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Effects of the Post-processing on Depth Value Accuracy of the Images Captured by RealSense Cameras

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Abstract

This paper presents the use of depth cameras in robotic applications, as well as the effect of post-processing on captured depth images. The aim is to test the capabilities of depth cameras in order to better detect objects in images based on depth information, as well as the effect of additional post-processing of depth images. In the paper, the Intel RealSense depth cameras are introduced briefly and their working principle and characteristics are explained. A series of experiments confirmed that camera D415 provides much more precise and accurate depth information than camera D435.

Keywords: Depth image, Post-processing, Depth measurement, RealSense cameras, Image processing, Obstacle detection

1 Introduction

Recently, computer vision applications based on 2D image processing have been largely limited due to a lack of information on the third dimension, i.e. depth. Compared to 2D vision, 3D vision makes it possible for computers and other machines to discern accurately and with great precision various shapes, shape dimensions, distances, and control in the real, 3D world [1 - 4]. For this reason, 3D optical systems have been successfully applied in various areas such as robotics, car manufacturing, mechanics, biomedicine etc.
Not so long ago, 3D cameras were expensive and their use was complicated and impractical. Today, thanks to technological advancements, the price of 3D cameras that are able to measure image depth has been significantly reduced and their use

has become much simpler [5 - 9].

2 Overview of Intel RealSense Cameras

2.1 The Technology of RealSense Cameras

RealSense technology in essence consists of a processor for image processing, a module for forming depth images, a module for tracking movements and of depth cameras. These cameras rely on deep scanning technology, which enables computers to see objects in the same way as humans. The full hardware is also accompanied by an appropriate open-source Software Development Kit software platform called *librealsense* [4]. This software platform provides simple software support for cameras of the D400 series, which allows users to use the cameras [9].

(a) (b)

Figure 1. (a) RealSense D435 and (b) RealSense D415 cameras [4]

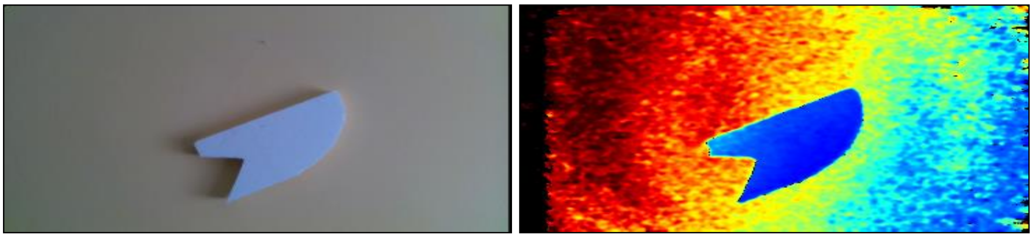
2.2 The Working Principle of the RealSense Cameras

This section will briefly outline the working principle of the cameras. These cameras have three lenses: a conventional RGB camera, an infrared (IR) camera and an infrared laser projector. All three lenses jointly make it possible to assess the depth by detecting the infrared light that has reflected from the object/body that lies in front of it. The resulting visual data, combined with the RealSense software, create a depth estimate, i.e. provide a depth image. RealSense cameras use stereovision to calculate depth. The implementation of stereovision consists of a left-side and a right-side camera, i.e. sensors, and of an infrared projector. The infrared projector projects invisible IR rays that enhance the accuracy of the depth information in scenes with weak textures. The left-side and right-side cameras record the scene and send data about the image to the processor that, based on the received data, calculates the depth values for each pixel of the image, thus correlating the points obtained with the left-side camera to the image obtained with the right-side camera. The depth values of each pixel processed in this way result in the depth frame, i.e. the depth image. An important role in the operation of the camera is also reserved for the RealSense D4 processor for image processing, which is capable of processing 36 million depth points in a second. Thanks to this performance, these cameras are built into numerous devices that require high-speed data processing [5 - 9].

