

CHARACTERIZATION OF A COMPACT LASER SCANNER AS A SENSOR FOR LEGGED MOBILE ROBOTS

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ABSTRACT

This article considers selected operational characteristics and measurement errors of the 2D laser scanner URG-04LX, which is a compact sensor suitable for walking robots. Quantitative errors in range measurement are evaluated considering the intensity output available from the sensor. The obtained intensity values help to correct the range measurements with regard to the optical characteristics of the observed surfaces. Moreover, mixed measurements are characterized and compared to the mixed measurements characteristics in the popular Sick LMS 200 laser scanner. Finally, it is shown how taking into account the error characteristics of the URG-04LX scanner improves its performance as the main exteroceptive sensor of a small walking robot.

KEYWORDS

mobile robot, walking robot, navigation, sensor, laser scanner, measurement errors.

Introduction

Nowadays the use of robots in industry is no longer related only to repeatable technological processes. More autonomous mobile robots, such as the Automated Guided Vehicles, are addressing the new requirements for flexibility and intelligence in industry. Moreover, in some areas of the industry robots are used also to improve security and safety in manufacturing plants. Mobile robots can localize gas or leakage sources, survey environmental conditions in hostile environments (e.g. in chemical plants), and perform patrol or area security missions (robotic guardians) [1]. Mobile robots are also useful for search and rescue teams in case of a disaster. Robots can safely enter areas and buildings (e.g. of a contaminated industrial plant) that are inaccessible to the human rescuers. It is obvious that in the safety, security, and rescue scenarios high mobility and agility of the robot may be extremely useful.

In particular, walking robots can cope well with the lack of roads, rugged terrain, debris, etc. How-

ever, despite major achievements in the past years, walking robots cannot compete with wheeled and tracked robots concerning their autonomy. A high level of autonomy can be achieved only if the robot perceives the surrounding terrain and plans its motion on the basis of on-line perception.

Nowadays laser range finders and 2D/3D laser scanners are the most used exteroceptive sensors in mobile robotics. However, walking robots require compact, lightweight, and energy efficient sensors. An example of a walking robot designed for search, security or reconnaissance missions is the six-legged robot Messor, developed in the Institute of Control and Information Engineering at Poznań University of Technology. Messor uses the Hokuyo URG-04LX miniature 2D laser scanners as its main sensors (Fig. 1). On Messor one URG-04LX is tilted down, to scan the terrain ahead of the vehicle with the fanning laser beam, enabling terrain mapping [2]. The second URG-04LX is level-mounted in order to acquire profiles of the surrounding walls for self-localization with scan matching [3]. The compact 2D laser scanner is

of particular interest for small, affordable walking robots like Messor, because such robots cannot carry bigger and heavy 3D laser scanners.

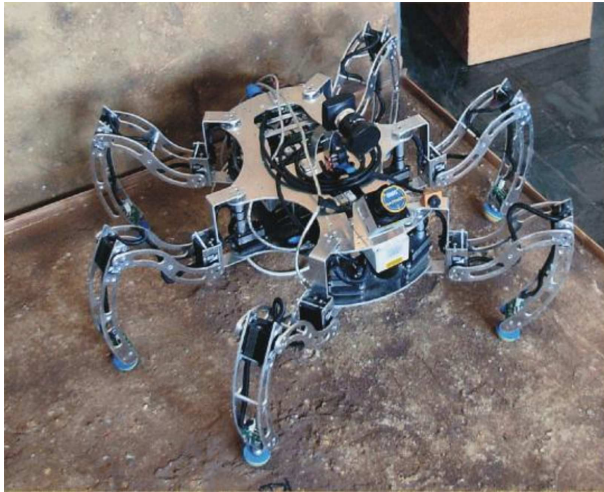


Fig. 1. Messor walking robot equipped with two URG-04LX laser scanners.

