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Benchmarking Close-range Structure from Motion 3D Reconstruction Software under Varying Capturing Conditions

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Abstract. Structure from Motion 3D reconstruction has become widely used in recent years in a number of fields such as industrial surface inspection, archeology, cultural heritage preservation and geomapping. A number of software solutions have been released using variations of this technique. In this paper we analyse the state of the art of these software applications, by comparing the resultant 3D meshes qualitatively and quantitatively. We propose a number of testing scenarios using different lighting conditions, camera positions and image acquisition methods for the best in-depth analysis and discuss the results, the overall performance and the problems present in each software. We employ distance and roughness metrics for evaluating the final reconstruction results.

Keywords: Multi-view 3D Reconstruction, Structure from Motion (SfM), Photogrammetry, Software Comparison, Benchmark

1 Introduction

Structure from Motion (SfM) for 3D reconstruction has come a long way in recent years. The technology is at a point where a multitude of commercial and free packages exist, enabling non-experts to quickly and easily capture high quality models from uncalibrated images. An example is given in Figure 1.

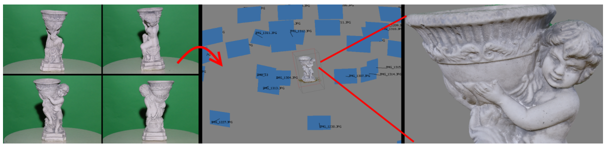


Fig. 1: Example of 4 out of N input images, taken from different view points and the resulting camera position triangulation and dense point cloud creation. The view is from Agisoft PhotoScan.

Most of these packages are used for landscape reconstruction, creation of orthomosaics and large scale reconstructions. They can be also used for close-range reconstructions. This makes them perfect for use in cultural heritage preservation, artifact digitalization, virtual museums and others. However, many of these solutions come with high initial and upkeep monetary costs. This makes choosing the one most suitable for a specific task an important first step for each project relying on 3D reconstruction - both in result accuracy, resource requirements and performance across varying conditions. Such an endeavour can require a large investment of time. This is why in our paper we provide an in-depth overview of the newest and most widely used commercial software solution tested across various conditions. We concentrate on close-range SfM, as opposed to aerial or long-range.

Six commercial 3D reconstruction software solutions are chosen for testing in the paper. Each of the solutions takes an unordered list of images as input, extracts features and creates a sparse point cloud, triangulating the camera positions. A dense point cloud and a mesh are created by interpolating the sparse point cloud. Texture of the reconstructed object is also created.

Six different objects are used for the reconstructions, depicted in Figure 2. They are selected according to their varying reconstruction difficulty and different problems that they present like textureless surfaces, repeatable patterns, symmetrical objects, glossiness, etc. Objects are scanned with a white light scanner for evaluating the meshes produced by the SfM packages.

Six different scenarios are tested. These scenarios cover different lighting, positioning and shooting setups. These experiments show that the environmental conditions have a noticeable impact on the final reconstruction and affect some software solutions more than others.

For verifying the accuracy of the output meshes from the different programs, two qualitative methods are chosen: 1) calculating the signed distance between ground truth objects and the reconstructions; 2) comparing the local roughness profiles between the ground truth objects and the reconstructions. The results show that some of the tested packages have more problems reconstructing glossy, symmetrical and textureless surfaces, than others, resulting in complete failures. Some programs sacrifice details for a less noisy final mesh, while others capture more detail, but are very sensitive to noise. A moving camera setup with uniform lighting also gives higher reconstruction accuracy than a turntable setup.

2 Related Work

SfM is just one of many techniques for 3D reconstruction of objects and artifacts. Other techniques are beyond the scope of the paper, but for a quick overview the work in stereo-vision reconstruction [13], structured light [8] or laser scanning [14] is available for reference.

For SfM reconstruction most resources for benchmarks and comparisons are either from archaeological context [15] or from geomapping context [16]. These give valuable information, but are mostly focused on one type of surfaces and objects to reconstruct under a more limited set of environment conditions. Other resources [17][9] give more in-depth comparison using both their own datasets and freely available ones, but lack the comparison for a larger number of software solutions.

3 Tested Software

We have chosen six of the state of the art software packages for 3D reconstruction. These products are *Agisoft PhotoScan Pro* [3], *Bentley ContextCapture* [1], *Autodesk Memento (ReMake)* [2], *Pix4D* [5], *3Dflow 3DF Zephyr Pro* [6] and *Reality Capture* [4]. For more information on some of the important features each of the selected software solutions has, please refer to Table 1. The prices are subject to change and are given as they are in the time of writing this paper and converted to dollars. In the output column four of the most widely used ones for close-range photgrammetry are given to preserve space - 3D mesh, texture, sparse point cloud, dense point cloud. Additional outputs like orthophotos, orthomosaic, fly-through videos, depth and normal maps, etc. are supported by many of the programs, but are out of the scope of this paper.

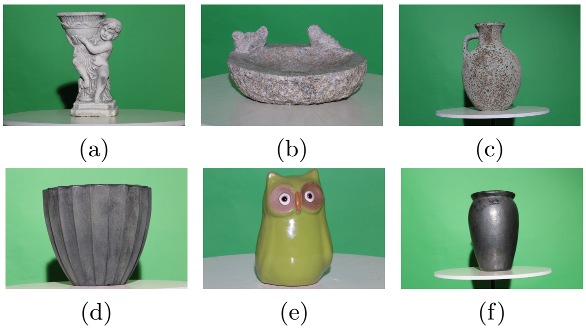
Table 1: Tested software solutions with some of their most important characteristics. In the output column the shortened names denote: dense point cloud (DPC), sparse point cloud (SPC). The price is given for both standard and pro versions. Bolded font denotes the one used for testing.

