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Low-Cost 3D Scanning in a Smart Learning Factory

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Abstract

With the increased focus over the recent years on digitalizing the factory, 3D scanning has become more and more popular. Acquiring a point cloud of a given factory has shown several benefits, such as better documentation, realistic simulation models, collision detection of materials, visualization of factory development, and more. This paper investigates the testing of a developed low-cost 3D scanner in a Smart Learning Factory based on parameters identified in literature. Furthermore, the paper compares the developed solution to a commercially available solution. This comparison indicates possible application areas for the developed low-cost solution. The 3D scanner is based on the Microsoft Kinect and a developed hardware platform combined with custom software for acquiring 360° point clouds. A discussion on the acquired results, as well as future works on the developed solution finalizes the paper.

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Keywords: Digital Twins; Point Cloud; Learning Factory; Laser Scanning

1. Introduction

Digitalizing factories has over the recent years increased in popularity as a part of the fourth industrial revolution, Industry 4.0. Acquiring a 3-dimensional representation of the factory has shown several benefits, such as collision detection [1], lean based optimization [2], and integration with discrete event simulation [3]. Typically, these 3D laser
scanning solutions are in the price range of ten thousand USD and upwards. The developed prototype, based on the Microsoft Kinect V2 combined with a custom-made hardware platform and MATLAB code reaches a price range of around 500 USD, excluding software licenses. In this way, the developed solution aims to be applied in areas where price is of higher importance than accuracy and acquisition speed. This could for example be in engineering education, where the approach to scanning a learning factory is of higher importance than the level of details in the model. Additionally, it allows users that would typically not be in contact with such hardware to get acquainted with the processes [4].

The key contribution of this paper is the test and comparison of the developed 3D scanning solution. In addition to this, the paper contributes by suggesting suitable application areas of the developed device compared to the commercially available solution. In the following section, related work is described, first in terms of technology, afterwards in different application areas where low-cost 3D scanners have been applied. In section 3, a brief description of the hardware and software is included, as well as a description of the calibration. Section 4 describes the testing and comparison with the commercial activities. In section 5, the possible application areas are introduced, and finally in section 6, the outcome is discussed, and future works identified. Section 7 concludes on the article.

2. Related work

Several low-cost 3D scanners have previously been developed, where different approaches have been applied to improve existing solutions. As identified in [5], the depth resolution of the Microsoft Kinect is in VGA resolution. By applying HD cameras combined with a depth super-resolution algorithm and the Microsoft Kinect, Patra et al. has increased the density of the point cloud, thus the quality. From this paper it is therefore possible to conclude that the resolution of the depth sensor as well as the camera is of high importance for the quality of the point cloud.

Another important parameter for acquiring high quality point clouds when applying the Microsoft Kinect solution is the scanning distance. Lachat et al. recommends a range from 0.5 meters to 4.5 meters. In the paper, test results show that at 4.5 meters, the variation between the measured and the true distance reaches 1.5 cm [6]. As identified in the paper, the distance to the object determines the deviation between the measured and true distance, where the closer the object is to the sensor, the smaller deviation.

Low-cost 3D scanning has been applied in several cases to acquire point clouds and in different application areas. The following table describes the different application areas, where a low-cost 3D scanner has been applied.

<table>
<thead>
<tr>
<th>Application area</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal mapping</td>
<td>[7]</td>
</tr>
<tr>
<td>3D shape scanning</td>
<td>[8] [9] [10]</td>
</tr>
<tr>
<td>Plant phenotyping</td>
<td>[12]</td>
</tr>
</tbody>
</table>

Low-cost 3D scanners are applied within several different areas. Originally, the Microsoft Kinect was designed for the gaming industry, although when the software development kit was released, it reached other application areas [13]. Common for all application areas is that they need as high resolution as possible in a low-cost solution. As the distance between the sensor and the object in the application areas above is fairly low, the Microsoft Kinect is mainly the applied solution. The suggested application area in this paper can therefore to a certain extent be compared to the application areas in Table 1. This is due to the low distance needed in the measured smart learning factory, illustrated below in Fig. 1. The dimensions of the laboratory are approximately 15 meters long and 12 meters wide.
3. Developed solution

3.1. Hardware

The developed solution consists of a Microsoft Kinect V2, a servo motor, a microcontroller connected to a custom-made control circuit and finally a computer for executing the code. Finally, an enclosure has been constructed by applying additive manufacturing technologies.

The custom-made control circuit enables the microcontroller to provide the required power to the servo motor in order to successfully rotate to the specified location. Furthermore, the control circuit enables the microcontroller to access the signal connector on the servo motor. The 3D printed enclosure contains circuitry, microcontroller, and servo motor. The following figure illustrates (a) the connection diagram of the developed solution and (b) the actual solution.

