Simulation of Multi-Camera Indoor and Outdoor 3D Scanner

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Abstract: Photogrammetry allows a three-dimensional reconstruction of the object based on its multiple photography's. The quality of the reconstruction result depends mostly on the gloss, the diversity of the texture, the lighting conditions, the quality of the camera calibration and the shape of the object. The article presents the results of a simulation of a multi-camera reconstruction system, for the needs of designing indoor and outdoor 3D scanner. The 3D reconstruction system works by simultaneously taking photographs of cameras located around the object. The simulation was created to investigate the optimal distribution of cameras and projectors casting a pattern that increases the number of characteristic points on the surface of the object. The impact of background removal in images on the reconstruction result as well as the texture quality of the object depending on the resolution and distance of the cameras from the object were also investigated. The graphic engine used to create the simulation also allows testing of impact of various conditions. The presented results prove that the parameters of the system structure, such as the placement of cameras, projectors, the selection of patterns projected by the projectors are important and their values can be determined at the stage of system simulation. The acquired results are promising and will be further investigated.

Key words: *Reconstruction 3D, photogrammetry, simulation*

INTRODUCTION

The aim of the work was to develop a solution that would allow moving the real world to virtual reality in a photorealistic way and possible to use both indoors and outdoors. We also set ourselves the challenge of developing a solution that allows 3D reconstruction of objects that are not rigid bodies, for example people.

As part of publication work, we investigated the possibility of simulating the 3D reconstruction system in the game engine. The demand for this type of research results from the intention to physical implement such a scanner. The simulation was to show whether it is possible to determine the specifications of the scanner, its structure, the components used, their arrangement based on tests carried out in a virtual environment. The identification of technical parameters and problems at the simulation stage of scanner may speed up the process of its construction and commissioning. The tests carried out in the simulation environment were repeated in the corresponding to them real conditions in order to verify the results obtained earlier.

The created scanner consists of cameras, projectors, lighting and a construction frame. Simulation engine allows you to create three-dimensional scene on which we can arrange elements of the reconstruction system and models of objects, whose shape and texture are to be recreated. Then the cameras spread around the object render the images, which serve as the entry point in the reconstruction software.

LITERATURE REVIEW OF 3D RECONSTRUCTION

Various methods are used to capture the object or scenery for 3D reconstruction. Recently, there is an increase number of 3D models built based on data acquired from combination of terrestrial surveying and unmanned aerial vehicles (UAVs) in order to close possible 3D modelling gaps and create orthoimages [1][2][3]. For ex-ample, UAV and terrestrial image acquisition platforms are used in [4] to study gullies with their complex morphologies. It has been shown that using both techniques allow for comprehensive gully models with high spatial resolution at frequent intervals. More and more often, scans are also being execute by robots, like e.g. in cooperative scanning performed by two industrial robot arms [5].

Cooperation between different approaches to acquire the data for 3D model are involved mostly in reconstruction of sceneries and vast spaces. UAVs are used e.g. for road mapping [6] and thermal analyses [7]. High resolution surface scanning, radio-logical MRI and real data based animation are used to reconstruct and analyze traffic accidents [8].

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Whole sceneries and localizations are scanned using approaches like CHISEL – a system for a house scale 3D reconstruction [9]. This particular reconstruction meth-od can be used with high resolution in real time on a mobile device. 3D scanning is commonly used for surveying and mapping of man-made structures and sites [10][11][12]. Usually, high quality 3D models of objects are constructed using different viewpoints, like it is shown when scanning the monument by [13]. It is especially useful to reconstruct a 3D digital model of objects with complex surfaces and sub millimeter-sized features [14]. Reconstruction of complex micro-structures are used for construction work, as well as damage detections of large-surface objects. For example, [15] collects 3D micro-texture of asphalt pavement and reconstructs using binocular vision method for rapid extraction of the 3D image.

