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3D-IMAGING FOR AN INTERACTIVE ROBOT SYSTEM

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Abstract: 3D-imaging with PMD (Photonic Mixer Device) sensors is considered to find a broad range of applications e.g. in the automotive field, in autonomous mobile systems, and in industrial automation. The aim of the student project presented in this paper is to integrate a 3D-camera into an interactive robot system and to evaluate the technology for applications in automation. The camera provides a 3D-image of the scene based on the time of flight principle. It is mounted on an industrial KUKA KR3 robot, which is used for an interactive equilibrium game between the robot and a human player. The robot has to react on varying situations in a non-planned 3D-environment of gaming objects. Similar tasks appear in flexible automated production processes where the spatial position of processed parts is not know in advance. Thus, the game is well suited to evaluate the 3D-imaging system for applications in industrial automation.

Key words: 3D-imaging, position measurement, object identification, robotics.

I INTRODUCTION

3D-imaging is an important technology for mechatronic systems in various applications such as safety and assistance functionalities in automobiles, autonomous field robots in agricultural technology, and industrial robots in flexible production processes. Current state-of-the-art optical sensors like CCD or CMOS cameras provide a 2D-gray scale image projected from the real 3D-environment. To obtain 3D-data of a scene sophisticated and costly technologies like stereo vision systems or scanning systems are required.

Innovative 3D-cameras with PMD (Photonic Mixer Device) sensors have recently been introduced [1, 2, 3, 4]. PMD sensors capture both gray scale and pixel-wise distance data. The scene is illuminated with modulated light. A pixel array measures the turnaround time of the reflected light for each pixel and provides the distance data according to the time-of-flight (ToF) method. Direct volume calculations of the scene or other advanced measurements are possible. Ambient light rejection facilitates outdoor applications.

Potential applications for 3D ToF cameras are industrial robots as well as autonomous robots. In both fields the detection can be used for the technical process (e.g. production or navigation) or for safety applications. Moreover surface reconstruction [5] is an interesting field in competition to laser scanners. Further possible applications such as ACC Stop&Go, driver assistance systems, PreCrash and pedestrian safety, smart airbags etc. can be found in the automotive field [2].

The student project [6], on which this paper is based, has the task to evaluate the new technology for applications in automation. For that purpose, the interactive robot system Roboleo [7,8,9] is available. Roboleo serves as a platform for research and education in mechatronics and optoelectronics. The robot is equipped with multiple sensors. It is capable of playing a mechanical balance game against a human player. For the project, a PMD sensor was integrated into Roboleo. The PMD sensor substitutes a prior conventional CCD-camera and distance sensors.

II IMAGING SYSTEMS

During the last decades imaging has become a major interdisciplinary technology. The sensor information from CCD and CMOS image sensors is interpreted with image processing algorithms taking into account artifacts of the camera systems as well as changing boundary conditions such as varying light conditions. In most cases colour and shape information are used. However, the image of conventional cameras is a 2D projection of the real world, where the depth information is lost. Many applications strongly need 3D information, examples are navigation or surface analysis. As a consequence several 3D imaging technologies have been developed by adding further equipment or replacing the camera by distance sensors [10]. The typical methods applied for the generation of a 3D image are as follows:

Stereoscopic imaging (or stereo imaging or stereoscopy): As compared to a human being two cameras are used and triangulation is applied. In order to match the two images corresponding points have to be found. Thus selective structures are necessary to generate 3D information, moreover the overall time to generate the distance information includes the image capture as well as the processing. The measurement range and the accuracy depend on the distance of the two cameras.

Line projection: This method includes the projection of a line – in most cases from high intensity laser lines – and the image capture of the camera. Due to the known positions of the camera and the light source, the distances for all points being illuminated by the (laser) line are calculated. After moving the camera/line system or the objects to be measured the next line is interpreted. The information of several 2D images is integrated for the generation of a 3D image. It has to be ensured that the intensity of the light source is dominant as compared to other light sources. It is also possible to use several lines.

Laser scanning: Optoelectronic systems can be used for distance measurements by applying the triangulation method or measuring the time between the emission of a high intensity optical pulse (laser or LED) and the detection of the reflected pulse (Time-of- Flight: ToF). The rotation of a 1D ToF system is the basic configuration for a 2D laser scanning device. If a movement perpendicular to the measurement line is included, a 3D image can be generated. Typically a large amount of data is generated, but a high accuracy is achieved.