![Connection diagram](image1)

![Developed solution](image2)

Fig. 1. Smart Learning Factory

Fig. 2. (a) Connection diagram; (b) Developed solution

![Nomenclature Table](table)

### Nomenclature

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>PSU</td>
<td>Power Supply Unit</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
</tbody>
</table>

3.2. Software

The custom software is developed in MATLAB and consists of two programs that respectively acquires multiple individual point clouds and stitches the point clouds together for illustration and further application. The point cloud acquisition program is divided into three main sections; Initialization, acquisition, and preparation for further execution. To acquire the point cloud, the servo motor is driven to the outer position. Afterwards, the Microsoft Kinect acquires an RGB picture, followed by a depth picture. The point cloud is then generated, and the servo motor is driven to the following position. This is repeated until the outer position is reached. The step distance can easily be adjusted to increase the number of scans in the point cloud thus the quality.

For the point cloud stitching program, the ICP algorithm is applied. By adjusting factors such as the grid size, it is possible to down sample the point cloud. This is done to partly remove noise in the point cloud, but also improve the stitching of several point clouds. This is done to speed up the process, although it is optional as it influences the quality of the point cloud. Afterwards the point clouds are merged together to one point cloud, following the ICP algorithm with variable merge cube size. This allows for fine tuning of the stitching.

3.3. Calibration

Prior to testing the developed solution, calibration of the Microsoft Kinect was performed in MATLAB. The calibration process followed the standardized MATLAB functions, applying a chess board pattern to acquire 20 pictures in different angles. Based on these pictures, the following parameters, as seen in Table 2 were calculated to calibrate the Microsoft Kinect camera.

![Calibration Table](table2)

### Table 2. Microsoft Kinect calibration parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Length</td>
<td>1221.1, 1210.7</td>
</tr>
<tr>
<td>Principal Point</td>
<td>977.77, 489.87</td>
</tr>
<tr>
<td>Radial Distortion</td>
<td>0.1638, 0.0492</td>
</tr>
<tr>
<td>Mean Projection Error</td>
<td>2.97 mm</td>
</tr>
</tbody>
</table>

Although calibration is of high importance, the factory-set calibration often meets the requirements for most applications. Whether the manual calibration process and corrections outperform the standard calibration settings is to be determined in another study.
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4. Testing

4.1. Testing parameters

Based on the paper presented by Khoshelham [15] and the identified points in the related work section, the following parameters are applied to determine the quality of a point cloud in the tests performed.

- Depth resolution
- Scanning distance
- Point density

The point density and depth resolution are closely connected parameters, as the point density can be expressed as inversely proposal to the distance squared. This can also be expressed as seen below in Equation 1. In other words, this means that the closer the object is to the sensor, the higher point density.

\[ \rho \propto \frac{1}{z^2} \]  

(1)

4.2. Test results

The developed solution is tested and compared against the Faro Focus S150 laser scanner. The point clouds generated from respectively the developed solution and the Faro laser scanner can be seen below.

Fig. 3. (a) Point cloud by developed solution; (b) Point cloud by Faro Focus S150.

As illustrated in the Fig. 3 above, the quality can both be estimated visually but also more quantitatively by analyzing the parameters identified in the previous subsection. The depth resolution of the Faro Focus S150 is stated to be 0.3 mm at 10 meters distance, measured with a reflectivity on 90% [16]. In comparison, the Microsoft Kinect solution has a fairly lower resolution. As identified by Yang et al. the depth resolution is approximately 3 mm at 3 meters distance [17]. As the Faro Focus S150 data sheet does not provide depth resolution data in the range, where the Microsoft Kinect solution is functional, a direct comparison of the data is not possible. Following Equation 1, it can though be estimated that due to the higher depth resolution of the Faro Focus S150, the point clouds, if acquired at the same distance as the Microsoft Kinect solution, will be of higher density. This corresponds to the acquired point clouds in Fig. 3.
5. Application area

5.1. Engineering Education

The key application area for the developed solution is in engineering education. The solution allows the professor to teach the principles behind 3D scanning by combining theory and practice. By illustrating scenarios with unwanted results, as well as the corrections to these scenarios, it will be possible for the students to adjust for these sources of errors by developing a good approach before working with commercially available solutions thus optimizing the learning output and minimizing the time with the high-cost equipment.

In addition to the application above, the developed solution aims to spark creativity among the students resulting in innovative solutions for the manufacturing environment. By simplifying a complex product, it allows the students to understand the basic concepts that is needed prior to developing more advanced solutions. As the developed solution is of low cost and highly customizable, it is easily integrated in prototypes that potentially could result in an innovation within the field.