The application of URG-04LX sensors to a robot capable of both indoor and outdoor operations revealed limitations of this miniature scanner. Compared to the well-known Sick LMS 200 sensor [4], the Hokuyo URG-04LX not only has shorter range of measurements, but the measured distances to a much bigger extent depend on the optical properties of the surfaces being observed. Moreover, significant qualitative errors occur when the laser beam hits simultaneously two objects at different distances. Such errors are known in the literature as mixed measurements or discontinuous points [5].

The Hokuyo URG-04LX was already characterized by others [6, 7], but in this article we focus on the use of this sensor to support particular navigation tasks carried out by the legged mobile robot. We provide case studies demonstrating the use of the URG-04LX scanner to support various tasks of the robot. Then, we show how to take advantage from the extended scanning modes that make it possible to obtain not only the range measurements, but also other parameters of the returning optical signal.

The URG-04LX laser scanner

Distance measurements in laser scanners are accomplished either by determining the time of flight of an emitted laser pulse traveling to a target and then reflected back (Time of Flight – ToF), or by determining the phase-shift between an amplitude modulated continuous wave (AMCW) and its reflection.

The Hokuyo URG-04LX laser scanner exploits a variant of the AMCW ranging technique [8], in which the distance to a target is proportional to the difference of phase between the wave of laser light, and a fraction of this wave reflected by the target surface back to the sensor. The URG-04LX uses two different amplitude modulation frequencies in order to avoid the distance ambiguity, which allows the sensor to detect distances between 0.02 m and 5.6 m. However, the actual measurement range is smaller – up to 4 m for most of the surface types. A near-infrared (785 nm) laser diode is used as the beam source [8]. The laser beam is deflected by a rotating mirror in the default range of 240° with the angular resolution of 0.352°. In this mode a single scan contains 683 range measurements. However, both the angular field of view and the angular resolution can be set by software.

The default control protocol (SCIP 1.1) allows only for range measurements, while the extended one (SCIP 2.0) makes it possible to obtain also the received intensity values, and the AGC (Automatic Gain Control) voltage, depending on the mode being selected. Unfortunately, the modes allowing for additional measurements have smaller angular resolution: 0.704° for the intensity mode, and 1.056° for the intensity/AGC mode. According to the manufacturer the URG-04LX scanner measures ranges up to 1 m with the accuracy of 10 mm, and ranges between 1 and 4 m with the accuracy of 1% of the measured distance. However, this is specified only for a white sheet of paper.

Measured range errors

The methodology of the range accuracy characterization was largely inspired by the approach used in previous research on the sensor [6, 7]. However, we experimented with the URG-04LX scanner using both the standard mode and the intensity modes available through our custom-made software. The simple mechanical setup we use allows to manually change the distance and incidence angle of the target surface, which is a sheet of paper of A4 size. Because the distance between the sensor and the target surface is measured by a 4 m long ordinary meter, we stacked the URG-04LX with the LMS 200 laser scanner with a common origin of the coordinate system in the xy plane, to obtain additional ground truth measurements, and restored intensity (C).

The URG-04LX scanner suffers from a strong dependency between the accuracy of the range measurements and the optical properties of the target surface because of the used ranging principle (Fig. 2).

The consequences of this fact are twofold:

- some black or shiny surfaces do not provide valid range measurements – the sensor signalizes a faulty reading, or the measured range is much shorter than it should be
- an universal calibration model is difficult to establish without the knowledge of the target surface properties.

