Are laser scanners replaceable by Kinect sensors in robotic applications?

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***Abstract*—Laser scanners are omnipresent in robotic applications. Their measurements are used in many scenarios for robust map building, localization, collision avoidance, etc. But regarding the required precise measurement and mechanical system a laser scanner is quite expensive. Hence the robotic community is looking for alternative sensors. Since 2010 a new 3D sensor system – Microsoft Kinect [1] – developed for computer games is available and applied in robotic applications. With an appropriate filter tool-chain its output can be mapped to a 2D laser scanner measurement. The reduced data set is ready to be processed by the established algorithms and methods developed for laser scanners. But will the Kinect sensor replace laser scanners in robotic applications?**

This paper compares the technical parameters of the new sensor with established laser scanners. Afterwards we investigate the possibilities and limits of a Kinect for three common robotic applications – map building, localization and obstacle avoidance.

I. Introduction

Each robotic application requires a reliable perception of the environment. The effort increases with the complexity of the tasks. In a well defined scenario without unexpected situations (encapsulated industrial manipulators) a limited sensor configuration guarantees a correct and reliable behavior. An autonomously navigating system which moves in complex (everyday) scenarios and interacts with humans has to monitor much more aspects of the environment. The related tasks in service robot applications demand different sensor requirements. For a collision avoidance a complete coverage of the area around the robot is important. In contrast, many localization algorithms do not need a complete "panorama view" but depend on representative number of samples. As a last example, the sensors of a gripper have to provide a precise contour of the object that has to be manipulated.

In many scenarios a laser scanner system can (partially) fulfill these different perception needs. The combination of a distance sensor (mostly time-of-flight method) with an actuator (one to three degrees of freedom) allows to reproduce the environment in 2D, $2^1/_2$D or 3D representations. The measurement distance ranges between a few millimeters and 10 km for geodetic systems. A permanent improvement of the sensor and the mechanical system allows an increased measurement precision, resolution and scan frequency. Hence, some systems for 3D scans generate such a large amount of data – 800.000 points/sec – that an online processing is not possible [2]. A detailed introduction into the functional principle of laser scanners is given in [3].

In navigation scenarios with ground driven mobile platforms 2D laser scanners are commonly used. With the assumption of height-independent obstacles, these sensors provide all information to derive an appropriate geometric map of the environment that is ready for localization, trajectory planning and movement tasks. As described in [4] a large number of algorithms and processing concepts for filtering, map generation, localization or obstacle avoidance exist. Tab. I summarizes the technical properties of two popular scanner types for robotic applications – the SICK LMS200 [5] and the URG-04LX-UG01 [6] manufactured by Hokuyo. Obviously, the SICK laser scanner provides a larger measurement range, precision and resolution but the benefits are bought dearly with a higher power consumption and an extended geometric size. A detailed statistical analysis of the measurement behavior is done by Ye and Borenstein [7] for a SICK LMS 200 and by Kneip *et al.* [8] for the Hokuyo sensor.

Figure 1. Our robotic platform prepared with the three sensor systems – Hokuyo URG-04LX-UG01, Microsoft Kinect, SICK LMS200 – for navigation tasks

The main disadvantage of both scanner types is the high price. If we assume a complex environment that requires a multi-level perception of obstacles, a second, third, etc. scanner would be necessary. In this case, the costs of a robot system would be dominated by the sensor equipment. Hence, many application developers are looking for alternative sensor systems with a similar coverage and accuracy of measurement. Beside single and stereo camera systems [9] and radar applications [10], a new 3D sensor system called Kinect is available since November 2010. The Kinect distributed by Microsoft Cooperation integrates a 3D and 2D camera system and a microphone array. Based on theses sensors, the system provides human recognition and tracking. Originally the Kinect was developed for video games but due to the 3D perception capabilities and the low price it is integrated in a number of robotic hardware configurations today [11].

The depth image of the Kinect sensor enables a wide variety of processing strategies for robot navigation in 2D or 3D. The applicability of navigation tasks based on 3D data sets is shown in different publications for the Kinect sensor [12, 13]. But the huge amount of data is reliant on a high performance computer for processing. The Kinect sensor generates a data stream of approximately $17.5\ \mathrm{MB/s}$ (640x480x2 Byte x30 fps). For instance, as described by Endres *et al.* [14] and similar by Henry *et al.* [15] none of the common used 3D Simultaneous Mapping and Localization (SLAM) algorithms is able to follow the sample rate of the Kinect sensor (30 Hz). A navigation stack using a reduced data set can be implemented on an embedded hardware without Graphics Processing Unit (GPU) support. Hence, in this paper we focus on a selective processing of Kinect's output. If a single horizontal line is isolated from the measurement set, it can be transformed into a laser scanner output. Following this approach, an expensive laser scanner can be replaced by a cheap 3D sensor system. Ideally, the applicability of the navigation algorithms tailored for laser scanners should not be affected by this replacement beside some parameter adaptations.