3D scanning was used e.g. for damage detection of wind turbine blades to maintain efficient and safe energy generation [16]. Building damage assessment was also used in [17] study, when the researchers reported the use of 3D scanning of residential buildings damaged during Hurricane Sandy. The researchers suggest that using 3D scanning can support post-disaster damage assessment needs for buildings, bridges or other man-made structures [18].

Archeology research is another example where 3D reconstruction is widely used and not only above the ground, but also underwater [19]. In archeology image-based 3D modeling is used to record entire excavations [20]. This approach increase the quality of obtained pictures and data and allows documentation and visualization of the archeological heritage.

Landscapes and their fragments can be reconstructed using 3D scanning approaches, like in [21]. In this study, the researchers scanned the rock slopes for obtaining the orientation of slope and possibility to monitor the slope for quantification of rock fall rates across wide areas. 3D reconstruction of the slopes allowed also to model detailed future deformations and possible rock damage. Therefore, 3D scanning may be used to alert residents about possible natural failure [22].

3D reconstruction of natural environments has been used extensively in agriculture, geology and botany studies. 3D models representing the shape and size of single plants and whole areas of fields and forests, can provide critical information for plant breeding and cultivation [23]. 3D representation of trees has been described e.g. in [24] and [25]. 3D scanning can help to predict phenotyping features, like size and number of leaves [26], what helps the producers in precision farming. 3D approaches are used also in

forestry for the vegetation monitoring or fires surveillance [27].

Living objects, like plants, animals and human's body can be reconstructed in 3D [28]. 3D reconstruction is used to measure body parts, like e.g. feet in order to personalize 3D printed shoes [29]. Companies develop applications, like VisuaLook, that allow the measurement-based 3D reconstruction of the body and provide a service for the visualization of virtual looks at online shops [30]. Moreover, efficient 3D re-construction is often use for face recognition [31].

3D scanners are used also on micro-level, e.g. to monitor the pulse in real-time [32] and reconstruct in 3D blood vessels from a limited number of projections [33]. 3D scanning techniques are used in biomedicine and science extensively, e.g. in super resolution fluorescence microscopy for reconstruction of thick tissue blocks [34][35]. By using it in research, like in ultramicroscopy for reconstruction of e.g. mouse embryos [36], it is possible to obtain high-level detailed insight into the anatomy of organisms and to screen for disease models.

Nowadays, not only body parts, but also full body scans are being designed. Full body shape scans are used for anthropometric surveying, clothing design or entertainment. For example, [37] developed a scanning environment based on multiple depth cameras for full-body scans, free of template markers and fully automatic. [38] Constructed a system that captures the human skeleton through a wall by tracing the 3D positions of the limbs and body parts. 3D scans can not only reconstruct the stationary objects and figures, but also the movements. [39] Used 3D reconstruction to model a moving person for long-term person re-identification based on difference in poses or walking. This approach is used also in sport training. 3D reconstruction of body postures can help athletes to master the techniques and improve the training program. 3D scans allow tracking of body movement and its parts, including the translational and rotational degrees of freedom [40]. 3D scanning can be used to characterize the golf swing [41] or underwater swimming [42].

Three-dimensional reconstruction use increases in field of medicine and biology re-search. 3D scanning is involved in surgery and preoperative clinical practice planning, prosthetic design and education tool for teaching and doctor-patient interaction [43], [44], [45]. 3D whole body scanners are commonly used for healthcare applications, like in rehabilitation engineering [46]. An example is described in [47] where photogrammetry is used for the data acquisition and processing of human body models for design of prostheses and orthoses. Preoperative 3D reconstruction and rapid proto-typing was applied for

treatment of complex severe spinal deformity in [48]. Rehabilitation and surgeries acquire advantages by suing 3D reconstruction methods. An example is neuronavigation using endoscopy by reconstructing patient specific anatomy in three dimensions [49]. Another example is use of 3D scanning techniques for corrective surgery for Lenke 1 AIS patients [50]. [51] Used 3D techniques for heart modeling and 3D printing for individualized planning for percutaneous structural intervention.

