mixed measurements in 2D laser scanners

3.1. AMCW Laser Scanner

The effect of spurious range measurements produced by simultaneous reflection of the laser beam from two surfaces separated by a certain distance was noted for the first time by researchers investigating the characteristics of 3D laser scanners based on the AMCW principle [5]. These early works suggested that mixed measurements are a phenomenon inherent to AMCW laser scanners. Adams [1] provided a detailed analysis of the mixed measurements effect in an AMCW range finder taking into account both the measured range and the returned signal amplitude.

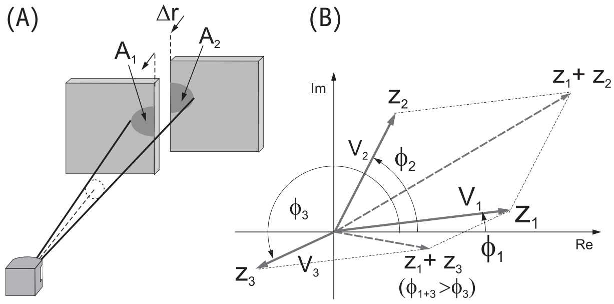

Fig. 3. Illustration of the mixed measurement (A), and interpretation of the (V, ϕ) pair as a complex number (B).

Consider a modulated signal $V_t \cos(\omega t)$ with the amplitude V_t, which is split at the target between two surfaces differing in range (Fig. 3A). The laser beam cross section is divided into two unequal areas: A_1 and A_2, and produces two different returning signals: $V_1 \cos(\omega t+\phi_1)$ and $V_2 \cos(\omega t+\phi_2)$, where ϕ_1 and ϕ_2 are different phase shifts resulting from the different distances to illuminated surfaces. In such a case, the effective signal in the scanner's receiver can be written as:

$$V \cos(\omega t + \phi) = V_1 \cos(\omega t + \phi_1) + V_2 \cos(\omega t + \phi_2), \quad (3)$$

where ϕ is the detected phase shift (proportional to the measured range), and V is the received signal amplitude. The resulting amplitude and phase in the receiver are given by the equations:

$$V = \sqrt{V_1^2 + V_2^2 + 2V_1V_2\cos(\phi_1 - \phi_2)}, \quad (4)$$

$$\tan\phi = \frac{V_1 \sin\phi_1 + V_2 \sin\phi_2}{V_1 \cos\phi_1 + V_2 \cos\phi_2}. \quad (5)$$

It should be noted from (5) that the effective phase shift measured in the scanner depends not only on ϕ_1 and ϕ_2, but also on the amplitudes of both signals involved in the mixed measurement. The amplitudes depend on the intensities of the returning laser signals, which in turn depend on the contributing beam cross-sectional areas, and on the reflective properties of the target surface.

Hebert and Krotkov [5] proposed to represent a (V, ϕ) pair as a complex number $z = a + bi$. The returning signal intensity is the modulus of z, while the argument of z represents the measured phase shift. The returned signal (3) can be written as:

$$V(\cos\phi + \sin\phi) = \quad (6)$$
$$= V_1(\cos\phi_1 + \sin\phi_1) + V_2(\cos\phi_2 + \sin\phi_2).$$

Using the trigonometric form of complex numbers one can write (6) as:

$$V(\cos\phi + i\sin\phi) = \\ = V_1(\cos\phi_1 + i\sin\phi_1) + V_2(\cos\phi_2 + i\sin\phi_2), \quad (7)$$

and in the algebraic form:

$$a + bi = (a_1 + a_2) + (b_1 + b_2)i = z_1 + z_2. \quad (8)$$

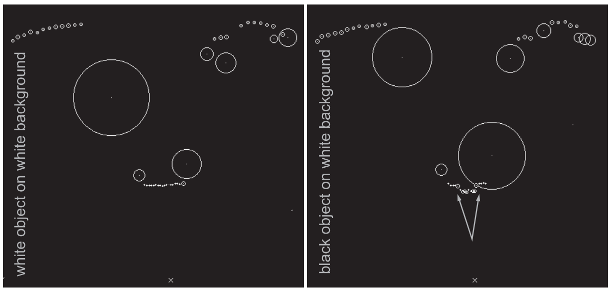

Fig. 4. Mixed measurements in the AMCW scanner readouts.