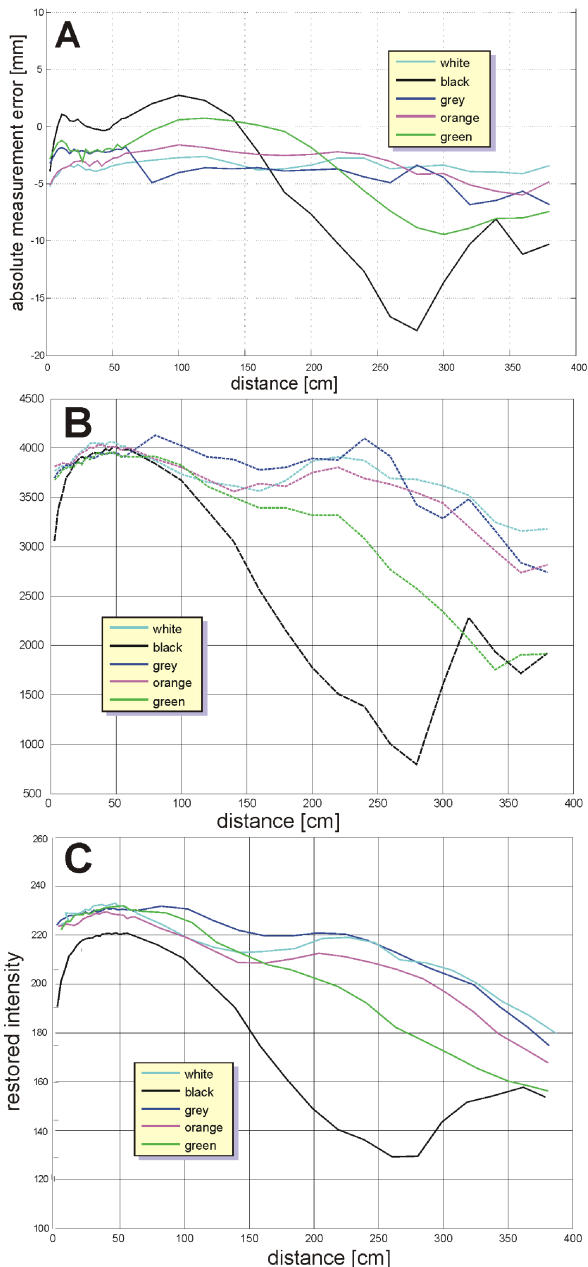


Fig. 2. Effects of surface type on range measurement accuracy (A), intensity (B,C).

A simple calibration model for reducing the systematic errors is proposed in [7]. However, this linear

model results in large residual distance errors whenever it is used in terrain mapping to correct distances smaller than 1000 mm at incidence angles of about 30° . Thus, a non-linear calibration model has been established, which is intended to capture behaviour of the URG sensor in the application of terrain profile acquisition [2]. The resulting calibration is given as:

$$r = r_m + \Delta r_m, \quad (1)$$

$$\Delta r_m = 38.6 + 0.18r_m + 0.3 \times 10^{-3}r_m^2 - 0.2 \times 10^{-7}r_m^3, \quad (2)$$

where r_m and r are the raw and the corrected range measurement, respectively.

The model given by (2) captures behaviour of the URG-04LX scanner for the distances from 50 mm to 1000 mm. With this calibration the residual errors of the corrected measurements are kept within the 1 cm boundaries for various surfaces (Fig. 3). However, for some dark surfaces this calibration does not work well, and the residual error is unacceptable.

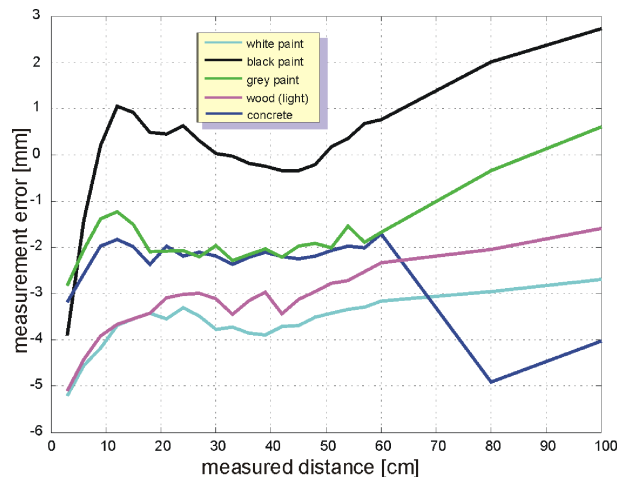


Fig. 3. Calibrated range measurements for five different target surfaces.