3 Experiments and Results

This section will describe the results of experiments conducted with RealSense cameras D415 and D435, as well as the effect of the post-processing on a depth image. The experiments were part of a project dealing with robotics, or more precisely, robotic vision, in which RealSense cameras were used. The aim of the project was to construct a robot that would automatically, based on information obtained from the cameras, paint the facades of buildings with a special paint.
Since the process of developing the mentioned robot is in its building phase, the experiments have been conducted with artificially created obstacles with both RealSense cameras. The first task was to determine via the experiments which camera behaves in what way under particular recording conditions and how it is possible to obtain the most accurate depth image of the obstacle in a complex image. Similarly, an important aspect of the research is to determine in what way it is possible to process a depth image with the aim of achieving as high an accuracy and precision in detecting objects based on depth images as possible. This is an important step, since the success of detecting the obstacles in a complex image greatly depends on the obtained depth image. The reason for using depth images lies in the fact that almost all obstacles on the walls protrude from the wall along axis *Z*, i.e. in their depth. In this way, based on the distance, i.e. depth, it is possible to determine the objects that are not in level with the surface of the wall and which could form some sort of obstacle that should not to be painted. Of course, this method of detecting objects is possible to be used in any robot for detecting and bypassing obstacles, as well as for locating certain objects in the movement field of the robot. In the described experiments, a depth camera and an RGB camera were used. The infrared camera has no significance in the present phase of the project, as the robot has been designed to operate under well-lit conditions, and not in the dark. Since in robotics a high degree of accuracy and precision are required for the robot to be able to bypass the obstacles without an error, the depth cameras need to be calibrated in the appropriate manner, so that the obstacle is clearly visible and can be detected in a complex image. There are numerous parameters and settings that affect the quality of the depth image, whose effect will briefly be described in the rest of the present paper.

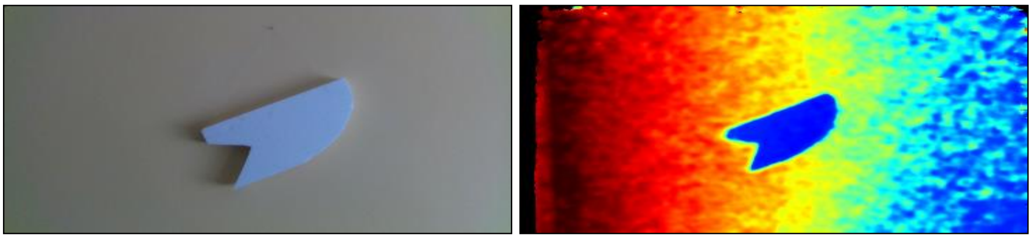
The first measurement was performed at a distance of 1m from the wall, since the aim was for the camera to capture as wide a surface on the wall as possible that would potentially need to be painted. Also, it is possible that in the later phases of developing the system, a higher number of cameras will be required for recording to cover the necessary surface. The RealSense software has the ability to control multiple cameras simultaneously; thus it is possible that a future research project will be dealing with this issue.



(a) (b)

Figure 2. The image of camera D415, default setting: (a) RGB image and (b) depth image

Fig. 2 shows images captured with camera D415. The image shows an obstacle of an undefined shape hanging on the wall, which was the aim of the experiment, to explore the capabilities of the camera. It is important to note that the resolution of the RGB and depth cameras was set to the very maximum, i.e. to 1280x720 and the so-called default mode of recording was used, which offers the best visual experience according to the manufacturer's specification [4]. It can be seen that the object of interest is very clearly discernible in the depth image.
The Fig. 3 shows an identical content, the recording was performed under identical conditions, but in this case by using camera D435.

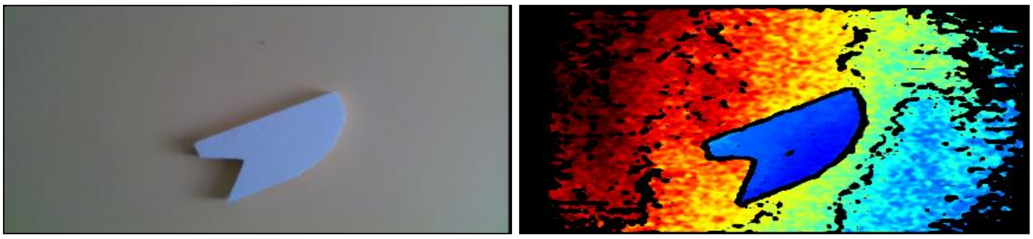


(a) (b)

Figure 3. The image of camera D435, default setting: (a) RGB image and (b) depth image