All methods mentioned above depend on the image capture and an image processing in order to generate the 3D image. Moreover the amount of data is typically much higher as compared to a single camera image. Another disadvantage is the mechanical sensitivity of the different methods. Misalignments of the two cameras (stereoscopy), the line illumination and the camera (line projection) or the rotating system can result in misinterpretations of the algorithms.

More recently, a new ToF technology for 3D imaging has become available [1,2,3,4].

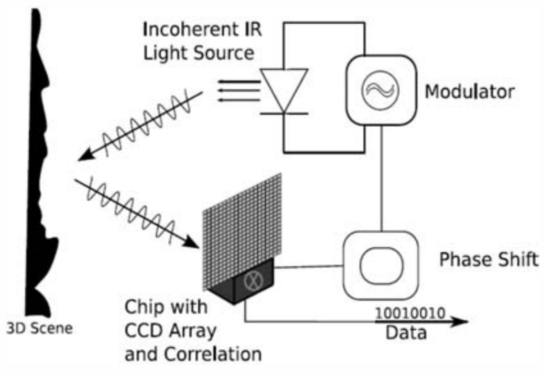

Figure 1: Time-of-Flight phase measurement principle [11]

The basic principle is explained in figure 1. A modulated infrared light source illuminates the scene. The image sensor is based on a CMOS technology with “smart pixels”, i.e. a functionality is included. Each pixel consists of two neighboring integration areas which are modulated with the same frequency as the light source. The potential change within the pixel acts like a swing: Depending on the time of arrival of the photon, the generated electrons are integrated in the “left” or “right” pixel half. If the reflection of the light takes place at a large distance, the ratio of electrons for both integration parts is different as compared to a lower distance. A phase shift algorithm determines the distance of the object for each pixel based on four sampling points.

The ToF camera thus directly provides the 3D information as an image without further processing. Due to the periodicity of the modulating frequency signal, an ambiguity occurs. A long distance might be interpreted as a very short distance. In order to avoid this effect, the modulation frequency and the light intensity – generated by several high intensity LEDs – are matched.

Since no image processing is necessary the direct 3D output offers a high potential for online 3D applications. Direct (projected) volume calculations of the scene with respect to a zero level are possible. Recent developments [7] are taking into account the compensation of sun light and the usage of multiple ToF cameras, where the light of one camera affects the others. 3D-sensors for industrial use have recently been introduced to the market. The resolution is still low, current sensors have between 64 x 48 and 204 x 204 pixels. However, for many applications the resolution is sufficient. ToF cameras capture both gray scale and pixel-wise distance data in real time, thereby offering options for sensor-fusion based algorithms. The object can be preselected by the distance information. Further analysis can be performed with the 2D pixel information.

III ROBOT SYSTEM

A. Roboleo Equilibrium Game

The 3D-camera is integrated into the robot system Roboleo. The robot system provides a basis for research and education in robot vision, sensor integration and robot programming. The initial idea of Roboleo is derived from the simple equilibrium game shown in figure 2.

The purpose of the game is to remove different figures from a plate, which is shakily pivoted on a ball as shown in figure 2. Cylindrical and cubic objects are placed arbitrarily on the plate. The equilibrium conditions change whenever a figure is removed. The plate then is transferred into a new position. The robot and the human player alternately remove figures from the plate and try to avoid slipping down the figures and destabilizing the plate.

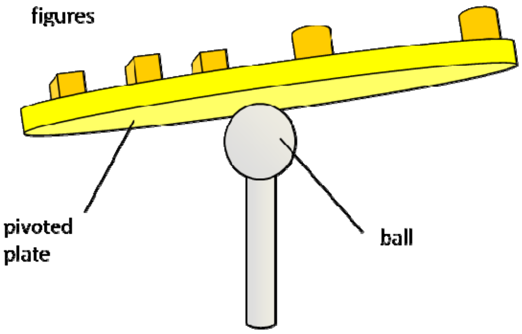

Figure 2: Roboleo equilibrium game

B. *Sensor System and Image Processing*

The position of the objects and the plate is of three dimensional nature. In the prior implementation of Roboleo, a CCD-camera was used to measure the orientation of objects on the plate. Additional distance sensors were required to obtain the spatial orientation of the plate. Figure 3 shows the Roboleo test setup. An industrial robot Kuka KR3 is mounted in a hanging position to the ceiling above the plate. Figure 3 also shows the CCD-camera for object recognition and the distance sensors beneath the board.