Therefore, we attempted to establish a more elaborated calibration model, which takes into account the intensity output available via the SCIP 2.0 protocol. However, the intensity I obtained from the URG-04LX scanner is not the true received intensity, but it is equivalent to the amplified output voltage of the APD (Avalanche Photodiode) used as the receiver in the device. Because in URG-04LX the amplification is controlled by the AGC unit, the intensity available to the user is a non-linear function of the true intensity [9]. By reading the AGC voltage values from the sensor it is possible to eliminate the AGC influence, and to obtain I_{res} – the so-called restored intensity [10], which is given by:

$$I_{\text{res}} = \frac{\sqrt{I} \cdot 1023}{v_{\text{AGC}}}, \quad (3)$$

where v_{AGC} is the AGC voltage, and 1023 is the range of the 10-bit A/D converter used on the voltage output. Results of some experiments with paper surfaces of different colours performed in the intensity/AGC mode are shown in Fig. 2. For the surfaces under study the absolute measurement error Δr_m fits within the limits specified by the manufacturer (Fig. 2A), however, the dependency between the error and the measured distance r_m is highly nonlinear, particularly for the black paper.

Results of experiments in the intensity/AGC mode (Fig. 2B and 2C) suggest that there is a dependency between the received intensity and the range measurement error. This hypothesis is also supported by the literature. For example, [5] shows how this dependency develops in the phase measuring circuitry of an AMCW range finder. However, unlike Adams [5], we do not have access to the internal structure of the sensor under study. Therefore, we try to approximate this dependency from the available experimental data. To this end we apply the approximation technique based on multi-dimensional Gaussians, which we already developed for approximation of the decision surface in the foothold selection problem of a walking robot [11]. The structure of the approximation polynomial is suggested by the generalized form of the Kolmogorov theorem:

$$\Delta r_m(r_m, I_{res}) = \sum_{q=0}^m c_q \cdot \exp(\lambda_{1,q}(r_m - a_{1,q})^2 + \lambda_{2,q}(I - a_{2,q})^2). \quad (4)$$

In (4) two-dimensional Gaussian functions are used, which are shaped to follow the available experimental data by the parameters $\lambda_{i,q}$ and $a_{i,q}$, with $i = 1, 2$ and $q = 0, \dots, m$, where m represents complexity of the calibration model and is a design parameter. The vector of c_q coefficients can be efficiently computed from Least-Squares Fitting using the Gram matrix [11]. However, finding optimal values of $\lambda_{i,q}$ and $a_{i,q}$ is an optimization problem. Here the Particle Swarm Optimization (PSO) [12] is used to find optimal values of $\lambda_{i,q}$ and $a_{i,q}$. The approximation procedure results in a closed-form function that can be later used in real-time to correct the range measurements.

Figure 4A shows the surface that represents (4) for the collected calibration data. To verify the calibration we used range data collected on real target surfaces: white painted wall, matt black painted furniture, wooden plate, and white styrofoam plate (Fig. 4B). The slanted background on the plot denotes the boundaries of the measurement errors given by the manufacturer. As one can see, the actual errors are far beyond these boundaries. However, when

calibration according to (4) is applied (Fig. 4C), the range errors are kept smaller than 1% of the distance, for all the targets under study.