As can be seen in Fig. 3, there is almost no difference between the RGB images captured with cameras D415 and D435. Still, the most important result of this pair of images is the drastic difference in the quality of the depth images captured with camera D435 compared to the depth image captured with camera D415. Due to the wider field of view, the pixel density is lower in case of the image captured with camera D435, and hence the depth image is also more blurred, the contours of the obstacle are less marked and the obstacle itself is of smaller dimensions compared to the background of the image. Also, there is a strong noise in the image around the edges of the obstacle compared to the image obtained with camera D415.
This result shows that it is necessary to use a different setting that would increase the accuracy of determining the obstacle on the wall, primarily in terms of more

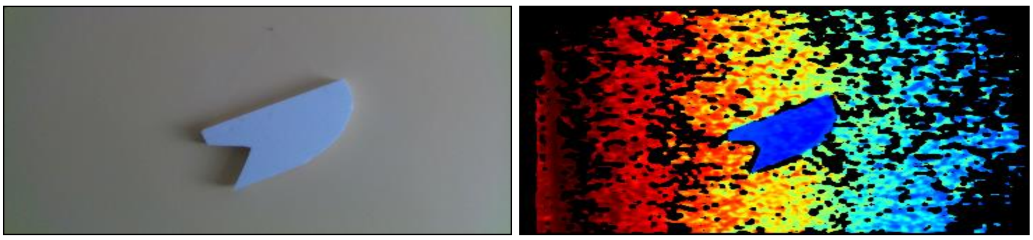
accurately determining the contours and edges of the obstacle itself that is present in the image. This is necessary for the robot to be able to fully know how far it is allowed or not allowed to paint. For the above reason, the next experiment was conducted with different settings, where the built-in setting for high-accuracy was used for determining a high-accuracy depth. It needs to be mentioned that in case of this setting, there is no additional processing of the depth image with any filters, just like in case of the default setting.



(a) (b)

Figure 4. The image of camera D415, high-accuracy setting: (a) RGB image and (b) depth image

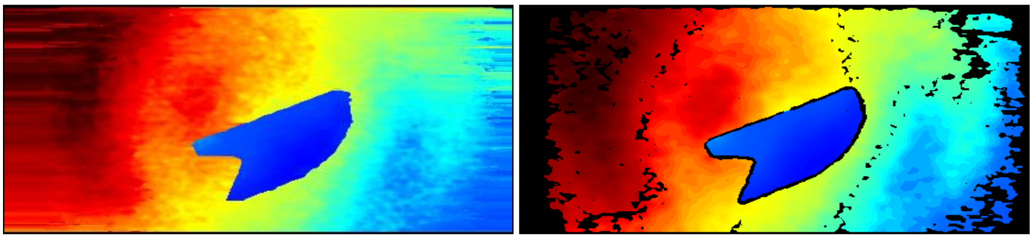
Fig. 4 shows the same obstacle that was also captured from a distance of 1m under the similar lighting conditions. The resolution of the RGB and depth cameras was also identical as before; only the setting for forming the depth image was changed to high accuracy. In this case, camera D415 was used. As can be seen, the RGB image is almost of the same quality, and the depth image is also of excellent quality where the contours of the obstacle are clearly visible. If Fig. 4 (b) is examined more closely, a darker line can be seen along the circumference of the obstacle, with the help of which it can be differentiated from the wall with great precision. This is a highly important result, as in robotics, it is crucial to clearly separate a possible obstacle so that the robot is able to do the work for which it has been intended. Still, within the obstacle, as well as outside of it, black spots can be seen that are a result of the setting itself, since in this case, there is no additional processing or post-processing of the depth image by the user.
In the following example, in Fig. 5, the same scene was captured, under similar conditions, only by using camera D435.



(a) (b)

Figure 5. The image of camera D435, high-accuracy setting: (a) RGB image and (b) depth image