An alternative application to the above is the 3D reconstruction of objects, in particular people, for the needs of professional simulation systems. Training of officers of uniformed services in the field of conducting anti-terrorist activities at the intervention level requires preparation of an officer for each possible situation. We believe that using photorealistic avatars animated using Motion Capture will contribute to improving the realism of the training.

SIMULATION OF 3D RECONSTRUCTION SYSTEM

We have designed and constructed a 3D scanner in virtual environment. This scanner consists of 145 virtual cameras arranged on rings around the central point. Rings there are arranged at different heights (Fig. 1). The cameras are directed towards the inside of the circles. The position and orientation of cameras and the number of rings are controlled by the created script and controlled by the user's panel. Apart from cameras, it is also possible to determine the position and number of projectors placed around the scanner. Projectors throw a pattern which increases the texture diversity. This allows to find corresponding image points in neighboring cameras. An additional element is the lighting control system enabling testing of reconstruction of glossy objects and tests of uniform illumination of objects, eliminating shadows.

The result of the simulation are images from cameras located in the scanner, which are next processed in software for 3D reconstruction based on photographs. The result of the reconstruction depends on the placement of cameras, their number, resolution, lighting, optical properties of the material and texture characteristics. By changing individual parameters of the system, it is possible to determine the best configuration for obtaining the best results.
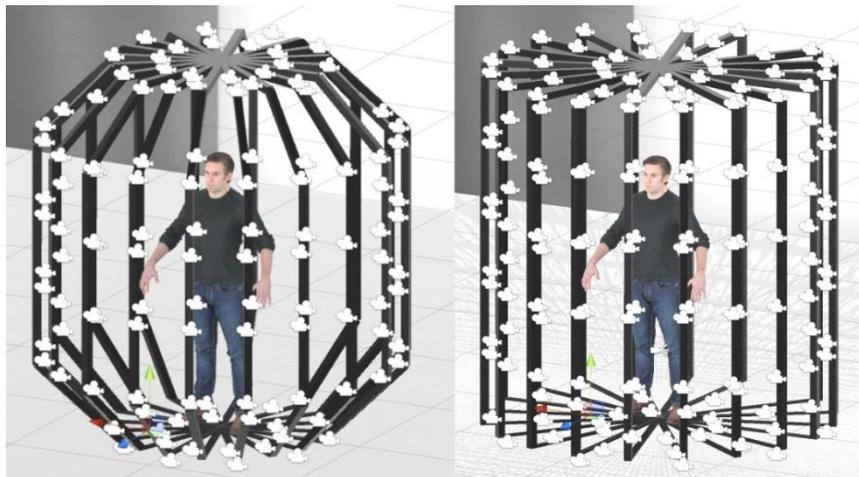

Fig. 1. Visualization of two different configurations of virtual cameras and projectors placement in the scanner.

RECONSTRUCTION IN VIRTUAL ENVIRONMENT

During the simulation, we examined the quality of the reconstitution result depending on the applied elements and system parameters. The results of the various reconstruction processes are presented in the next chapter.

As a test object, we chose the 3D model of a person with a high-resolution texture. We placed the object at the central point of the scanner. The reconstruction consisted of processing photographs from virtual cameras placed around the object. We set up a uniform lighting of the stage, simulating LED strips arranged on the vertical elements of the scanner structure. As part of the test, we modified the position and orientation of the cameras to find the optimal configuration for human scaling. The number of cameras was also changed. In addition, we tested the configuration with cameras with close-ups on the hands and face in order to find more characteristic punts and a more accurate representation of the shape.

We tried to improve the result of the reconstruction by subtracting the background from the acquired

images. Because the scene was static, it was possible to take two shots. The first one where the scanner was empty and the second with the object inside. On the basis of the difference of images, it was possible to determine the mask of reconstruction.

In this case, we added four projectors to the scanner to illuminate the object. As a result, the uniform texture surfaces on the object became more characteristic. The tests consisted in determining the resolution and pattern projected by the projector, for which the reconstruction gives the best result.