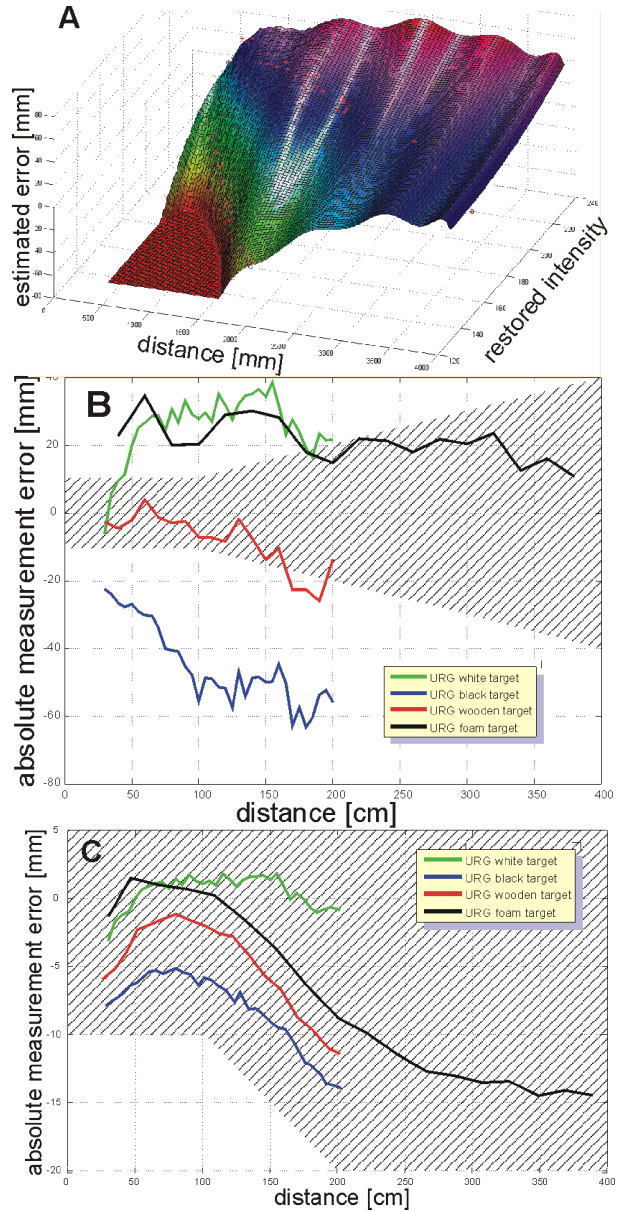


Fig. 4. Obtained calibration surface (A), measurement errors prior to calibration (B), and after calibration (C).

Measured range uncertainty

Rigorous modelling of measurement uncertainty, e.g. obtaining the variance of the measured ranges is problematic for the compact scanner under study. As shown by others [6] the standard deviations observed for URG-04LX measurements are small even for large absolute errors in the measured distance. Our experiments show that there is also no clear dependency

between the intensity output and the observed standard deviation. Therefore, the method for estimating the range variance in a phase-shift-based range finder upon the known intensity output proposed in [5] cannot be applied here. We hypothesize, that this behaviour of the URG-04LX scanner occurs due to the use of two different modulation frequencies in order to avoid the distance ambiguity. Eventually, we take a rough but conservative approximation of the range errors.

We used experimental data for measured distances from 50 to 1000 mm with five different surfaces and the incidence angle of 30° . We picked the largest standard deviation for every measured distance, and then established a mathematical model that approximates the change of the range standard deviation σ_r as function of the measured range. The approximated curve shown as the solid line in Fig. 5 gives standard deviation values larger than most of the used actual measurements (shown as small circles), only errors of measurements from a black-painted surface are slightly underestimated.

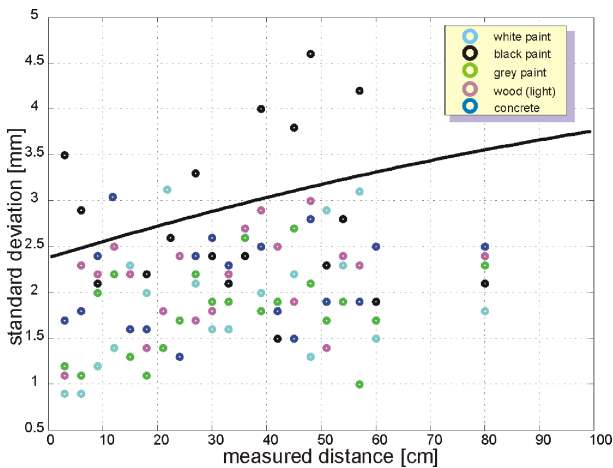


Fig. 5. Dependency between the range standard deviation and the measured distance.