Considering graphical interpretation of the complex numbers it is easy to note (Fig. 3B) that the phase ϕ of z can be located not only between ϕ_1 and ϕ_2. Such a situation is possible when the difference between the phase shifts of both signals involved in the mixed measurement is greater than 180°, what taking into account (1), means a separation between the two target surfaces $\Delta r > \frac{\lambda_{AM}}{4}$, i.e. a distance greater than half the unambiguous range r_u. In that case, the mixed measurement is particularly misleading, because when the resulting phase shift falls in the range $(\phi_2, 2\pi)$ the measured distance indicates a non-existing obstacle behind the furthest object, and when ϕ is in the range $(0,\phi_1)$ the spurious measurement suggests an obstacle somewhere in front of the nearest object.

To investigate thoroughly the mixed measurements effect in the ICIE-built AMCW laser scanner, we conducted a series of experiments [13]. In the first experiment we positioned a white target surface at 1 m in front of the scanner with a uniform white wall in the background, about 2 m behind the target. We attached alternatively A4-size sheets of white or black paper on the target surface. A series of 30 scans has been performed, computing the means and standard deviations for all the range measurements in a scan. The results are depicted in Fig. 4, where the measurements are represented by circles of the radius equal to the standard deviation of the measured range.

In case of the matte black paper sheet attached to the target surface, the effect of bigger systematic error of the range measurements to the low-reflective surface is clearly visible. The measurements incident on the black part of the target have also bigger standard deviation. However, the biggest standard deviation of range measurement is observed when there is a sudden change in reflectivity of the surface (indicated by arrows in Fig. 4). Such an effect cannot be observed when a sheet of white paper is attached to the target object – both surfaces have similar reflective properties. In both experimental setups shown in Fig. 4 some range measurements can be observed between the target surface and the background (note that shape of the more distant wall is distorted by systematic errors in the measured ranges). These points do not match any existing objects – they are mixed measurements caused by the laser beam split between the two surfaces. While the scanning beam moved from the target surface to the background wall, the "phantom" objects appeared at first closer to the target, then closer to the wall. As the white target surface (made of styrofoam) and the white-painted wall have quite similar reflective properties, the result of a mixed range measurement depends on how the beam is divided between the two surfaces.

An important conclusion from the above described experiment is that in all cases of mixed measurements the standard deviation of the resulting range is much bigger that standard deviations of the other ranges in a scan.

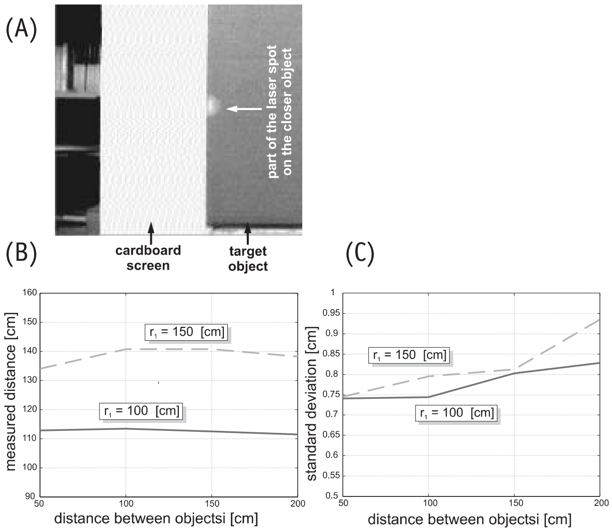

Fig. 5. Influence of the mixed measurements on the accuracy of the AMCW scanner range measurements.

In the second experiment the range of observability of the mixed measurements has been investigated. The rotating mirror of the scanner was stopped, and a flat cardboard panel was positioned in front of the sensor in such a way, that about a half of the beam spot was visible on it (with a B/W CCD camera). The remaining part of the beam was incident on another cardboard panel, placed behind the first one (Fig. 5A). The panel in the background was moved with regard to the foreground object to obtain different separations between the surfaces. The movable panel has been positioned at the distances Δr=0.5, 1.0, 1.5 and 2 metres from the foreground surface. Two series of measurements were taken, one for the distance between the scanner and the first target $r_1 = 1$ m, and one for $r_1 = 1.5$ m.

