Experimental Study of the Performance of the Kinect Range Camera for Mobile Robotics

Technical report

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Abstract: Despite Kinect has been quickly integrated into a variety of robotic systems and applications in substitution to traditional sensors like range scanner lasers, not too much attention has been paid to its characterization for typical mobile robots' environments. This characterization is basic to understand how the sensor behaviour depends on the nature of the environment, which allows the robot to tackle possible sensor errors due to such a nature. In this report we present an experimental study of the performance of the Kinect range camera, which differs from other studies in addressing a thorough evaluation for assessing the sensor performance and reliability under diverse environmental conditions and factors, including radiometry and reflectivity of objects, lighting conditions, repeatability, interference with other sensors, and coverage. The results and the conclusions of the experiences presented here provide useful insights about the performance of the Kinect RGB-D camera that help to understand and exploit the characteristics of this device.

1 INTRODUCTION

The Kinect device (Kinect, 2013) is receiving great attention from research areas related to perception and mobile robotics due to its remarkable advantages in comparison to traditionally used sensors, as for example laser scanners. In particular, the characteristics of its range camera turns Kinect into a suitable 3D sensor for robotic applications overcoming most of the limitations of others devices that also provides 3D information, like stereo vision systems, actuated laser rangefinders or time-of-flight (ToF) cameras. Stereo vision systems require a high computational cost and usually provide sparse 3D data (Hartley and Zisserman, 2004). On the other part, actuated laser range finders (aLRF) include mechanical components that negatively affect to both, the weight and the system refresh rate (Newman et al., 2006, Marder-Eppstein et al., 2010). Finally, time-of-flight cameras (ToF, Lange and Seitz, 2001, Ruiz-Sarmiento et al., 2011) exhibit a limited resolution (176x144 pixels) being inappropriate for practical, ambitious applications.

In contrast, Kinect is a compact, lightweight and low-cost device able to provide RGB and depth measurements with acceptable precision, which fit on most of robotics projects nowadays. As a result, Kinect has rapidly settled down into the sensorial systems of leading robotic systems like for example, TurtleBot or PR2 (Willow Garage, 2013), and TUM-Rosie (TUM-Rosie, 2013).

The Kinect range camera has been utilized for covering the typical robotic needs such as robot localization (Ganganathm and Leung, 2012), reactive navigation (Gonzalez-Jimenez et al. 2013), human-robot interaction (Van den Bergh), or semantic object detection (Günter et al., 2013). Despite this intense utilization, there is not, to the best of our knowledge, a comprehensive study of the performance of the Kinect range camera under different conditions and environmental factors. Some works can be found in the literature addressing the study of the range measurement errors of the Kinect device (Khoshelham, 2011). Also in (Dutta, 2012, Smisek et al., 2011, Stoyanov et al., 2011) the performance of the Kinect device is compared to other devices, e.g. a TOF camera and a short-range laser scanner. Also of interest is the work in (Teichman et al., 2013), where a method for calibrating its intrinsic parameters is presented.

In this report we present a comprehensive experimental study of the range camera of Kinect. This study differentiates from others in addressing a thorough evaluation for assessing the sensor performance and reliability under a variety of environmental conditions and factors: i) radiometric characteristics of objects, ii) reflectivity , iii) translucent or transparent objects, iv) different lighting conditions, v) repeatability, vi) interference with other sensors working in the IR spectrum, and vii) resolution and coverage. Note that although more recent versions of the PrimeSense (PrimeSense, 2013) range sensor present in Kinect exist, they are based on the same working principles, so this study also stands for them.

Next, the Kinect sensor as well as its working principle for gathering 3D information are described. This permits a better understanding of the experiments presented in section 3. Finally, in section 4, it takes place a discussion on the results obtained in such experiments and the report conclusions are summarized.

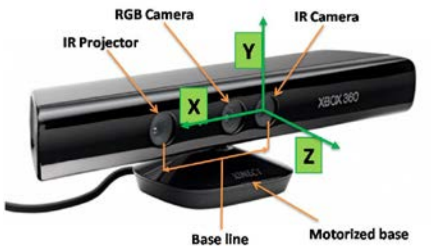

Figure 1.Kinect device and its components.