The aim of this paper is a navigation task oriented comparison of the Kinect sensor with a common used laser scanner. We choose the Hokuyo URG-04LX-UG01, with a similar range and measurement accuracy for our investigation. A SICK LMS200 with a much better performance is additionally included as a reference. The complete experimental setup that combines the three sensors on a mobile platform is shown in Fig. 1.

A similar investigation is described in [16] but the focus is on the spatial registration of construction sites. Rafibakhsh *et al.* argue, that the Kinect cannot take over the tasks of high-end terrestrial laser scanners. But they realize a high potential related to the low price, the increased resolution and depth accuracy in multi-Kinect systems and the possibility of an online modeling of the environment. The authors of [17] describe an experimental setup for an evaluation of the angular and linear resolution of different sensors – Kinect, Hokuyo URG-04LX (more precise version of the URG-04LX-UG01) and Asus Xtion. The sensors are oriented on a board with holes of different sizes (2.5 mm-10 cm). The authors present a detailed analysis of the detectability of a certain size related to the measurement distance and orientation.

The paper is organized as follows. The subsequent section addresses the technical parameters of the Kinect sensor compares them with the Hokuyo and SICK laser scanner. Beside we discuss possible disturbances and interferences for both sensor types. Sec. IV investigates the behavior of the sensors in three typical robotic applications: Obstacle avoidance, map building and localization. Finally we want to give an answer to the title question and describe future work.

II. Technical Comparison

A. Functional principle and main properties of the Kinect

The Kinect transmits an infrared pattern generated with a diffraction grating and receives the reflections of the environment using an IR camera. A pseudo-stochastic distribution allows an assignment of a subset of dots to a specific area. For performance reasons 3 different light densities are implemented. The highest level is reached by nine calibration dots to provide a fast raw localization. The processing unit compares the position of the reflected dots on the baseline with a reference pattern that was generated as a reference distance and is stored in the memory of Kinect's processor. For each dot a 11 bit value is calculated. A "0" indicates an invalid or out of range measurement while all other values represent the corresponding distances in a non-linear relation. Accordingly, the depth resolution of the Kinect is varying between 0.25 cm (d =0.8 m) and 4.8 cm (d =4 m). The minimum distance of 0.8 m is fix but a maximum range is not implemented in the Kinect sensor. Different authors recommend to reject distance values larger than 3 m [18] or 4.6 m [19] due to the uncertainty level in the software. We will discuss about the accuracy of Kinect measurements more detailed in following paragraphs.

Tab. I compares the technical parameters of the Kinect sensor with the two common used laser scanners. Obviously, the SICK laser scanner is in a different league compared to the Kinect and Hokuyo sensors. It provides a significantly higher performance related to range and precision. Additionally, the SICK firmware allows a specific adaptation of the sensor for a specific application (range, resolution, measurement angle, etc.). Neither the Kinect nor the Hokuyo sensor provides such a detailed configurability. Hence, this system is not comparable directly with the Kinect sensor but its capabilities are used as a reference for the following investigations. A detailed discussion of the SICK LMS200 is given by Ye and Borenstein [7].

A more suitable competitor for the Kinect is the Hokuyo URG-04LX-UG01, a simplified and cheaper version of the URG-04LX [20]. This laser scanner has a maximum range and accuracy comparable to the Kinect sensor. One important difference is the size of the dead zones. The Kinect cannot differ infrared dots on close obstacles due to blooming effects. Hence, the sensor is not able to monitor the immediate environment of a robot. The new version of the Kinect – Kinect for Windows – reduces the dead zone by the half while running in a special close area mode. In this case the resolution and the maximum range are reduced.

Related to the different operation principle the laser scanner provides a larger measurement angle. Like many laser scanner devices, the Hokuyo delivers its measurement in a polar coordinate system, with a constant angular resolution. In contrast, the output of the Kinect sensor bases on a Cartesian system and depends on the distance and deviation to the zero axis. It is noticeable that the nominal angular resolution of the Kinect is much smaller than the value of the Hokuyo sensor. Additionally, the distance resolution of the Kinect sensor is variable, too.