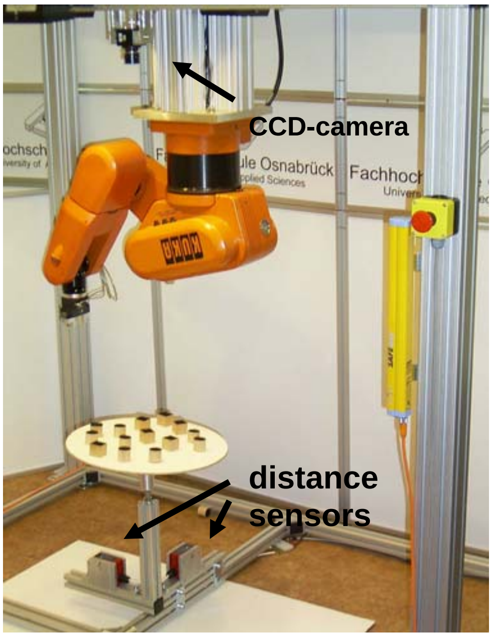

Figure 3: Roboleo test setup with CCD-camera and distance sensors

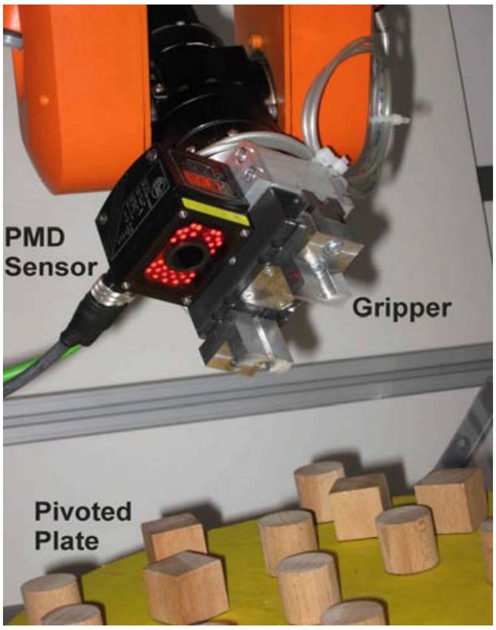

Figure 4: Robot and PMD sensor

Based on the camera data, the image processing provides the position, orientation, and shape of the objects on the plate in 2D. For a complete description of all objects in 3D-world coordinates, the inclination of the plate must be measured by the distance sensors. The distance data has to be combined with the 2D-data gained from the camera in a mathematical model of the plate and the objects [6,7]. This procedure can be overcome by directly using the 3D-data of a PMD-sensor.

The PMD sensor “efector PMD3D” by IFM Electronic GmbH substitutes the CCD-camera and the distance sensors. The sensor provides a gray scale image and a 3D-image of 64x48 pixels with a Z-resolution of about 6 mm. It is mounted at the gripper of the robot and not in a stationary position above the scene. Thus, the robot arm can bring the PMD sensor into an appropriate position to obtain measurements with a reasonable resolution. Figure 4 shows the robot and the PMD sensor.

Due to the restricted resolution of the sensor, the robot system needs two measurements to decide which object to remove next. The inclination of the plate and the spatial position and orientation of the objects on the plate must be known.

First, the robot brings the camera into a position above the plate from where the overall scene of the plate can be viewed. Figure 5 shows the pixels of the 3D-image as dots in a top view (1) and a side view (2). Pixels out of a certain range d of interest are directly neglected. Given the height of objects and the thickness of the plate, the pixels on the surface of the plate can be distinguished from those of the objects and those off the plate.