2 KINECT RANGE CAMERA

Kinect is a well-known device released in 2010 that contains, among other sensors, a range camera composed of an IR light projector and a monochrome CMOS sensor (also called IR camera). Its main features are:

- A VGA resolution (640x480 pixels) with 11-bits depth.
- A working frequency of 30 Hz.
- A horizontal field of view of 58º, and a vertical view of 45º.
- An official operational range from 1.2 m. to 3.5 m. as reported by the manufacturer, although this range can be higher (approx. from 0.5 to 4 m.) depending on the particular characteristics of the scanned objects, e.g., reflectance, IR light absorption, etc.

The range camera of Kinect uses a novel technique for obtaining depth information called *Light Coding* (Freedman et al., 2010), patented by PrimeSense. This technique, based on IR images, relies on an IR projector and an IR camera with parallel optics axis, separated a known distance called *baseline* (see figure 1). Concretely, the projector and the camera are aligned through the X axis of the sensor and the baseline, i.e. distance between them, is approximately 75mm.

Broadly speaking, the Light Coding technique computes depth data by projecting an uncorrelated IR pattern on the scene (see figure 3) and analyzing the projection using an IR camera. This analysis is carried out by means of correlation and triangulation processes (Garcia and Zalevsky, 2008).

Patches of the image captured by the IR camera (i_c) are correlated against patches at the same location and the horizontal neighbourhood of a number of pre-loaded reference images (i_r). Reference images, codified into the Kinect device, correspond to images of the uncorrelated pattern projected on a planar surface at different and known distances $z_{ref}=\{z_1, z_2, \dots, z_n\}$. The result of the correlation of patches of the i_c and the set of i_r produces a disparity image, i_{ref}, that is used to compute depth information through triangulation. Concretely, the equation used by Kinect for obtaining depth data is:

$$z = b\frac{f}{d_{ref} - d_k} \quad (1)$$

where z is the depth (in meters), b is the baseline (in meters), f is the focal length of the cameras (in pixels), d_{ref} is the disparity of the reference image i_{ref} considered in the correlation step, calculated as in a typical stereo vision system with an ideal configuration (two identical, aligned cameras with parallel optical axis), that is:

$$d_{ref} = x_l - x_r \quad (2)$$

but in practice it is computed by:

$$d_{ref} = b\frac{f}{z_{ref}} \quad (3)$$

where z_{ref} is the known distance of the planar surface at the corresponding i_{ref}. Finally, d_k corresponds to the disparity between the i_c and the set of i_r, calculated as (see figure 2):

$$d_k = x_l - x'_l \quad (2)$$

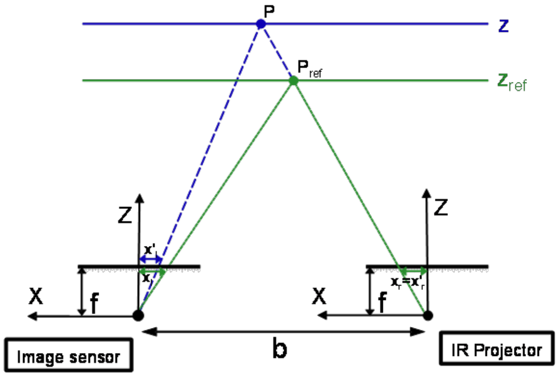

Figure 2. Kinect IR projector and IR camera configuration. *P* is a studied point into the scene, and x'_l and x'_r are its horizontal coordinates when it is projected on the image taken by the Image sensor and on a hypothetic camera placed at the IR projector respectively, emulating a stereo vision system. On the other hand, x_r and x_l refer to the coordinates of its matched point P_{ref} into an i_{ref} image. Notice that x_r and x'_r are the same, and as in the case of x_l and x'_l, they are unknown during the Kinect depth computation.

3 EXPERIMENTAL STUDY

In this section we present an experimental evaluation of the Kinect range camera with respect to different factors and environmental conditions. From the perspective of mobile robotics, the result of this study is relevant for predicting the behavior of the sensor while gathering data from the challenging real world where mobile robots operate.

In the following, we have recorded range and RGB images from Kinect using the Freenect open-source library (OpenKinect, 2013). Other alternatives for accessing the visual data captured by Kinect are the open source library OpenNI (OpenNI, 2013) and the official API from Microsoft (Kinect API, 2013).

3.1 Color

Objective. The aim is to test the accuracy and repeatability of Kinect with respect to the color of the observed objects or surfaces. Color is a radiometric characteristic of surfaces that normally influences IR-based sensors. This is due to the fact that each color, apart from being shown different in the light visible spectrum by the human eye, they also exhibit different IR absorption profiles, which causes variations in the intensity of the infrared images gathered from colored objects.