The plot of mean values of the measured distance against the separation between the targets is given in Fig. 5B. Figure 5C shows the standard deviation of the range measurements as a function of the separation Δr. The effect of mixed measurements is observable over the entire range of separation distances investigated in this experiment. Moving the background panel farther caused weakening of the intensity of the signal reflected from this surface, thus reducing contribution of this signal to the range measurement (5). When the separation between objects has been increased the standard deviation of the range measurements was bigger, what is consistent with the theoretical relationship between the expected range variance and the detected signal amplitude in an AMCW range finder [1]. Because the practical range of measurements of the distance in the ICIE AMCW scanner is smaller than $\frac{1}{4}\lambda_{AM}$, there is no possibility to observe with this sensor mixed measurements that are located behind the furthest object or in front of the nearest object.

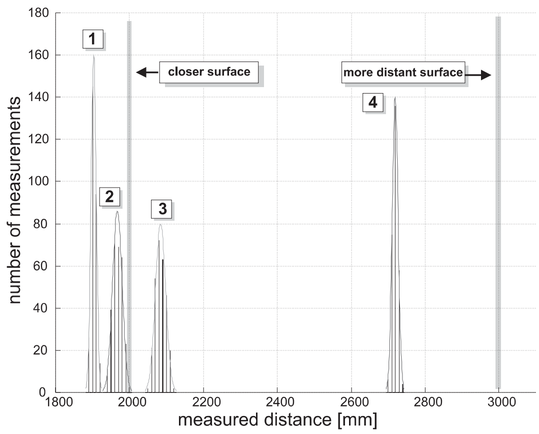

Fig. 6. Influence of the mixed measurements on the distribution of the AMCW scanner range measurements.

In the third experiment we investigated influence of the sizes of areas illuminated by the split scanner beam on both surfaces on the certainty of range measurements. In that case a white cardboard panel was placed at 2 m in front of the scanner, and a second panel (also white) was fixed 1 m behind it. In this experiment the panel closer to the sensor was moved in a direction perpendicular to the laser beam and placed in four positions, to obtain different sizes of the light spots on both surfaces. In each position 300 range measurements were done.

Results are shown in Fig. 6 as histograms of the measured ranges. The curves overlaid on these histograms are Gaussian distributions obtained with the mean and standard deviation calculated upon the results of measurements. The measurement denoted by 1 on Fig. 6 was taken with the beam spot completely on the closer surface, while the measurement no. 4 was taken with the whole spot on the background object (with the first panel removed). Measurements de-noted 2 and 3 were taken under the mixed measurement condition, with the light spot partially on the closer surface, and partially on the background panel. From Fig. 6 it is clearly visible that the range readings obtained under the mixed measurement condition have a greater spread. In all cases the measured range values have approximate normal distributions, however, the histograms no. 1 and no. 4 match closer their theoretical Gaussian curves than the histograms of mixed measurements.

Results of the presented experiments confirm the observation from Fig. 4 that the mixed measurements have increased range variance, and they appear in different areas along the scanner beam depending on relative amplitudes of the signals involved. The amplitudes are determined by such factors as the separation between observed objects and the light spot sizes on these objects.

3.2. TOF Laser Scanner

The LMS 200 laser scanner exhibits many advantages over the low-cost AMCW sensor characterized in the previous section, including much greater measurement range, higher angular resolution, and low quantitative uncertainty of the range measurements. However, the results of tests of the LMS/PLS family sensors available in the literature [4, 15, 16], as well as the characteristics of other TOF-class laser range finders applied in robotics [10] and industrial measurements [9] suggest that the qualitative errors, and the mixed measurements in particular can appear also in the LMS 200 sensor measurements.

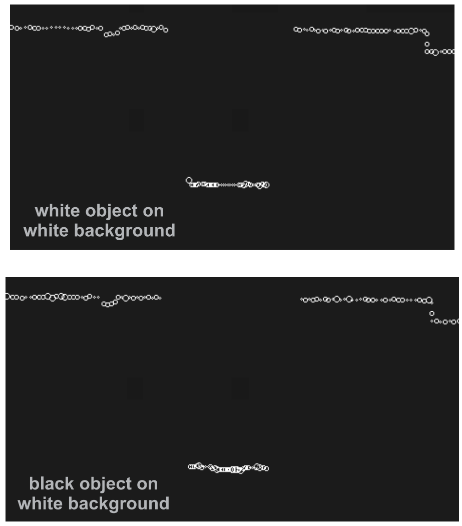

Fig. 7. Investigation of the mixed measurements for the LMS 200 TOF-class scanner.