RECONSTRUCTION IN REAL CONDITIONS

In order to compare the results of tests obtained in simulation conditions with the results of the reconstruction of real photographs, we created a test stand consisting of two test objects and a camera. The first object was a rocker, covered with metallic varnish and the other a semi-transparent coolant tank. The type of objects guaran-teed the lack of good results of reconstruction in the absence of any modifications. This is due to the optical properties of reflecting or transmitting materials and the uniformity of their texture.

Reconstruction based on photographs of unmodified objects ended in failure due to lack of detected characteristic points on the surface of the objects. Therefore, we introduced the first modification of the reconstruction process which consisted in increasing the texture characteristics of the object by covering its surface with mat-ting agent (Fig. 2). We chose this measure due to the ease of its application and the possibility of later washing. Images recorded with the camera have been processed using the same software as images rendered from virtual cameras.

Fig. 2. Photographs of scanned objects. On the left, a translucent coolant tank and a rocker arm covered with a matting substance. On the right, the same objects with matting agent and additionally illuminated patterns from the projector.

As in the previous method, we covered the objects with a matting agent. Then, we placed projectors with a resolution of 1920x1080 on two sides of scanned objects. High image resolution guaranteed a high specificity of texture on the object. Then we made a series of 50 photos. We have repeated this process once again using another type of matting agent, with a smaller size of individual particles covering the entire surface once more.

RECONSTRUCTION OF INDOOR SIMULATED DATA

We underwent a visual evaluation of the results of our tests due to the lack of other quality indicators for reconstitution. First of all, we paid attention to the shape of the mesh of the reconstructed objects. We asked ourselves whether the shape of the obtained object resemble the original object. Is it possible to observe inequalities of the surface or holes in the model. We also compared the input and output texture of the object and paid attention to the areas where the texture is missing or badly mapped.

Below we present the results of the reconstruction for the data collected in the scanner simulation and for the data recorded on the objects by the camera. The main purpose of creating the simulation was to determine the proper configuration of the camera layout, which would ensure correct human reconstruction. We have carried out several reconstructions, changing the number of cameras and their location, step by step increasing the quality of reconstitution. In the last simulation 145 cameras were deployed on the surface of the cylinder and directed towards the center of the scanner. Attempts to use additional cameras, closer to hands, failed because the reconstruction software could not find characteristic points that would connect points to a similar image with points that were indexed to them on other cameras. As an example of the object we chose the hand due to its complex shape and the fact that we could easily assess the quality of the resulting reconstruction.

Below we present the test result for the scanner in three configurations (Fig. 3). In the first configuration

the cameras are placed only on the vertical elements of the scanner's structure and are directed in front of each other. In the second configuration the cameras are also placed on the floor and ceiling of the scanner. In addition, the cameras located on the circumference of the ring look alternately 5 degrees down and 5 degrees up. The last configuration also contains 4 projectors illuminating the model from 4 sides.

We obtained the best result using cameras in the second configuration and using projectors with a resolution of 1920x1080 (Fig. 1, right).

The tests of reconstructing objects strongly reflecting the light ended in failure be-cause no configuration of cameras, settings of projectors and the type of pattern did not allow to obtain data from which reconstruction would be possible. Improvement in quality tests by removing the background also did not produce better results than the solution obtained in the third scanner configuration described above.
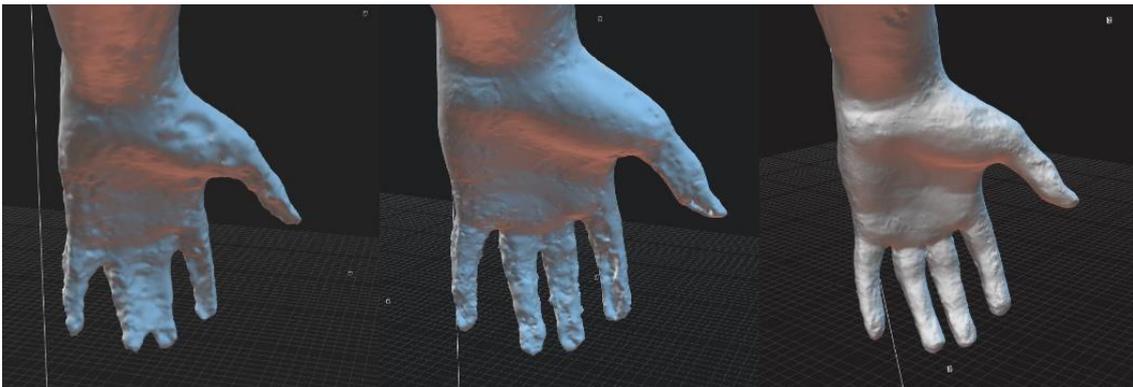