Table I
COMPARISON OF TECHNICAL PARAMETERS OF THE MICROSOFT KINECT, HOKUYO URG-04LX AND SICK LMS200

	Sensors		
	Kinect	Hokuyo	SICK
Maximum range [m]	3-6	4	8-80
Dead range [m]	0.8/0.4	0.06	0.07
Horizontal angle [°]	57	240	100-180
Distance resolution [mm]	2.5-48	1	1-10
Angular resolution [°]	≈ 0.097	0.3515	0.25-1
Accuracy [mm]	+/-6 (1m) +/-130 (4m)	+/-30 (1m) +/-120 (4m)	+/-10 (10m)
Geometry [mm]	65x290x70	50x50x70	155x156x210
Weight [kg]	0.55	0.16	4.5
Power voltage [V]	12	5	24
Power consumption [W]	5	4	30
Refresh rate [Hz]	30	10	18-75
Output data [kB/s]	18000	5.4	500
Interfaces	USB	USB	RS232, RS422
approx. costs $	150	1000	5000

It is difficult to compare the accuracy of both sensors due to the different fault models. The data sheet of the Hokuyo scanner describes a constant error of +/-30 mm for distances smaller than 1 m. For larger ranges a proportional offset of 3 % has to be considered. The capabilities of the Kinect related to the accuracy were analyzed in [18]. The author derives a polynomial relation between measurement distance and standard deviation of the depth result. For a range of 400 cm, σ_K reaches 2.5 cm. If a normal distribution is assumed, each measurement is located in a window of +/-7.5 cm. For reaching this noise level the user has to calibrate its Kinect sensor [18]. It is remarkable that for distances smaller than 1.5 m the Kinect provides a higher accuracy than the laser scanner. If the object is out of this range the Hokuyo sensor generates the better results.

As shown in Tab. 1, the Kinect sensor is much larger than the Hokuyo sensor. An additional challenge is the required power supply voltage of 12 V. The laser scanner operates with the power level of a USB connection.

In comparisons, the SICK sensor needs a 6 times higher power supply. But it outputs data in a significant higher frequency (using the lowest angular resolution). Accordingly, the output data rate is much higher for the SICK LMS200 scanner. Related to the 3D representation the Kinect generates a data stream of 17.5 MB/s. The required performance for filtering and feature extraction limits its applicability in embedded devices. Consequently, the Kinect is much cheaper than the Hokuyo sensor but cannot be integrated in a small size (8-Bit) application.

III. Disturbances for Kinect measurements

Chiu *et al.* [21] and Khoshelham [18] list a number of disturbance types responsible for Kinect faults. We want to address the most important in the following paragraphs.

A. Parallax Problem

Related to the displacement between infrared transmitter and camera parts of the environment are "visible" for one of the interfaces only. If the camera monitors a surface that cannot be reached by the infrared pattern the Kinect produces a gap in the point cloud. The same result occurs in the contrary case if the dots are not in the line of sight of the camera. The effect of the parallax problem is amplified by reflective surfaces.

The laser scanners described in this paper combine the transmitter and receiver component point symmetric. Due to the missing displacement a parallax problem cannot appear.

B. Obstacle material

In Chiu *et al.* [21] the authors examine different material properties that make a correct depth measurement difficult. They define 3 categories affecting the detectability and/or measurement accuracy. The first one is the surface color. We found out that a dark area disturbs both sensor types. For the Hokuyo sensor the deviation can reach up to 2 cm. The effect on the Kinect is much smaller.

As expected, both sensors have large problems to perceive reflective surfaces. Especially chrome-plated furniture legs are mostly invisible. The same was measurered for the last category, transparent materials made from glass or plastic. In both cases a redundant sensor with a non-optical measurement principle is needed. Very detailed discussions about the effect of obstacle surfaces are described in [22, 23].

C. External disturbances

Due to the operating principle of the Kinect sensor a correct measurement depends on the lighting conditions. If the transmitted infrared pattern is superimposed by strong ambient light, the laser dots appear in low contrast and the camera reaches its saturation level. Consequently, the noise level and the probability of outliers increases significantly [18]. A similar effect occurs when a light source is shinning into the infrared camera itself. Hence, for outdoor robotics the Kinect seems to be not suitable [19]. The integrated webcam should be used to evaluate the lighting conditions in order to minimize this influence.

The data sheet of the Hokuyo laser scanner describes a similar behaviour of the laser scanner. It emphasizes that this sensor is made for indoor applications only [6].