Experiment setup. The distance to the surface of three colored cardboards, yellow, blue and black, were alternatively measured by Kinect. The Kinect device was placed at two “grounf truth” distances from the cardboards: 1.2 and 3.0 meters, which were surveyed with a measuring tape, in such a way that the cardboards were parallel to the X axis of the sensor. The mean and the standard deviation (*std*) of 100 measurements at each distance and for each cardboard were computed.

Results and conclusion. Figure 3 shows the IR image of each cardboard. As expected, dark colors absorb more IR light, which may cause, in general, erroneous readings in most of IR-based sensors. However, in the case of the Kinect device, the working principle described in the previous section is robust enough to yield similar results, in terms of mean depth and *std*, while computing the distances from the sensor to the black, yellow and blue cardboards. Similar results were obtained placing at 3 meters from the cardboards. This shows that the sensor keeps its performance when scanning IR absorbent surfaces, and thus it is not affected by the color of the scanned objects.

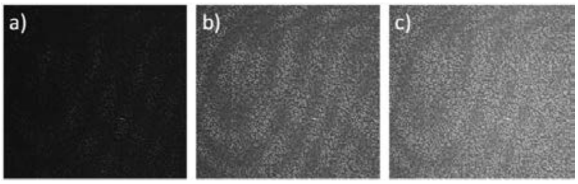

Figure 3. IR images of the projected pattern on three cardboards with different colors: a) black, b) blue and c) yellow.

Table 1. Results of depth measurements over the different cardboards.

Data\Color	Blue	Yellow	Black
Mean depth (1.2 m.)	1.1749 m.	1.1729 m.	1.1748 m.
Mean std. (1.2 m.)	0.0014 m.	0.0016 m.	0.0014 m.
Mean depth (3 m.)	2.9179 m.	2.9317 m.	2.9185 m.
Mean std. (3 m.)	0.0066 m.	0.0099 m.	0.0097 m.

3.2 Reflectivity

Objective. With this test we aim to study the performance of the Kinect range camera when scanning surfaces with different reflectivity profiles. Reflectivity is a directional property that refers to the fraction of incident light which is reflected in a particular angle. In general, surfaces can be categorized as: i) specular, where reflectivity is close to zero in all directions, except at the exact reflected one, and ii) diffuse, where the reflectivity is uniform, i.e. the fraction of light reflected is similar in all directions (Born et al., 2003).

Experiment setup. Two paper sheets, a first sheet with a specular surface and a second one with a diffuse surface, were mounted vertically on a Pan-Tilt unit (PTU) (Eagletron, 2013), and placed at a distance of 1.5 from the sensor (see figure 4-a). Depth measurements from both sheets were gathered while the PTU performed a rotation movement of ± 55 degrees w.r.t. the X axis of the Kinect (see figure 1). As long as the angle of the surfaces varies, the angle of the incidental IR light over the sheets also does, affecting both the reflected IR light directions and the measurements of the range camera.

Results and conclusion. Figure 5 shows the percentage of lost measurements over both surfaces. In the case of the diffuse surface, no measurements are lost. However, when a specular surface is considered, the higher the absolute angle w.r.t. the Kinect, the larger the number of lost measurements. Moreover, the IR camera is saturated when the specular surface and the X axis of Kinect are approximately parallel (see Figure 4-b), also resulting in failed measures.

Regarding the accuracy of the measurements, the error, computed as the mean distance from all the measurements over a sheet to a plane fit using such measurement, was similar in both diffuse and specular cases: ~1 mm.

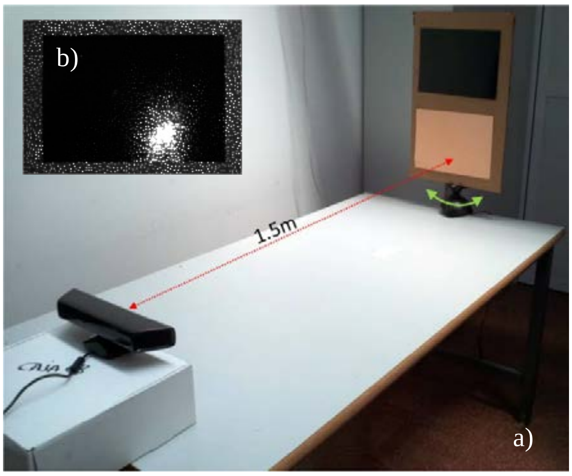

Figure 4. a) setup where two sheets with different reflectivity profiles are mounted on a Tilt Unit placed in front of the Kinect device. b) the IR image over the sheet with specular surface is saturated when it and the Kinect X axis are parallels.