We have performed a series of experiments in order to investigate what types of objects and surfaces cause the mixed measurements in the LMS 200 sensor, and to determine the range of observability of this effect. The experiments were similar to the tests of the AMCW scanner described in the previous section.

Testing the LMS 200 scanner against a pair of white and black sheets of paper on a white background, we found no clear evidence of the mixed measurements effect at the edges of the black paper sheet, where there is a sudden change in reflective properties of the target surface. In that case the range readings incident on the areas where the reflectivity changes sharply exhibit spread similar to other measurements incident on the matte black surface. Moreover, we could not find any "phantom" measurements between the test panel and the wall located 2 m behind the foreground object (Fig. 7).

Results of this simple experiment suggest that in the LMS 200 sensor the mixed measurements resulting from sudden changes of the reflectivity of a target surface cause errors small enough to be ignored. The results show also that for some separations between the objects the mixed measurement effect does not occur. Hence, the range of observability of this phenomenon ought to be investigated more thoroughly.

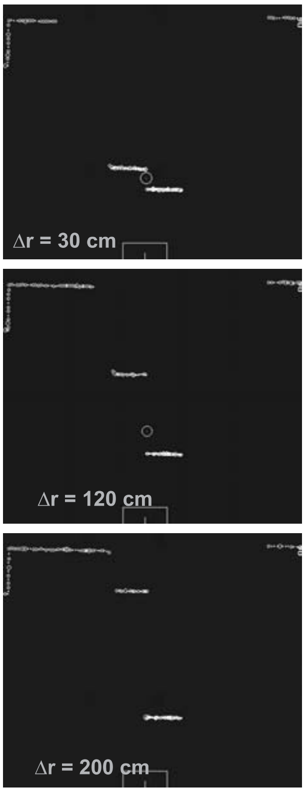

Fig. 8. Range of distances in which the mixed measurements are observed for the LMS 200 scanner.

To determine the range of observability of the mixed measurements in the LMS 200 sensor a cardboard panel was positioned in front of the sensor in such a way, that about a half of the light spot of the middle beam (measurement no. 179 in a scan) was incident on it. Another cardboard panel was placed behind the first one at the distances $\Delta r = 30, 50, 100, 120, 150$ and 200 cm from the foreground panel. For each position a mean and a standard deviation of the measured distance was calculated. The mixed measurement effect was observed only for the separation between the two surfaces up to 1.2 m. For the separations of $\Delta r = 150$ cm and $\Delta r = 200$ cm the range reading was a correct distance to the closer surface (Fig. 8). The range readings taken under the mixed measurement condition exhibit greater spread than the correct ones, however the difference in standard deviation between the spurious and correct range measurements is smaller than in the previously tested AMCW sensor.

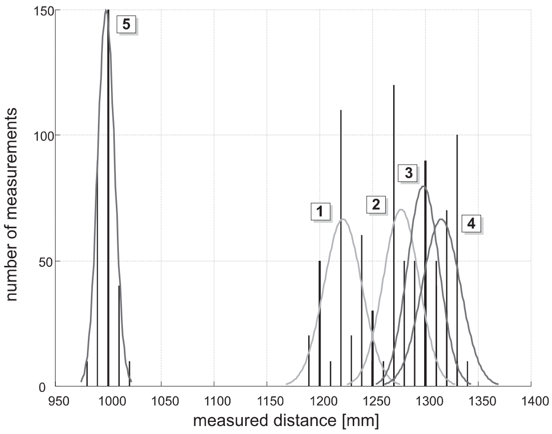

Fig. 9. Influence of the mixed measurements on the distribution of the LMS 200 scanner range measurements.

Analysis of the spread of the range readings obtained in the last experiment is possible upon the histograms depicted in Fig. 9. A plot of Gaussian distribution calculated from the series of measured ranges is overlaid on each histogram. The measurements denoted by numbers from 1 to 5 on the figure were taken for the separations $\Delta r = 30, 50, 100, 120$ and 200 cm, respectively. The mean values of the measured range are similar for all series of range readings that exhibit the mixed measurement effect. Also the standard deviation is similar for all these measurements, and does not depend on the separation between objects. However, spread of the mixed measurements is greater than spread of the correct measurement (no. 5). It is worth noting that distributions of the mixed measurements exhibit some local maxima.