Fig. 3. Results of human hand reconstruction in three simulated scanner configurations. From left to right there are results acquired using configuration: I, II, III.

VERIFICATION OF SIMULATION TEST RESULTS

Studies of the reconstruction process on real objects have allowed us to refer to problems encountered in simulation tests and verify the quality of the approximation of real phenomena by simulation. Selected objects (Fig. 2), subjected to modifications described in chapter 3.2, were photographed and the collected data served as input information in the reconstruction process carried out in the ready

software. Below we present only the test results for three different process modifications carried out (Fig. 4). In the first of them, the object was covered only with matting agent and increasing the number of characteristic points on its surface. In the second case, the object was additionally illuminated by a pattern from the projector. In the last case, the matting agent has been changed to one that covers the entire surface of the item being scanned. Re-constructions on data collected from non-modified objects ended in failure.
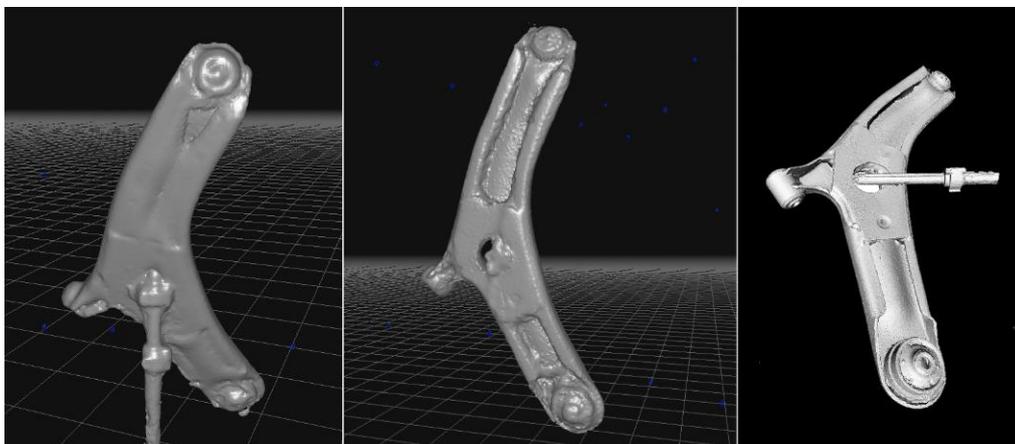

Fig. 4. Comparison of the results of reconstruction of the actual object for various modifications of the data collection process, on the example of the rocker.

In the case of the rocker the best result was obtained using a matting agent, covering the entire surface of the object and illuminating the object with the pattern from the projector.
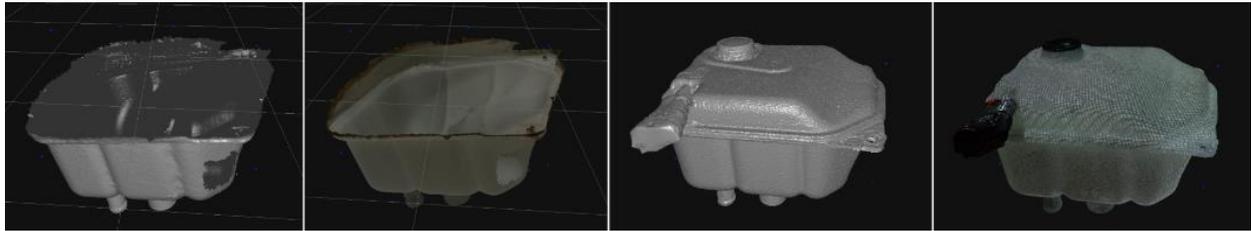