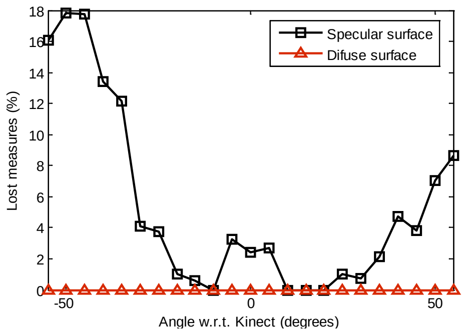

Figure 5. Percentage of lost measurements for specular and diffuse surfaces according to their orientation w.r.t. the Kinect sensor.

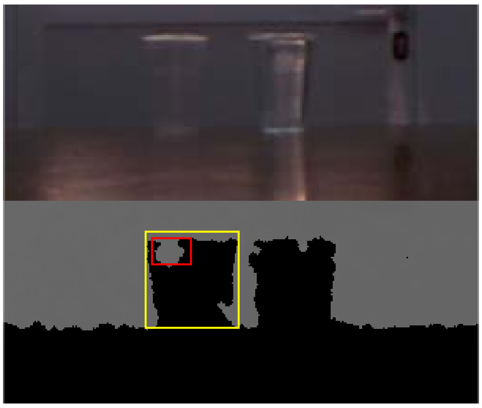

Figure 6. Up, RGB image of part of the scene. Bottom, range image. Black pixels represent lost measures. The red rectangle marks a sample area where Kinect returns the depth of the door placed behind the plastic cup.

3.3 Translucent and transparent objects

Objective. This experiment aims to determine the effect that light refraction, i.e. the change of the light direction when considering translucent and partially or totally transparent objects, has on the sensor measurements.

Experiment setup. Two plastic cups were placed in front of the Kinect device at a distance of 1.2 m. The left cup was empty, while the right one was full of water (see figure 6-top).

Results and conclusion. When computing the depth to the plastic cups, the refraction of the projected IR pattern caused that most of the measurements were erroneous; they failed or shown abnormal values (see figure 6-bottom). There are some areas, like the one marked with a red rectangle in the figure, where the range camera is able to obtain valid measurements. However, these measurements do not correspond to the plastic glass but to the door behind it, and they are prone to errors due to the deviation of the IR rays produced by refraction. Concretely, the *std* of the depth measurements belonging to the yellow area in the image is three times higher than that shown by the measurements of the same area if the plastic glass is removed.

3.4 Repeatability

Objective. In this experiment the repeatability of the Kinect range camera is studied, i.e. the variation in the measurements of the same surface while the sensor is working under the same conditions. An interesting issue we pursuit here is to check whether the repeatability of the camera is uniform over the perceived area or, in contrast, it exhibits quantifiable differences.

Experiment setup. The Kinect sensor was placed in front of a white wall at three different distances: 1.5, 2 and 3 meters.

Results and conclusion. Figure 7 a), b) and c) show the results of computing the mean and the *std* of the measurements of the central row of the range image at the tested distances in increasing order. Data is obtained by analyzing 100 range images from each distance. Note that the *std* increases according to both, the horizontal angle of the measurement w.r.t. the X axis, i.e., the column in the range image, and the distance to the wall.

However, as illustrated in figure 11 d), *std* does not depend on the vertical angle of the measure. Thus, a repeatability value of the measurements of Kinect can be derived by approximating a lineal function per column in the range image in terms of the distance. For example, equation (6) gives the repeatability, in meters, of the measurements of the first-left column, where d is the distance to perceived object:

$$r(d) = 0.0218d - 0.0275 \quad (3)$$

3.5 Lighting conditions

Objective. The purpose of this test is to analyze the influence of different lighting conditions in the range camera performance.

Experiment setup. A Kinect device was placed in front of a white box with a planar surface at a distance of 1.3 m. in a scenario where the lighting conditions were modified by combining three illumination components: a lamp hanging from the ceiling of the room, a reading lamp, and the rooms' blinds. Six different scenarios were studied (see table 2).