Qualitative errors

The calibration does not eliminate corrupted range measurements, which are not suitable for further processing. Some of these errors are caused by the mixed measurements, and they can be removed by clustering the range measurements and analyzing discontinuities in the scanned sequence [11].

Taking advantage of our experimental setup, we made a comparison of the mixed measurement characteristics between the Hokuyo URG-04LX and Sick LMS 200 scanners. The most important differences in the spatial characteristics of mixed measurements

are illustrated in Fig. 6. The number of mixed measurements (generated by a plastic net) in the LMS scan (Fig. 6A) is much smaller than in the scan of the URG sensor (Fig. 6B). Note that in the URG scan there are mixed measurements located in front of the closer obstacle (denoted as '1'). More differences appear if the two scanners are moved towards the net, making a pair of scans in one-centimeter increments. From Fig. 6C one can see that the mixed measurements of the LMS scanner are spatially isolated, but in the URG-04LX scan (Fig. 6D) there are mixed measurements in front of the closer object ('2') and some behind the farther object ('3').

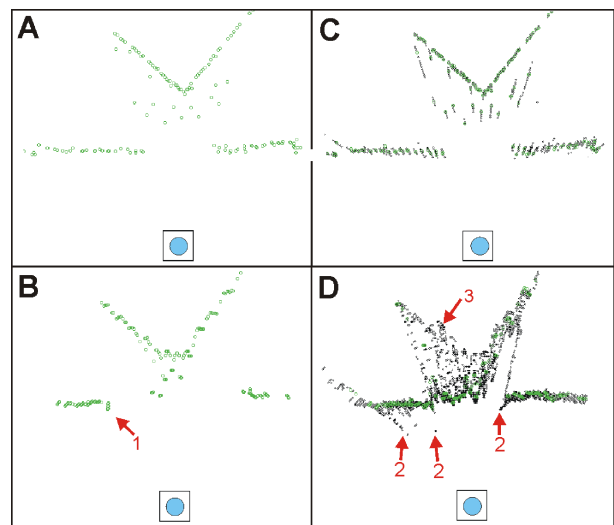


Fig. 6. Comparison of mixed measurements in the LMS 200 and URG-04LX scanners.

Experimental results involving different types of surfaces show that the range measurement noise distribution is approximately Gaussian, as long as the measurements are not mixed (Fig. 7A). However for mixed measurements, a distribution with two prominent peaks is usually obtained (Fig. 7B). These two peaks roughly indicate the distances at which the two surfaces involved in creation of the mixed measurement phenomenon are located.

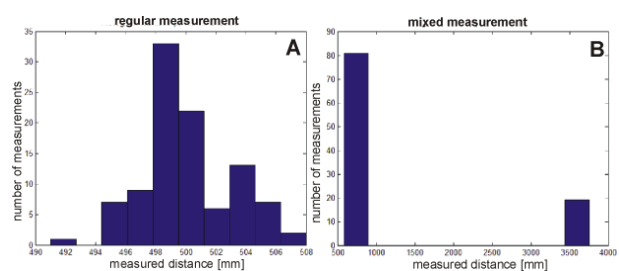


Fig. 7. Range measurement distributions for a normal measurement (A), and a mixed measurement (B).

Erroneous range readings are also caused by black, highly reflective or semi-translucent surfaces. However, they can be removed by taking into account the obtained intensity values. Figure 8 shows an example laser scan from the URG-04LX working in the intensity mode (no AGC available). The intensity values of range measurements are visualized by the size of the black circles. A bigger circle means weaker intensity output. The green points indicate the measurements of the co-located LMS 200. Matt black objects ('1' in Fig. 8) are perceived at ranges shorter than the real distances, with low intensity. Shiny surfaces located close to the sensor can appear farther than in reality ('2'), with high intensity values. Small-size surfaces (e.g. table legs) often yield very weak intensity output, with much shortened distance measurements ('3'). However, lower intensity values are also registered for surfaces of good reflective properties, if they are located at bigger distances ('4'). Therefore, simple intensity thresholding is insufficient, and we experimentally identified the range-intensity characteristics of the most common erroneous readouts. We use thresholding in the range-intensity space to remove them, by discarding measurements of very low intensity values and high intensity values with short measured range.