Fig. 5. The result of reservoir recollection based on a series of photos from the camera. On the left, the result of the tank reconstruction covered only with artificial snow. On the right the result of the reconstruction of the tank covered with a matting agent and a patterned projector

We have also tested the effect of the matting agent and pattern lighting on the outcome of reconstruction of the rambler. With the use of the matting agent alone, reconstruction is not possible because the object in the sequence of the sequence has a homogeneous texture, consisting of points that are difficult to explicitly characterize. The illumination of the object with the pattern from the projector made it possible to reconstruct the object.

Research was also carried out on the applicability of the simulation solution developed outside. For this purpose, a sequence of photographs of the building was made, which was then processed with a previously developed processing sequence. Selected source photographs of the building are shown in Fig. 6. 3D reconstruction of buildings' elevations is important for their subsequent recognition by both artificial intelligence systems and the human operator.

Fig. 6. Samples images from outdoor 3D reconstruction image dataset.

Fig. 7. Virtual world reconstructed using images from outdoor 3D reconstruction image dataset. Additional 3D objects and different lighting conditions were added in order to visualize the possibilities of virtual reality.

The recorded images from the set presented in Fig. 6 were used to test the 3D reconstruction of the building's outside surroundings. Obtained results of reconstruction in virtual reality with artificially added elements and modified lighting are presented in Fig. 7. The presented results are very promising and show that the solution developed after introducing appropriate hardware modifications allows 3D reconstruction of both objects and the environment.

SUMMARY OF RESULTS

Performing tests of the scanner's operation in a virtual environment has many ad-vantages. The first

of these is the cost associated with changes in the project. The change involving the camera relocation in a virtual environment involves a much lower cost than changing the position or orientation of the camera in a physical construction.

Another advantage of the simulation is the possibility to test the scanner on objects with different shapes, different textures and different optical properties. The object can be placed in any position inside the scanner, so you can check which parts of the object's surface are not visible for several cameras at the same time. Simulation results provide information on what types of surfaces or textures consist of a sufficient number of characteristic points or prevent the correct pairing of points on images from neighboring cameras.

The simulation also serves to determine the size and construction of the supporting structure for cameras and projectors, designing diagrams and length of electrical and transmission connections between system components.

We realize that the virtual environment can to some extent only approximate conditions in reality, which is why all tests carried out in a virtual environment have been also confirmed in the real environment. The results of tests carried out in a real environment have proven that the results obtained from simulation tests can serve as a guide at the design and construction stage of the scanner. The problems observed in the simulated reconstruction system are reflected in those we observed during real tests.

Data obtained from the simulated scanner and from photos in real tests can be processed using the same methods and used for the purpose of 3D world reconstruction for the purpose of navigation and observation [52].

CONCLUSIONS

As part of the work preceding the preparation of the article, simulation studies were carried out to determine the relevant parameters and their impact on the quality of 3D reconstruction. Obtained results allowed to notice challenges, eg. scanning semi-transparent objects or objects with a metallic surface. Based on this, remedial actions were developed for each of the detected difficulties, and then simulation tests were repeated. The obtained positive results encouraged the authors to physically implement the 3D reconstruction device based on the results of simulation tests. Conducted tests under operating conditions confirm the effectiveness of simulation methods of counteracting difficulties identified during laboratory tests.

Summing up, the first simulation tests carried out and then in the operational conditions allowed to develop an effective method of 3D reconstruction of objects of any type and surroundings. On this basis, the design of the device for automatic 3D reconstruction of the human form has been developed, which requires simultaneous registration of the human body from many shots due to the lack of the possibility of effective long-term immobilization of the living entity. The prototype device has been pre-constructed and tested. The obtained results confirm the effectiveness of the method developed and presented in this article.

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