Results and conclusion. Figure 8 shows, for each of the most relevant scenarios, the 1) IR channel image, 2) the RGB channel, 3) the IR channel without the projected pattern (which provides information about the amount of light in the IR spectrum present in the scene given by another light sources), and 4) the range image (where black pixels are associated with lost measures).

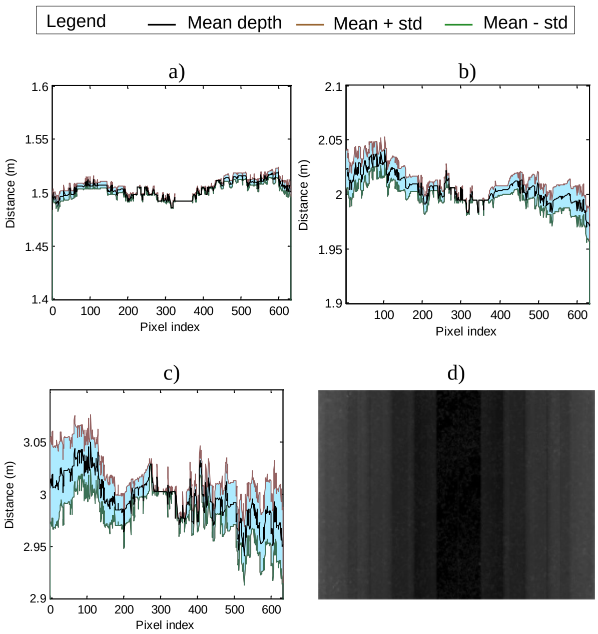

Figure 7. a), b) and c) Mean depth (plus and minus the *std*) from Kinect to the wall for each pixel in the central row of measures where the sensor was placed at 1.5, 2 and 3 m. respectively. d) *std* of the measures for each pixel. Pixel intensity is normalized: black pixels correspond to a *std* of 0, and white ones with the higher *std* obtained at any distance.

Table 2. Combination of components for each scenario.

	Environmental light (*e1*)	Artificial light (*e2*)	Artificial light directed over the object (*e3*)	Artificial light directed to Kinect (*e4*)	No light (*e5*)	Sunlight (*e6*)
Lamp	OFF	ON	ON	ON	OFF	OFF
Reading Lamp	OFF	OFF	ON	ON	OFF	OFF
Blind	OPEN	CLOSED	CLOSED	CLOSED	CLOSED	OPEN