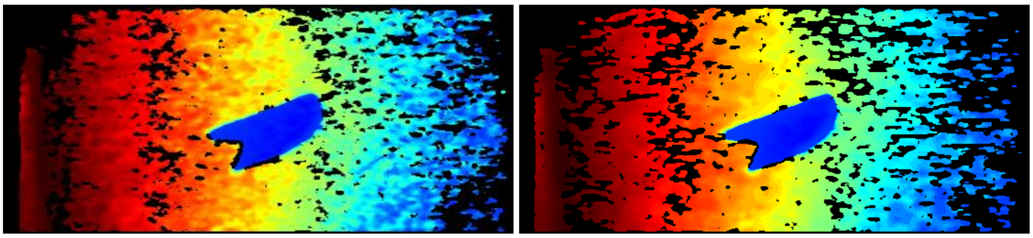
It can be seen that the RGB image has practically remained unchanged, but in case of the depth image, the difference is drastic. This is because in this case, as well, due to a wide field of view of camera D435, the pixel density is lower, and so is the resolution. There is also a strong noise, stronger than when recording with the default setting, but the most noticeable difference is a high number of blind-black spots in the image. The reason for this is the changed setting of the recording, since camera D435 is not designed for determining high-accuracy depth, but for creating a depth image that gives a good visual experience. This camera is primarily used at longer distances up to about 30m (in some cases, even longer), whereas camera D415 is used at shorter distances up to about 5-6m, but the recommended distance quoted in the literature [4] is up to 1m. In this case, somewhat more pronounced contours of the circumference of the obstacle can be seen in the depth image compared to the image captured with the default setting that is shown in Fig. 4 (b). The reason for this is in using the setting for high-accuracy depth. In this case, the filters for additional processing of the depth image were also turned off.
In the following example, the measurement results are shown in cases when the filters for post-processing the depth image were turned on [6], [8] with factory and later with random settings that have been empirically defined. First, results obtained via camera D415 will be described, followed by the results obtained via camera D435.
Numerous settings can be achieved by changing a high number of parameters that control the operation of the RealSense cameras [4]. Some of these settings are included by the manufacturer of the devices, but users can also make their own settings according to their needs. Still, in most of the cases, some of the built-in settings give the best results [4].



(a) (b)

Figure 6. The image of camera D415, high-accuracy setting: (a) with factory-set filters for keeping the edges and (b) with random-set filters for keeping the edges

Fig. 6 shows results in cases when the filters for post-processing of the depth image were turned on. Fig. 6 (a) shows the results in case when the factory settings were used, while Fig. 6 (b) shows the case when random settings were used, where the parameter values of the settings were obtained empirically. In both cases, it can be noticed that the obstacle was very well detected and compared to the example in Fig. 4, there are no black spots and there is no noise within the obstacle. Still, when using empirically obtained settings [6], [8], the depth image is much clearer, the contours and edges of the obstacle are much more pronounced, which was the exact aim of the experiment, as the robot can only bypass an accurate and precisely detected obstacle when painting. In Fig. 6 (b), black spots can be seen in the background, but they have no effect on the detection of the objects of interest. A much more important result is the clearly defined edge of the experimentally projected obstacle on the wall.



(a) (b)

Figure 7. The image of camera D435, high-accuracy setting: (a) with factory-set filters for keeping the edges and (b) with random-set filters for keeping the edges

The example in Fig. 7 shows the results obtained with camera D435 in cases when the filters for post-processing the depth image are turned on. Fig. 7 (a) shows an image obtained with factory-set filters, while Fig. 7 (b) shows an image obtained with random-set filters, in the very same way as in the example in Fig. 6 (b). It turned out that it is not important which camera is used, the best depth image is obtained with identical empirical settings. In this case, the better results are also obtained with empirically-set filters, since the obstacle was more discernible in a complex image and less noise and fewer artefacts were present around the edges of the obstacle.

Based on the experiments, it can be concluded that the RealSense D415 camera gives a much more accurate and precise depth image and is more suitable for applications in robotics. This is because camera D435, due to its wide field of view, has a lower resolution of depth images, which is automatically reflected on the quality of the depth image itself, being of a lower quality in this case. As in robotic applications a high degree of accuracy and precision is required, in further research the emphasis will be on testing the capabilities of camera RealSense D415, which gives much better results in forming and post-processing depth images.

4 Conclusions

In the present paper, the working principle and properties of Intel's RealSense depth cameras are briefly described. Appropriate experiments were conducted with two cameras, D415 and D435, and an evaluation of the experiments was performed. The aim of the experiments was to show the possibilities of use of depth cameras in robotics with the aim of developing systems of robotic vision. The use of a depth camera and forming a depth image represents the initial and most important step in developing such a system with the help of digital image processing algorithms, after the robot would have the capability of automatically detecting obstacles in its field of movement. The main conclusion of the present paper is that the camera D415 gives a much higher-quality depth image with emphasized edges, with or without post-processing, where the objects and the obstacles are clearly discernible based on the information on the depth of an image compared to camera D435.

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