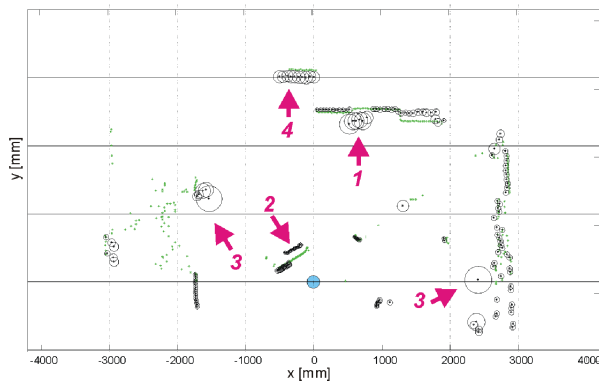


Fig. 8. Example range measurements identified by their intensity values.

Applications in the walking robot Messor

The self-localization system of the Messor robot that uses scan matching with a level-mounted URG-04LX scanner takes advantage of our characterization of the range data errors (cf. Fig. 8) by eliminating the vast majority of corrupted range measurements through range/intensity thresholding [3]. In this application the intensity mode is used, because

the number of 227 scanned points over the 240° field of view in the intensity/AGC mode is too small for the point-to-point scan matching method being used. The received intensity output alone gives no reliable characteristics of the scanned surfaces, but provides useful hints that some range readings may be in error.

To prove the correctness of the scan matching procedure and test the possibility to clean-up the URG-04LX range data from qualitative errors experiments in a large indoor environment were carried out. This environment, depicted in Fig. 9A and 9B contains surfaces that cause larger range measurement errors of the URG-04LX sensor, e.g. glass panels and brick-covered walls. The robot walked on a flat, tiled surface, which caused much slippages. The map computed by registering the laser scans with the dead reckoning data is unacceptable (Fig. 9C). Applying the scan matching procedure to the cleaned-up URG-04LX range data resulted in a map that not only correctly reconstructs the overall geometry of the environment, but also captures most of the details, such like the rectangular pillar, and the entrances to the two elevators (Fig. 9D).

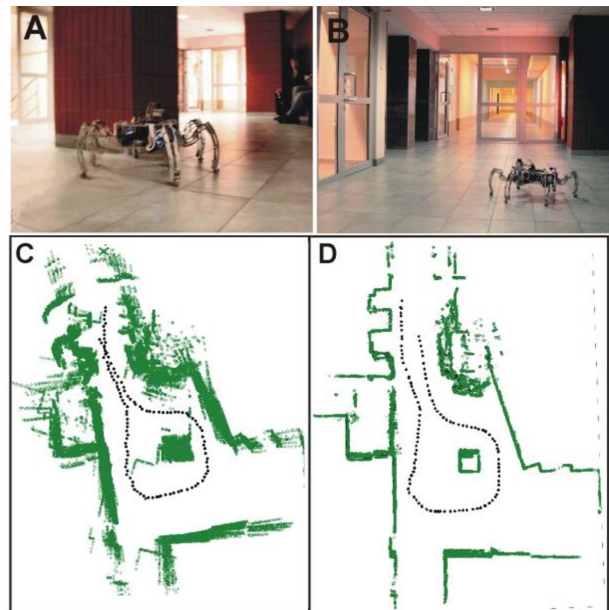


Fig. 9. Experiment in a realistic environment: Messor during the experiment (A,B), scans registered by odometry (C), and results of scan matching (D).

Because of the differences in the spatial characteristics of the range measurement errors described in Sec. 5 the terrain mapping system for the Messor robot has been augmented with new procedures that eliminate the erroneous range measurements at the pre-processing stage, before these measurements are

integrated into the elevation map. These procedures are described in details in [11] and [13].