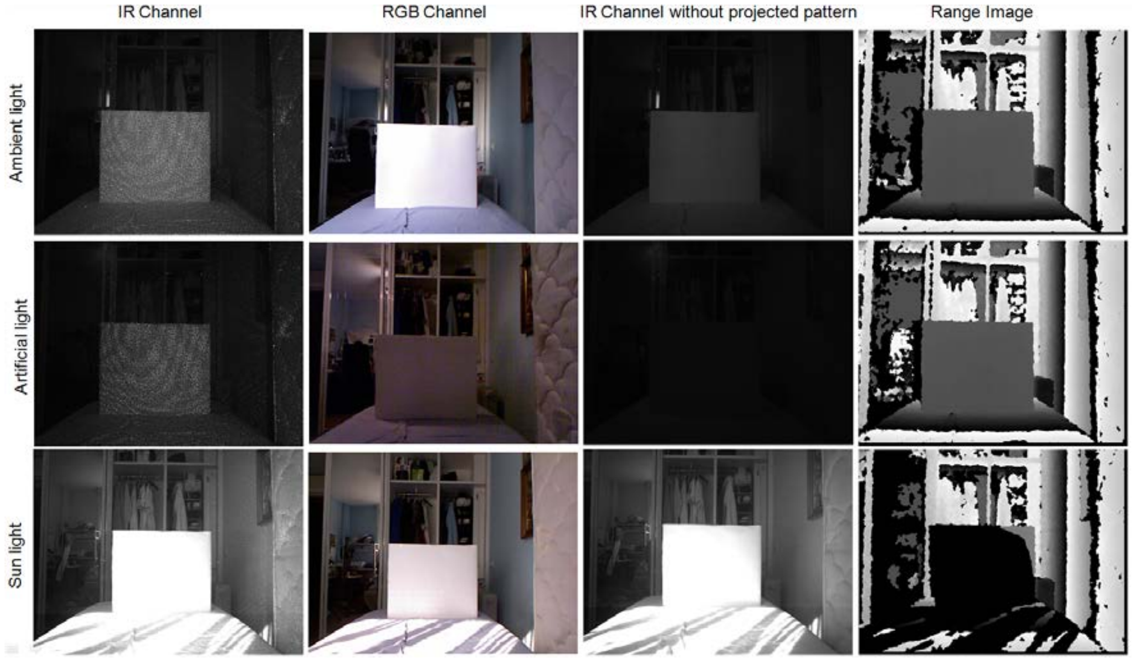

Figure 8. Images from the IR Channel, RGB Channel and IR Channel without the projected pattern, and range image from the most relevant scenarios.

Analyzing the results (see table 3), in the scenario *e5*, in absence of external light sources, Kinect has no problems to measure distances to the box. For scenarios *e2*, *e3* and *e4*, where artificial light is present, the Kinect performance is also acceptable. In these cases, we can observe in the *IR Channel without the projected pattern* image that the intensity of the IR light over the box is low, given that regular lamps emit out of the IR spectrum. Scenario *e1* shows a higher intensity over the box, since the sunlight has an IR component, but Kinect measures are obtained correctly.

Table 3. Mean depth to the box and their associated std for 100 range images in each scenario.

Scenario	(*e1*)	(*e2*)	(*e3*)	(*e4*)	(*e5*)
Mean depth to the box (m)	1,326	1,323	1,321	1,320	1,32 5
Standard deviation (cm)	0,24	0,20	0,18	0,17	0,22

However, problems appear when the intensity of the sunlight over the box is high, as illustrates the scenario *e6*. Although the sunlight does not directly fall on the box, the IR intensity in the scene is significantly high, as shows its *IR Channel without the projected pattern* image. In fact, in the area of the *IR channel* image belonging to the box it is hard to discern the speckles projected by Kinect. Its range image shows how the device fails computing practically all the distances to the box.

To support these conclusions we have analyzed the computed depth data in all the scenarios with the exception of *e6*, where Kinect was not able to obtain depth information. For this, we have captured 100 range images from each scenario, analyzing the regions corresponding to the box. It was observed that the mean distance and the *std* of the range measures was quite similar in all the scenarios, as well as the number of lost measures, which is close to zero. That confirms the good performance of the Kinect range camera in these scenarios.

3.6 Interference with other sensors

Objective. The sensorial system of a mobile robot usually entails a variety of sensors (probably of different type). Time of Flight Cameras (ToF) and 2D radial laser scanners are widely used and both work emitting light in the near IR spectrum, so it becomes clear the interest of studying their reliability while working with a Kinect device.

Experimental setup. For this test we have used the following sensors: a ToF camera SwissRanger™ SR4000 from Mesa Imagin (MESA Imagin, 2013) and a radial laser scanner UTM-30LX from Hokuyo Automatic (Hokuyo, 2013). The measurements of these sensors were compared when working separately and together with the Kinect range camera. The devices were placed at a distance of 1.5 m. of a white wall and measures were taken without either artificial or natural illumination into the scene.

Results and conclusion. The considered ToF camera works by emitting a continuous wave modulation through an array of IR leds. The IR light emitted has a wave length of 805nm. In figure 9 we can see four images which were taken using the Kinect IR camera under the conditions shown in table 4. Figure 9.c) shows how Kinect captures the light emitted by the ToF camera, and figure 9.b) and d) remark the difference between the Kinect sensor working alone or with the ToF camera pointing to the same wall. The effect is the same that while working with a moderate ambient light. Analyzing the measures of both sensors working together and separately any interference was noticed.

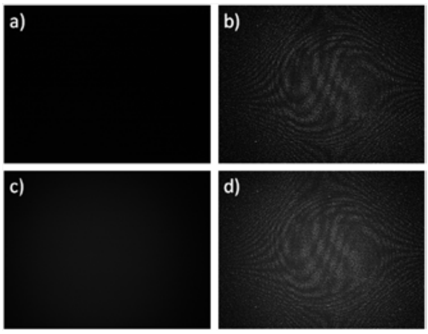

Figure 9. Images captured by the IR camera of the Kinect sensor while working alone or with a ToF camera.

Table 4. Configurations considered in the experiment.