5.2. Smart Learning Factories

Another important application area for the developed solution is in smart learning factories. By applying the developed solution in this setting, the students get a practical and real case, where they can apply the theoretical knowledge acquired during their education. In this way, it is possible to create the necessary skills for the future engineers as an addition to the theoretical knowledge. By acquiring a point cloud with a commercially available solution, it is furthermore possible to practically show how the industry would solve the task, as well as illustrate the importance of a good point cloud. Discussions on similarities in terms of planning, acquisition, and scanning distance allows the students to reflect on future cases. In this way it is possible for the students to reach all levels in the SOLO taxonomy.

6. Discussion

As the presented results illustrates, the point clouds acquired by the developed solution is not of the same quality as the commercially available solution. Whereas the Faro Focus S150 applies physical spheres for an improved stitching, the developed solution does not apply this procedure. The developed solution does not apply this approach, and therefore relies solely on the algorithm. This could lead to an inaccurate stitching thus a lower quality point cloud.

Another source of error is the measurement setup. As the light conditions change during the testing, the results will be different as well. As an example, stronger light will result in measurement gaps due to the functionality of the sensor. As the different solutions apply slightly different technologies, the measurement setup should therefore either correspond to the actual setups in the industry, or a more ideal setup that allows good repeatability, depending on the aim of the tests. Another important factor in the measurement setup is the orientation and distance to the object measured. As the accuracy of the measurements change depending on the distance to the object, the importance of standardizing the measurement setup is high [15].

In terms of application areas, the developed solution is fairly limited. In order to expand the application area to improve the functionality, secondary software for 3D shape scanning could be developed. In this way, it will be possible to completely digitalize a factory and the materials. Additionally, when fully digitalizing the factory, possibilities for realistic discrete event simulations exist. By acquiring relevant data of the material flow and factory processes, simulation models can be created, potentially providing new information in the smart learning factory.
6.1. Future works

One of the key points to improve in the current setup is the point cloud density. As the density of the point cloud is closely connected with the level of details, clearer representations of the scanned objects will be possible. This will furthermore allow other application areas, such as collision detection, as described in [1]. In order to improve the point cloud density, adding high resolution cameras in combination with the Microsoft Kinect has shown good results [5]. Despite the slightly increased cost from integrating this solution into the developed solution, the depth resolution will be greatly improved in combination with the density of the point cloud.

In addition to the suggested improvement, an improved approach for processing the point cloud is needed. Currently, the ICP algorithm is applied, although different improvements are suggested in literature [18], [19]. Future works will include improving the stitching and post-processing of the point clouds in order to maintain a high density while stitching the point clouds together in an efficient and precise way.

The final upgrade of this solution would be to create a graphical user interface as an alternative to running MATLAB scripts. This graphical user interface could include tools to assist and improve stitching of the point clouds. Adjusting parameters such as the number of point clouds when acquiring, as well as the parameters for denoising could be beneficial to improve the results.

7. Conclusion

It is concluded that a low-cost 3D scanning solution has been presented and tested towards a commercial solution. Parameters for determining the quality as well as the calibration process has been identified in literature. The acquired point clouds from respectively the developed solution and a commercial 3D scanner has been compared with both an identified equation as well as qualitatively. The commercial scanner acquires high resolution point clouds, whereas the developed solution acquires point clouds of a lower quality. Possible application areas, such as engineering education of the developed solution are suggested and discussed. Furthermore, application of the developed solution in smart learning factory is discussed as a tool to improve learning through practice. Future works on the developed solution is discussed and improvements are suggested.

8. Acknowledgement

This work is supported by the InProReg project (project no. DD01-004). InProReg is financed by Interreg Deutschland-Danmark with means from the European Regional Development Fund. In addition, InProReg is financed by Syddansk Vækstforum, which recommended the project to be funded by means for regional industrial development.
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Future works on the developed solution are suggested and discussed as well as the calibration process. The acquired point clouds from respectively the developed solution and a commercial 3D scanner has been compared in literature [1], [18], [19].

One of the key points to improve in the current setup is the point cloud density. As the density of the point cloud increases, the quality of the generated 3D model also increases. However, the developed solution acquires point clouds of a lower quality. Possible application areas, such as engineering, manufacturing, and architecture, require high-resolution point clouds. Therefore, improving the point cloud density is crucial.

Despite the slightly increased cost from integrating this solution into the developed solution, the depth resolution will be improved, and the accuracy of the generated 3D model will be increased. This will also allow the developed solution to be used in further application areas, such as collision detection, which is closely connected with the level of details.

Currently, the ICP algorithm is applied, although different improvements are suggested in literature [6], [9], [10]. The acquired point clouds from the developed solution are compared with point clouds acquired from a commercial 3D scanner. The acquired point clouds from the developed solution are of lower quality, as expected, but they are still usable for many applications.

In conclusion, the developed solution is beneficial to improve the results. A low-cost 3D scanning solution has been presented and tested towards many application areas. However, further improvements are suggested and discussed as well as the calibration process. The acquired point clouds from respectively the developed solution and a commercial 3D scanner has been compared in literature [1], [18], [19].

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9. References