Results of the above-presented experiments can be explained looking on the physical phenomena occurring in the receiver of a TOF laser range finder. In [9] a simple theoretical model of a TOF range finder has been presented. This model assumes that a laser beam spot on the target surface is divided into tiny areas, which can be considered homogeneous with regard to their reflectivity properties. A part of the signal reflected from such a small area preserves in the time domain original shape of the transmitted pulse. In a range finder's receiver the received pulses are summed up over the whole area of laser spot and form the effective signal waveform. Then this signal is used to detect the timing point. If the elementary areas forming a beam spot are located on two surfaces differing in range the arrival times of these pulses in the receiver differ as well, altering the shape of the received signal collected over the whole spot area. Variation in the shape of the received signal is in turn a reason for errors in the time-of-flight measurement, and then errors in the measured range. It is worth noting that the error induced on the range reading by a particular variation in the shape of the stop pulse depends on the timing point determination method used in the sensor.

The timing circuitry of the Sick LMS 200 accepts a reflected signal waveform only if its pulse width is similar to the pulse width of the emitted signal. Received pulses of other width are not treated as valid returns. Because of this particular design of the sensor mixed measurements occur only if the separation distance between the two surfaces illuminated by a split laser beam is not much bigger than the emitted pulse width, which is about 1.05 m for the scanner under study.

4. Removal of Qualitative Errors in Laser Scanner Range Measurements

4.1. Related Work

Qualitative errors due to the interaction of the laser beam with particular objects or structures in the environment can significantly degrade the quality of range data, for both AMCW and TOF scanners. The robotics literature offers only few methods to correct the qualitative errors in laser range data, most of these methods being confined either to a particular application area, or a particular type of sensor. Early papers dealing with 3D AMCW scanners [5] proposed to apply a median filter to the "range image". However, it has been shown in [1] that for a 2D laser scan such an approach can fail, selecting a spurious point as the median value, and removing the correct data. Adams [1] proposed a method capable of detecting the mixed measurements in 2D laser scanner data. This method identifies discontinuity of the returning signal amplitude by evaluating numerically the second derivative of the square of this amplitude with respect to the current spot area. The algorithm is effective, but has two very important limitations: (*i*) it is specific to AMCW laser scanners; (*ii*) it requires fast sampling of the returning signal amplitude, what is rarely possible in commercial laser scanners. Due to these limitations it was not possible to use the method from [1] for either the LMS 200 scanner (a TOF sensor) or the ICIE home-built scanner (amplitude sampling not available).

Other interesting approaches to the removal of mixed measurements and correction of other qualitative errors in laser scanner data are those of Tuley *et al.* [15], and Ye and Borenstein [17]. In both cases 3D laser scanning for outdoor vehicles is considered. The method of Tuley *et al.* uses the specific distribution of mixed measurements in 3D outdoor scenes to detect them, while the algorithm from [17] uses the physical constraints on motion continuity of a vehicle and spatial continuity of a laser-based elevation map to identify and remove artefacts. Both methods are sensor independent, but cannot be applied to planar 2D scans.

4.2. Removal of the Qualitative Errors by Using a Fuzzy Grid

Mixed measurements can be easily identified in the scans from both sensors considered in this paper by their increased spread. Whenever the standard deviation σ_r calculated from a series of readings is known for a given range measurement, this measurement can be qualified as correct or spurious (mixed or caused by a non-stationary object). For the AMCW scanner checking for spurious readings is implemented as part of the correction procedure, which compensates the systematic errors in range measurements on the basis of σ_r calculated from a batch of samples. However, using this approach in the Sick LMS 200 has an important drawback. Because the Sick's TOF scanner is much faster than the low-cost AMCW sensor, it is possible to scan the environment during the robot motion. Implementing a qualitative error correction procedure, which requires a batch of range readings to calculate σ_r we no longer can use the scanner in motion.