Sensor\Image	a)	b)	c)	d)
ToF Camera	OFF	OFF	ON	ON
Kinect IR Projector	OFF	ON	OFF	ON

On the other hand, the considered radial laser scanner works emitting IR light rays through an IR laser. The wave length of the emitted light is of 905nm. In this case, the ray projected by the laser range finder is not visible for Kinect. It can be due to some facts:

- The wave length of the light emitted could not be perceivable by the Kinect IR sensor.
- The resolution of the Kinect sensor could be insufficient for detecting only a ray over the wall surface.
- The time that the radial laser scanner projects the ray over a certain position could not be sufficient for being detectable by the Kinect sensor.

Again, the measures of both sensors were compared workingalone and together and any interference was detected.

3.7 Resolution and coverage

Objective. Essential sensors' features for successfully carrying out robotic tasks as reactive navigation, surface reconstruction, etc., are (i) reliability for detecting objects which are difficult to perceive, either because their position or their thickness, e.g., chairs, shelves, the tabletop or the legs of a table, etc, i.e., the resolution of the sensor, and (ii) how the distance from objects affects to their detection, i.e., the coverage area of the sensor. The aim of this experiment is to test the resolution and the coverage area of the Kinect sensor while perceiving narrow and distant objects.

Experimental setup. We have completed a total of 15 tests based on alternatively placing objects with different thickness (1, 2 and 4 cm.) in front of the sensor (at a fixed height) and verifying if they were detected from different distances. The experiment was performed in a corridor (see figure 10) with the Kinect sensor mounted on a mobile robot. Thus, the odometry information permits us to calculate the sensor position with respect to the object at any moment. To avoid measurements from the floor or walls of the corridor, we have only used measurements from the 16 centrals columns of the range image that also show a certain height. The robot was initially placed to a distance of around 4 meters from the object, reaching the obstacle.

Results and conclusion. Figure 11 shows the results of two tests using the objects with 1 and 2 cm. of thickness. The results for the object of 4 cm are not shown since the object was detected in all the range. In these histogram graphs, the vertical axis represents the sum of the object detections in the 16 studied columns, and the horizontal axis the distance from the Kinect sensor to such an object. The distances have been discretized in intervals of 5cm.

Analyzing these results we can conclude that the Kinect range camera resolution and coverage enables the detection of objects with a low thickness, up to 1 cm, within an admissible distance range.

Figure 10. Test process for detecting thin objects. In this case the thickness of the object was 4 cm.

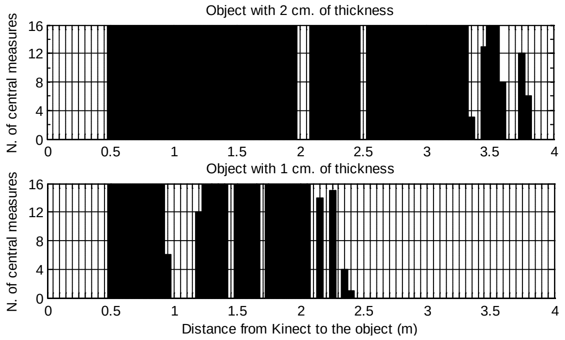

Figure 11. Results of the resolution and coverage tests.

4 DISCUSSION AND CONCLUSIONS

In this report we have described the working principles of the Kinect range camera and presented an experimental study of its performance. A number of experiments have been conducted in order to assert the sensor reliability and functionality under different environmental conditions and factors.

As a result of these experiments, we can extract the following positive aspects of the Kinect device:

- It has been shown the Kinect reliability for measuring objects with different IR light absorption profiles (dif. radiometric traits).
- No interferences have been detected between Kinect and two of the most used sensors in mobile robotics: radial laser scanners and ToF cameras, which also work emitting light in the near IR spectrum.
- The resolution and the coverage area of the sensor are convenient enough for mobile robot applications, like reactive navigation, enabling the perception of narrow and distant objects.

On the other hand, it exhibits some of the drawbacks of common light-based sensors:

- Specular surfaces cause the loss of measures and saturation of the IR camera.
- Translucent and transparent objects are not detected by the sensor.
- The presence in the scene of ambient or artificial light does not affect to its performance, thought direct sunlight over objects arises measure errors.

Regarding to the repeatability of the sensor, a general value cannot be obtained since it depends on the distance from the sensor to the object and the horizontal angle of the measure. In this report an approximation to this value has been empirically obtained according to both factors.

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