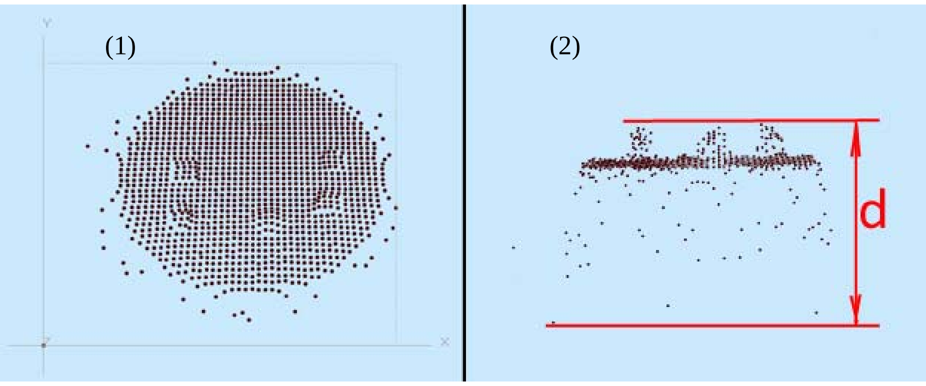

Figure 5: Pixel wise 3D-data of plate (top and side view)

Figure 6 depicts the steps from the raw data (1) to the pixels of the plate ((2), (3)) without objects. The inclination of the plate is calculated solely from the pixels of the plate. For removing an object, the robot gripper has to approach the plate in normal direction. The normal vector can easily be calculated from the inclination of the plate.

In the next step the position of the objects is determined. Therefore object pixels neighbouring side by side are assigned to groups and the centre is calculated. Plausibility checks of the sum of pixels in a group prevent that objects in direct contact with each other are falsely recognized as one.

Based on the data obtained from the overall view of the plate the game algorithm decides which object shall be removed. However, the position data is not precise enough to accurately grip the object. Moreover, the gripper has to be aligned along the edges in case of a cubic object.

A second 3D-image from a closer point of view is required. Figure 7 shows the 3D-image of a cubic object. The depth of the image is colour-coded.

C. *Game Algorithm*

As described in the previous chapter, the 3D-ToF-camera provides all information necessary to calculate the inclination of the plate and the position and orientation of all objects in 3-D world coordinates. Afterwards an algorithm is required to choose the object that shall be removed by the robot.

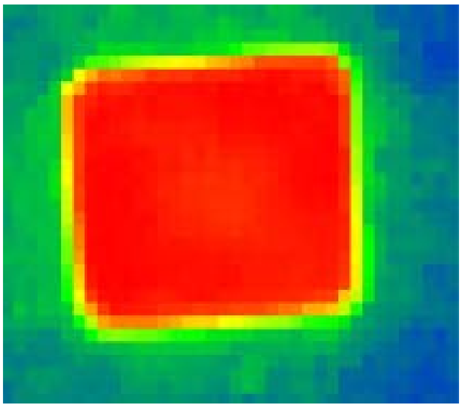

Figure 7: Colour-coded 3D-image of a cube

A first heuristic strategy would be to simply choose the nearest object on the lower side of the plate. A more offensive strategy is to remove an object on the higher side of the plate and thus create a critical situation for the following player.

The performance of the game algorithm can be improved if the mass properties and the geometrical distribution of the objects given by the sensor system are taken into account. In the current implementation only the distribution and the shape of the objects are recognized by the sensor whereas the mass is a predefined parameter of the algorithm.

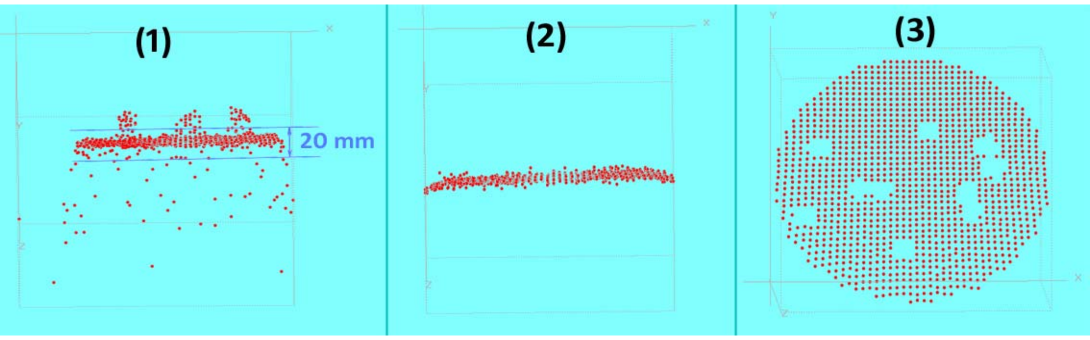

Figure 6: Processing of pixel data of the plate

The new 3D-sensor technology offers direct volume calculation from depth data. This feature would in principle enable a sensor-based recognition of the volume of the objects and their mass, respectively. For time shortage this issue was not focused in [6].