D. Interference

The functional principle of the Kinect sensors results in interference between multiple sensors of this type. If the two infrared patterns are projected on the same area, the processing units cannot separate individual points or are not able to assign them to the correct sensor. Obviously, the disturbance is most significant when both sensors are assembled with a similar orientation. A partial overlapping of two sensors generates complex areas of incorrect measurements. The effect is determined by the geometrical relation of the sensors and by the distance and orientation of the obstacles. The worst case occurs if the calibration dots (the nine brighter ones) are in conflict.

The interference problem was investigated by Rafibakhsh *et al.* [16] in detail. At the end an angle of 35° is recommended between two Kinect sensors mounted on the same height in order to minimize interferences. Two approaches [24, 25] have been presented that reduce the effect of interference by exploiting motion blur. Lets assume there is a first sensor looking at a plane in front of it. The whole sensor moves translationally in parallel to the plane. As the projector and the camera are coupled and therefore perform the same movement, the motion doesn't effect the depth image. A second sensor viewing the infrared pattern of the first sensor notices that the pattern is blurred by the motion of the first sensor. In general, the accuracy suffers because instead of a translational motion, the motion blur is induced by vibration, but the degradation is negligible. Another solution to the problem is presented in [26]. Mechanical shutters in front of each sensor prevents interference. In a two sensor setup the cloud of one sensor is only updated when the other sensor returns at least 90% zeros.

For redundant laser scanner systems interference phenomenas have to be considered, too. If two SICK sensors are operating close together with a similar orientation, it is recommended to synchronize both sensors with a Master/Slave protocol [5]. With this configuration the mirrors are maintained in a orientation displaced by 180° relative to each other. More than two sensors are not supported. Hokuyo recommends to implement different mirror frequencies for multiple scanner scenarios.

IV. Application oriented Comparison

Many robotic applications integrate laser scanners with three elementary purposes: obstacle detection, map building and localization. Precondition of all scenarios is reliable and precise measurement of the environment, but with different focuses.

For the further experiments we transform the Kinect output into a laser scanner measurement. A Point Cloud Filter implemented in ROS extracts a single horizontal scan with a height of one dot.

A. Obstacle Detection for collision avoidance

One important aspect of the environment monitoring is the avoidance of collisions. The main challenge here is a complete coverage of all objects close to the robot. A non-observance of an obstacle can occur due to two main reasons:

- An obstacle is overlooked because of the geometrical configuration of sensor's monitoring area:
  - In the simplest case the obstacle is not in range or angle of the sensor system. A scanner with a large opening angle has an advantage here.
  - If an object is tall compared to the sensor resolution, it can probably not be detected. The sensor system has to be selected according to the environment conditions.
- The already mentioned measurement disturbances (total reflections, transparent objects, etc.) make a correct perception difficult and probably lead to danger situation.

For this section we compared the theoretical and practical resolution of the Kinect and Hokuyo scanner. Afterwards, the detection capabilities were tested with different obstacle types.

The Hokuyo sensor shows due to its point symmetric operating principle a constant angular resolution of $0.3515°$. The theoretical gap between two ideal laser beams depends on the measurement distance d_m and can be calculated as visible in Fig. 2. Close to the maximum range the theoretical value of an invisible object is around 2.4 cm. The Kinect emits a larger number (640) of measurement dots with a smaller opening angle in horizontal direction. If a uniform distribution of the measurement dots in x-direction is assumed, the angular resolution of $0.0974°$ can be calculated. Objects smaller than 0.8 cm should not be perceived in a distance of 4 m. The Kinect sensor is superior from a theoretical viewpoint.

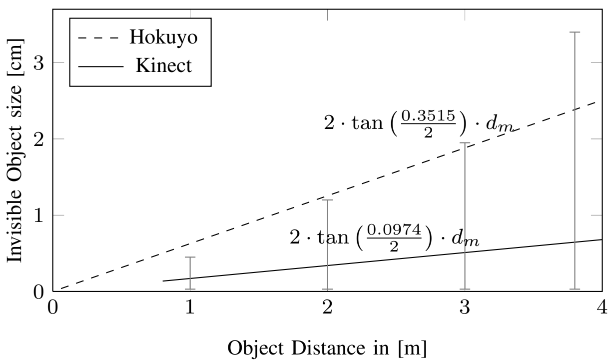


Figure 2. Theoretical size of invisible objects related to the angular resolution for different obstacle distances d_m

As it will be shown, this theoretical model does not provide a realistic evaluation. We installed the Kinect in front of a wall with different distances ($100 - 380$ cm) and isolated a horizontal scan of the Kinect point cloud. Based on the number of measeuements we determine the distribution of the distance between two neighboring dots. The minimum and maximum values are additionally depicted in Fig. 2 by error bars. The maximum value increases with larger distance d_m in a non-linear manner. For 380 cm there are gaps with a much larger size (up to 3.4 cm) than expected. Our investigation outputs a distribution combining two aspects. Between 85 % and 70 % are in a very small corridor close to the theoretical value. The other distance where distributed in a uniform manner between minimum and maximum values.