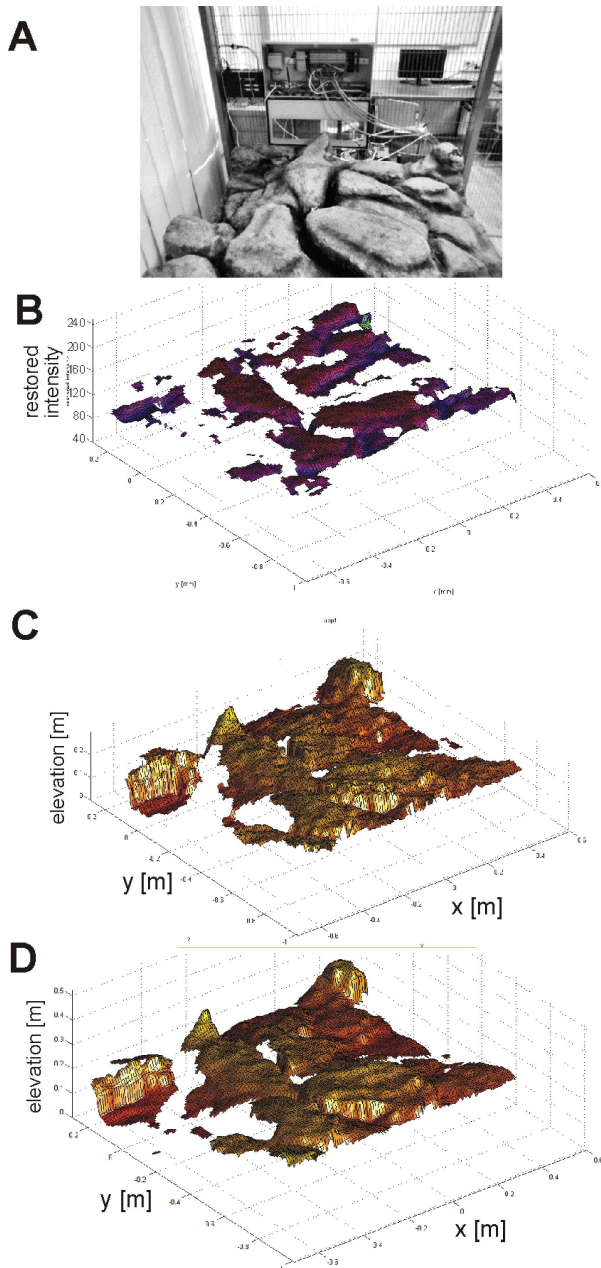


Fig. 10. Example terrain maps: experimental setup with terrain mockup (A), restored intensity (B), elevation with SCIP 1.1 (C), elevation with SCIP 2.0 (D).

Using a realistic rocky terrain mockup (Fig. 10A) and an industrial robot arm to move the URG-04LX scanner (to have “perfect” localization) we experimented also with the intensity/AGC mode for terrain mapping. Although the range measurements in the intensity/AGC mode have much lower angular resolution, it is enough for short-range terrain map-

ping, as shown in Fig. 10, where an example map built in the default (range only) mode (Fig. 10C) is compared to a map built using the intensity/AGC mode (Fig. 10D). The restored intensity values can augment the usual elevation grid map by providing information about the optical characteristics of the terrain in front of the robot (Fig. 10B).

Conclusions

This paper characterizes the miniature URG-04LX laser scanner, which is suitable for walking robots. The contributions include

- evaluation of the uncertainty of range measurements taking into account the restored intensity values;
- adaptation of our own Gaussian-based surface approximation method to correct systematic errors in the range measurements;
- analysis of the mixed pixel phenomenon and other quantitative errors due to varying optical properties of the observed surfaces.

Moreover, we show that in applications of such a low-cost, miniature sensor, its error characteristics have to be carefully taken into account. This helps to obtain reliable range data for navigation of a walking robot that cannot use a more reliable full-size laser scanner.

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