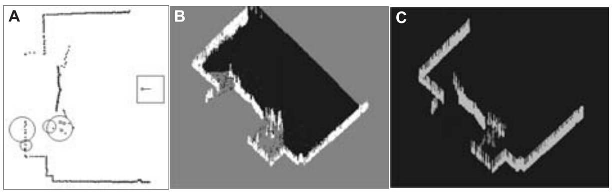

Fig. 10. The LMS 200 data containing a high number of mixed measurements (A) and the grid maps obtained from these data with Bayesian (B) and FSG (C) methods.

To circumvent this problem, we developed an intermediate grid-based representation for the range data. The grid-based map represents space as an array of equal cells. Such a map is able to accumulate data taken from several consecutive poses of the robot while filtering out spurious measurements. The robustness to spurious range data exhibited by the grid-based map stems mainly from the fact, that the given state of the particular cell is a result of many sensory readouts, taken at different moments and from different vantage points. These data are compared and integrated according to the chosen uncertainty calculus. The most popular grid update scheme is based upon the Bayesian theory, which has well-established foundations, but does not have ability to represent the lack of information. An alternative is the fuzzy-set-based method proposed in [11], which provides a good representation of different forms of uncertainty and incompleteness of information.

In the fuzzy-set-based mapping method, originally developed for a sonar-equipped robot, the sets of occupied $\mathcal{O}_i^k$ and empty $\mathcal{E}_i^k$ cells are determined by computing their membership functions according to the sensor beam model [12] for every i-th range measurement taken from the k-th robot pose. The data gathered from a single robot pose are aggregated to the sets $\mathcal{O}^k$ and $\mathcal{E}^k$, representing locally the occupied and empty cells, respectively. The sets $\mathcal{E}^k$ and $\mathcal{O}^k$ generated at the k-th pose are aggregated with the previously available information. Two sets describing the lack of information, by identifying the cells being ambiguous ($\mathcal{A}$) or indeterminate ($\mathcal{I}$) are computed:

$$\mathcal{O} = \mathcal{O} \cup \mathcal{O}^k,\ \mathcal{E} = \mathcal{E} \cup \mathcal{E}^k,\ \mathcal{A} = \mathcal{E} \cap \mathcal{O},\ \mathcal{I} = \bar{\mathcal{E}} \cap \bar{\mathcal{O}}. \quad (9)$$

Then, the sets of cells, that are useful for particular robot tasks can be defined upon the known values of $\mathcal{O}$, $\mathcal{E}$, $\mathcal{A}$ and $\mathcal{I}$.

We are looking for cells containing reliable (correct) range measurements. To this end, we define a set of "support" cells, being very occupied and unambiguous:

$$\mathcal{S} = \mathcal{O}^2 \cap \bar{\mathcal{A}} \cap \bar{\mathcal{I}}. \quad (10)$$

In the fuzzy support grid (FSG) computed according to the above formula reliable measurements are identified in cells of high membership degree to the $\mathcal{S}$ set.

Alternatively, we can look for areas that can be dangerous to the mobile robot, and should be avoided. We define a set of "dangerous" cells that are occupied or contain ambiguous evidence, possibly caused by dynamic objects or hardly-observable obstacles:

$$\mathcal{D} = \mathcal{O} \cup \mathcal{A}. \quad (11)$$

From the experimental results we have found that the fuzzy grid map update scheme is most appropriate for the application under study, being able to filter out most of the mixed pixels and other corrupted measurements, e.g. caused by dynamic objects in the vicinity of the robot. Figure 10 shows grid maps obtained from LMS 200 data collected with a stationary robot observing an obstacle containing thin vertical rods, which cause many mixed measurements (Fig. 10A). The Bayesian scheme (Fig. 10B) is less efficient in removing the false evidence of occupation caused by mixed measurements, because it requires a large number of readings supporting the ”empty” assertion to discount the effect of past measurements. In contrary, in the fuzzy framework the occupied and empty sets are not complementary, what enables to identify the level of contradiction between the consecutive measurements and to remove the spurious readings from the map of support cells (Fig. 10C).