But for a statement about the detectability additional investigations are necessary. We enhance the setup of the already mentioned work from Bernhard *et al.* [17] and evaluate the detection capabilities of the sensors with flat and round objects of different sizes. We prepare a set of stripes and columns with a width/diameter from 0.5 cm to 8 cm. The surfaces are covered by white paper.

Table II
OBJECT DETECTION CAPABILITIES DEPENDING ON THE OBJECT TYPE AND SIZE

		Obstactle distance d_m [cm]				
		30	100	200	300	380
minimum diameter of a column [cm]	Hokuyo	0.5	2.0	3.0	6.5	7.0
	Kinect	-	1.0	2.0	2.5	3.0
minimum width of a stripe [cm]	Hokuyo	0.5	2.0	3.0	6.0	7.0
	Kinect	-	0.5	1.5	2.5	5.0

Tab. II lists the minimum object size that was detectable in a certain distance d_m to the sensor.

In a summary, the table shows two common results:

- The Kinect sensor recognises obstacles larger than 0.5 cm/0.5 cm in a distance of 100 cm. The Hokuyo scanner guarantees a correct perception under this conditions. But due to the significant smaller minimum detection range it is able to detect such obstacles in distance of 30 cm.
- The Hokuyo laser scanner shows similar results for both object types. The Kinect shows a more differentiated behaviour. Its detection capabilities depend on the opstacle shape and distance.
- The Kinect detects much smaller objects of both types. It perceives both object types in case of a width/diameter larger than 2 cm.
- The benefit of the Kinect correlates to the obstacle distance and increases with higher ranges.

Based on the results of Tab. II the Kinect represents the better collision avoidance system. It detects smaller objects in a larger distance. To overcome the large dead range the system should be combined with additional sensors.

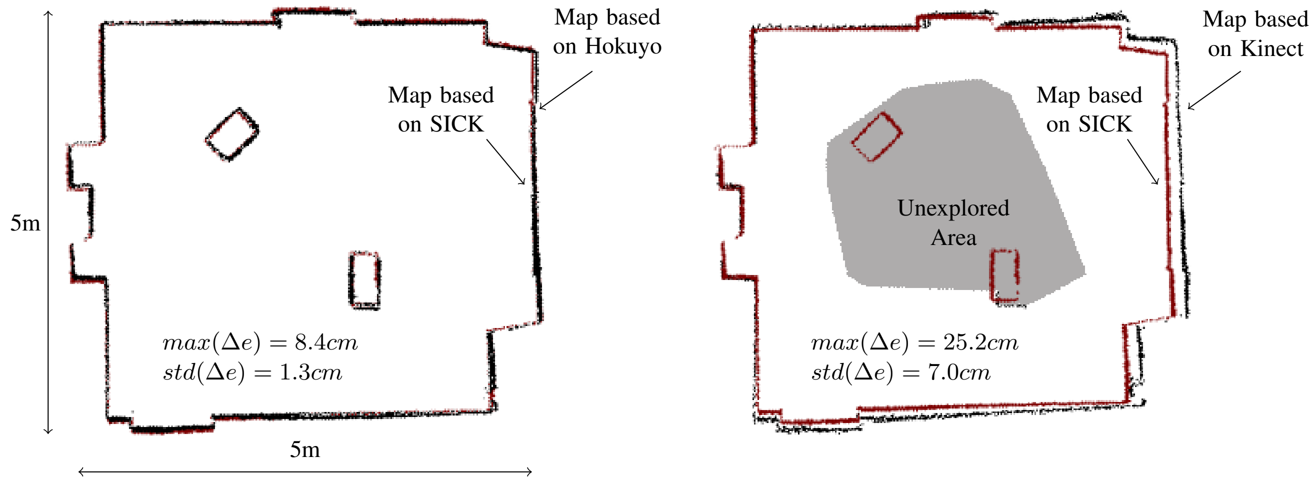
High performance laser scanners offer a safety mode, which implies a beam conture in a way that all objects within the apex angle are detected [27]. The Hokuyo sensor does not provide this function.