In [7] an algorithm is described that the static equilibrium conditions taking into account the distribution and the masses of the objects on the plate. The algorithm predicts the inclination angle α_j of the board after removing each particular object j. In a final step the algorithm chooses the object to be removed.

Experiments have shown, that stability is lost, if the static inclination angle α_j exceeds a critical value α_{crit} = 10°. Any object with an inclination angle $\alpha_j < \alpha_{crit}$ is possible.

Again, “offensive” or “defensive” strategies can be applied. A defensive strategy is to remove the object that yields the smallest inclination angle. An offensive strategy on the other hand would try to achieve a critical situation with a maximum inclination angel α_j smaller α_{crit}. The preferred strategy can be chosen via the GUI of the game.

IV RESULTS

The major aim of the project was to evaluate the feasibility of the 3D-camera for position measurement and object identification in automation. The 3D-camera was successfully implemented in the robot system. For realization of the game a program in C++ was developed. It is executed on a standard PC. The main tasks of this program are processing camera data, object recognition, calculation of equilibrium conditions, game algorithm and communication between robot and camera [6].

The 3D-camera replaces the 2D-CCD-camera and the distance sensors. The previously used algorithm that calculated 3D-data from 2D-data and singular distance measurements is now unnecessary. The camera directly provides all data required for automated moves of the interactive robot system. Moreover, it offers a complementary gray-scale image, which is matched with the 3D-data.

Compared to the 2D–camera, however, the resolution of the 64x48 pixel camera is a crucial parameter. Misalignment due to lack of resolution may lead to inacceptable positioning of the robot gripper. For a robust performance of the robot system and a precise grasping of objects an additional close-up measurement of the object position and orientation turned out to be necessary. Since the Roboleo equilibrium game is not critical in terms of process time, the second measurement is not restricting the functionality of the system. In an industrial production process, however, process time is important. New 3D-cameras with 204x204 pixels for industrial use have recently been announced [3,9].

Another important factor influencing the measurement is the colour and dispersion of the surface. PMD sensors illuminate the scene with modulated light and measure the turnaround time of the reflected light at each pixel. The intensity of the reflected light depends on the colour of the surface. In the previous version of Roboleo, which utilized a CCD-camera, black objects were placed on a white plate to facilitate the 2D-object recognition (see fig. 2). The different features of the surfaces have a significant effect on the 3D-data.

To evaluate the effect, measurements with different surfaces have been done. The highest errors of up to 20 - 40 mm appeared at a black and white checkerboard pattern. Figure 8 shows the color-coded results (2). Similar effects can be observed at monochromatic glossy surfaces.

To avoid such measurement errors, wooden material with matt surface was used for the objects and the plate in Roboleo (see fig. 3).

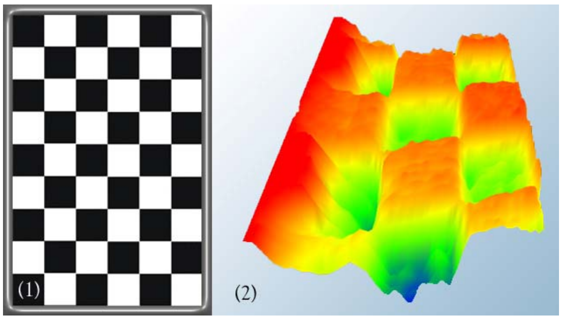

Figure 8: 3D-image of a checkerboard pattern

With the measures described above a robust performance based on the new 3D-camera could be realized.