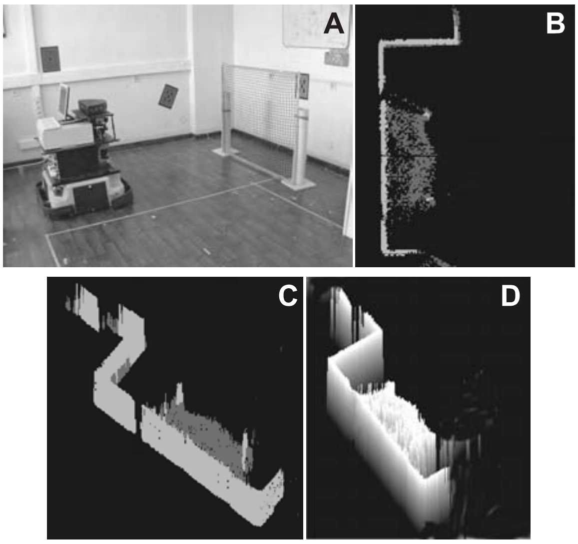

Fig. 11. Experimental set-up (A), the resulting fuzzy support grid (B), its 3D view (C), and the 3D view of fuzzy map of dangerous areas (D).

The FSG map also removes effectively mixed measurements obtained in-motion, assuming a good pose estimate is available to the robot. The grid-based mapping paradigm provides no means to accommodate the spatial uncertainty induced by pose errors. Because of that, if the FSG is built using scans registered with the odometry, it can become inconsistent due to registration errors. To avoid such problems, the robot odometry is corrected with estimates of relative displacements obtained from incremental scan matching [12]. Figure 11 shows grid maps built from LMS 200 data obtained from a moving robot. The robot approached a net-like obstacle (a plastic net typically used for fences) located about 1 m from a wall (Fig. 11A). The net-like obstacle generated a lot of mixed measurements, rendering the wall behind it almost undetectable to the navigation system of the robot. Using the FSG it was possible to eliminate the mixed measurements and to build a correct map of the observed area (Fig. 11B, C). This map supports feature extraction by identifying the areas, containing information on static, reliably detectable objects (walls, poles supporting the net). Then, the features are used in the simultaneous localization and mapping, which forms the core part of a mobile robot navigation software [12, 14]. Also, a fuzzy map of dangerous areas was built (Fig. 11D). This map enables the robot to identify the net-like object as an obstacle, and to avoid it.

Results of another experiment, performed with the LMS 200 laser scanner in a corridor, are presented in Fig. 12. In this experiment, a dynamic object was introduced (a person walking in front of the robot) in the field of view of the scanner, and the robot poses have been obtained from scan matching. In Fig. 12A a grid map of the occupied areas obtained with the Bayesian method is depicted, while Fig. 12B shows a map of the support cells obtained with the fuzzy method. The Bayesian method failed to eliminate the data produced by the moving object. The map of fuzzy support cells correctly identifies the areas corresponding to static objects (walls), while efficiently removing the spurious range readings.

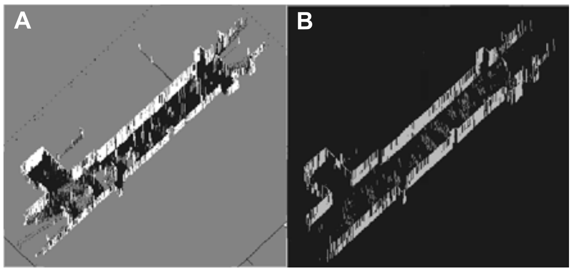

Fig. 12. Comparison of grid maps produced by the Bayesian (A) and the FSG (B) algorithms.

5. Conclusion

Qualitative-type measurement errors have been investigated experimentally for two different classes of the 2D laser scanners, and explained by analysing the physical phenomena underlying their operation. It was found that the qualitative uncertainty in laser range measurements is caused mainly by interaction of the finite aperture laser beam with the environment. Such interaction manifests itself by the mixed measurement effect.

Due to the range-intensity coupling in the AMCW laser scanner the mixed measurements may appear not only between the two surfaces illuminated by the beam, but also in front of the closer object or behind the farther object. In contrary, in the TOF laser scanner the mixed measurements appear only between the two objects. Moreover, in the particular case of the Sick LMS 200 sensor the mixed measurements are observed only if the separation between the two objects is not much bigger than the emitted pulse width. For the LMS 200 scanner we have observed no mixed measurements caused by a sudden change in the target surface reflectance.

In both the AMCW and the TOF scanners the range readings taken under the mixed measurement condition exhibit greater spread than the correct ones, i.e. the measurements are not repeatable. This observation gave rise to the grid-map-based method that removes the spurious range readings, being either mixed measurements, or caused by dynamic objects.

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