B. Map building

In a second scenario we investigate the map building capabilities of the three sensors. For this purpose we moved the robot system depicted in Fig. 1 in different office environments and record all sensor outputs as well as the odometry measurements. Afterwards the scans were merged using a Rao-Blackwellized particle filter to merge the scans [28]. Fig. 3 shows the exemplary results for a single room. The occupancy grids (resolution = 2 cm) represent a part of our laboratory with a size of approximately 5 m x 5 m. In both figures the map generated based on the SICK measurements is added as reference.

As visible in Fig. 3(a), in a closed area the performance of the Hokuyo sensor meets the capabilities of the SICK scanner. Only some outliers and smaller displacements are significant. By comparing the grids of the SICK and Kinect sensors in Fig. 3(b) three facts are remarkable:

1) The most obvious difference is the inhomogeneous distribution of the dots along the walls for the map based on Kinect measurements. This property is visible in Fig. 3(b) in the right upper corner for instance. In contrast, the laser scanners generate a uniform distance between neighboring measurements (Fig. 3(a)).
2) The higher accuracy of the Hokuyo sensor system provides a more precise map. Its maximum deviation from the SICK measurements is just 8.4 cm. The map generated out of the Kinect data shows an maximum displacement of 25.2 cm.



(a) Map build with the Hokuyo laser scanner

(b) Map based on Kinect measurements

Figure 3. Comparison of occupancy grids generated with different sensors. The results of a SICK LMS200 were added as a reference with red dots.

3) The limited observation angle of the Kinect (57°) – four times smaller than for the Hokuyo sensor – increases the time and movements necessary to generate a complete map of an environment. The two separate boxes in the center are not or only partially detected.

Of course, the described example does not evaluate the capabilities of the Kinect in 2D scan matching and mapping. But the three mentioned results are representative for all measurements we did. Especially for larger scenario setups than depicted in Fig. 3 the Kinect based solution does not fulfill the requirements for SLAM application.

C. Localization

A challenging application for laser scanners on mobile platforms is self localization. Two common approaches to this problem are Scan Matching [29] and Monte Carlo localization [30]. While scan matching looks for a transformation of the actual laser scan that best fits the map, for example by iterative closest point-algorithm, Monte Carlo localization uses particle filter. A large number of hypothetical configurations is generated and based on the scan data a probability for each configuration is computed. In first measurements the Hokuyo laser scanner has shown better results than the Kinect sensor. As both approaches heavily depend on the features of the scene, a wide horizontal scan angle is essential for a reliable localization. Regarding the characteristics of the sensors shown in Tab. I the Hokuyo laser scanner is much superior to the Kinect senor in terms of scan angle.

V. Conclusion and Future Work

The contribution of this paper can be divided in two parts. Firstly, we present a comprehensive summary of the fundamental technical parameters Tab. I of the Kinect and comparable laser scanners. Generally it allows a fast evaluation of the applicability of a certain system related to geometrical, electrical, measurement, etc. properties. The second contribution addresses the replacement of laser scanners by a Kinect in robotic specific applications. Here we assume the extraction of just a horizontal scan from the Kinect output to simulate a laser scanner. With this method the established algorithms for laser scanners could be used.

The general question formulated in the title of this paper can be answered with "No". Laser scanner systems meet the requirements of (robotic) scenarios more than a single Kinect. The most important disadvantage of a Kinect sensor related to comparable laser scanner systems is the small monitoring angle. It limits the capabilities for mapping and localization tasks significantly. In case of an obstacle detection application the Kinect is more reliable under certain conditions than the common used Hokuyo scanner. Related to the costs, it can be argued that the cheaper Kinect needs a more powerful processing platform than the more expensive laser scanner.

The future work of our group related to the Kinect sensor will be focused on the following goals:

- At the moment we use just one of the 480 lines of the Kinect output. Multiple measurements merged into one simulated laser scan should stabilize the output. The precondition for such an extension is a homogeneous environment in a certain vertical interval. Adaptive filter strategies should provide a flexible definition of the scan height.
- The timing of the perception and processing were actually considered with regard to the sensor refresh-rate only. For an estimation of real-time capabilities the whole process including transmission and filtering has to be evaluated.
- With the Asus Xtion a further sensor with same physical principle will be available. We will consider this device as well as the Kinect version 2 announced for 2013 in further investigations. Additionally, we will enhance the selection of sensors with stereo-camera systems.

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