V CONCLUSIONS AND OUTLOOK

An innovative 3D camera has successfully been integrated into a robot system and evaluated for applications in automation. The 3D-camera captures both gray scale and pixel-wise depth data of the scene. It replaces a previously used 2D-CCD-camera and distance sensors and directly provides the 3D data for an interactive balance game between the robot and a human player. Mathematical models to gain the 3D-data from 2D-data and singular distance measurements are not required any more. Technical constraints e.g. due to the limited resolution of the camera could be overcome. New 3D-cameras for industrial use will offer improved features. 3D-imaging based on PMD sensors seems to be a promising approach not only for the project presented here but for several applications in industrial automation. A classical task in robotics that can be addressed with the

3D ToF cameras is the bin-picking problem. The direct online access to 3D data offers new approaches.

Moreover the 3D online information is essential for autonomous robots [12]. For many applications, such as field robots, the accuracy of one or a few centimetres is sufficient. Thus the authors see a high potential in this market. For outdoor applications the robustness of the camera has to be investigated, such as sun light, shadows, colour influence, dust or vibrations. First results are available [13], the integration of such cameras in an autonomous field robot is planned [14].

REFERENCES

[1] T. Ringbeck, B. Hagebeuker. *A 3D time of flight camera for object detection*. 8th Conf. on Optical 3-D Measurement Techniques, 09-12.07.2007, ETH Zürich, Switzerland

[2] B. Hagebeuker. *Mehrdimensionale Objekterfassung mittels PMD-Sensorik*. Optik & Photonik, März 2008 Nr. 1, pp 42-44, Wiley-VCH, Weinheim

[3] PMDTechnologies GmbH. Available at http://www.pmdtec.com/, 15.02.2009

[4] Ifm-electronic GmbH. Available at http://www.ifmelectronic.com/ifmde/news/news_7PLHNX.htm , 15.02.2009

[5] Fuchs, S., May, S.: *Calibration and registration for precise surface reconstruction with Time-of-flight cameras*, International Journal of Intelligent Systems Technologies and Applications, Vol. 5, No 3-4, 2008, pp. 274-284.

[6] D. Jaerger, *Integration einer 3D-Kamera in ein interaktives Robotersystem*, Diploma Thesis, Fachochschule Osnabrück - University of Applied Sciences, Faculty of Engineering and Computer Science, Osnabrück, February 2009

[7] G. Thösink, F. Peters, W. Prescher, A. Ruckelshausen, B. Lammen. *An Interactive, Seeing Robot as a Platform for Research and Education in Mechatronics and Optoelectronics*“. 5th Int. Workshop on Research and Education in Mechatronics, 01.-03.10 2004, Kielce , Poland

[8] B. Lammen, A. Ruckelshausen. *ROBOLEO – An Interactive Seeing Robot*, 2004 IEEE Conference on Robotics, Automation and Mechatronics, 01.- 03.12.2004, Singapore

[9] G. Thösink, J. Preckwinkel, A. Ruckelshausen, B. Lammen. *ROBOLEO – Ein sehendes Robotersystem mit Mensch/Maschine-Interaktion.* Workshop Intelligente Mechatronische Systeme (IMS), Paderborn, 2004, S. 133 -144

[10] Girod, B., Griner, G., Niemann, H.: *Principles of 3D Image Analysis and Synthesis,* The Springer International Series in Engineering and Computer Science, Vol. 556, 2000.

[11] Kolb, A., Barth, E., Koch, R. (2008): *ToF-Sensors: New Dimensions for Realism and Interactivity*; Computer Vision and Pattern Recognition Workshops, 2008. CVPR Workshops 2008. IEEE Computer Society Conference on 23-28 June 2008 Page(s):1 – 5

[12] Siciliano, B., Khatib, O.: *Handbook of Robotics*, Springer-Verlag , 2008.

[13] Klose, R., Ruckelshausen, A.: *Usability study of 3D Time-of-Flight cameras for automatic plant phenotyping*; accepted abstract, CIGR-Workshop Image Analysis for Agricultural Products and Processes, to be published, 2009. Ruckelshausen, A.; Biber, P.; Dorna, M., et al. (2009): “BoniRob – an autonomous field robot platform for individual plant phenotyping” JIAC 2009 Wageningen (to be published)

[14] Ruckelshausen, A., Biber, P., Dorna, M., Gremmes, H., Klose, R., Linz, A., Rahe, F., Resch, R., Thiel, M., Trautz, D. and Weiss, U.: “*BoniRob – an autonomous field robot platform for individual plant phenotyping*” JIAC 2009 Wageningen (to be published)