Program	**Outputs**	**Online/Offline**	**OS**	**Scripting**	**Price (USD)**
ContextCapture	Mesh/Texture/DPC	Offline	Win	Yes	N/A
Memento	Mesh/Texture	Online/Offline	Win/Mac	No	**Free**/190 annual
PhotoScan	Mesh/Texture/SPC/DPC	Offline	Win/Mac/Linux	Yes	**179**/3499
RealityCapture	Mesh/Texture/SPC/DPC	Offline	Win	Yes	**110**/8351 annual
3DF Zephyr	Mesh/Texture/SPC/DPC	Offline	Win	No	**199**/3200
Pix4D	Mesh/Texture/DPC	Offline	Win/Mac	No	**3222** annual

4 Datasets

The six chosen objects are shown in Figure 2. These objects are selected based on a number of criteria concerning the properties of the materials that they are made of. These criteria are used to judge the capability of each software to handle different difficult cases, which are considered weak points for SfM. The criteria are as follows - *glossy/smooth surfaces*, *monochrome colors*, *very dark/black color*, *repeating patterns*, *partial occlusions*, *symmetrical surfaces*. They may result in failures in reconstruction, decreased overall accuracy, cause holes and noise in the resultant point clouds and mesh [20][21].

As an initial observation the objects are divided into two groups depending on their perceived reconstruction difficulty. The easy to reconstruct objects -



(a) (b) (c)

(d) (e) (f)

Fig. 2: Testing Objects: a) angel statue, b) bird bath, c) sea vase, d) plastic vase, e) owl statue, f) black vase. Typical size of the objects is between 25 and 60 cm

angel statue, sea vase and bird bath and the hard to reconstruct objects - black vase, plastic vase and owl statue. The angel statue and sea vase are perceived as easy because they have a lot of surface detail and features, both global and local, which should make them easy to reconstruct by all the programs. They also have some partial self occlusion, which will be tested. The bird bath is also feature rich and has both very smooth and glossy surface parts, as well as rough ones. The black and plastic vases are perceived as hard, because of their color, glossiness and repeated patterns. The owl statue is chosen as an intermediate object, which has a lot of glossiness and feature poor parts, as well as non-glossy more feature-rich ones.

The input images are taken using a *Canon 6D* camera at maximum resolution of *5472 x 3648*. A zoom lens with focal length of $70 - 300mm$ is used to accommodate the different zoom levels needed for the different objects. The reconstructions are carried out on a stand alone laptop equipped with *Intel Core i7 - 4710HQ at 2.50 GHz, 16 Gb of RAM and a GeForce GTX 970M.* The operating system is Windows 8.1. Each of the six objects has been scanned with a high resolution, high accuracy white light scanner from *Aicon.* These scans are considered detailed enough to be used as a benchmark for the performance. To demonstrate the accuracy and detail of the scans, a cube with known dimensions is also scanned and the measurement of the 3D model's sides are compared to the real world ones. The two differ by an average of $1.03mm/1.12mm/0.93mm$ in width/height/depth. Henceforth these scans will be referred to as ground truth objects, while the outputs from each of the tested programs will be referred to as reconstructed objects.

5 Testing Scenarios and Results

5.1 Main Test Scenario

All six objects are used in the initial test scenario, together with all the tested programs. The distance between the reconstructed and ground truth objects is calculated, together with the local roughness. The scenario aims to determine how are the selected programs fairing when tested with both easy and hard to reconstruct objects, as well as noting their speed, accuracy and robustness against noise. The test also aims to determine the object factors which make reconstruction hardest for each of the programs.

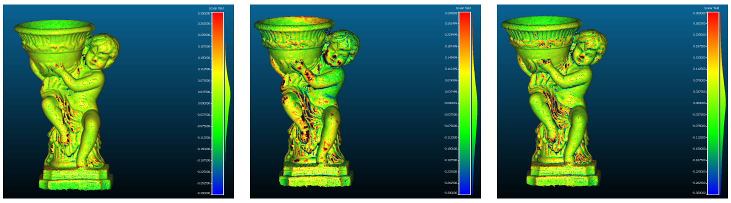
The test scenario uses photos captured in an indoor controlled environment. The image capturing algorithm is as follows - the captured object is positioned on a turntable; the camera on a tripod is facing the object and is lower than it for capturing the first set of images at lower angle; one light is positioned on a stand above the camera so it shines directly at object; a photo is taken and the turntable is turned 20^o; this is done 18 times, so the object is captured from all sides; the camera on the tripod is then repositioned higher two times, each time 18 more photos are taken; a total of 54 photos of the three different height sets. The $CanonD6$ camera is used for taking photos as it gives high detail photos, without straining the hardware of the testing machine.

The total processing time of creating the 3D model is noted for each program. For the online version of Memento, the processing time does not give a proper estimate of the working time. It is given just for a more full presentation of the data. This data is given in Table 2. A course visual inspection is done on the created model, focusing on severe problems with the objects.

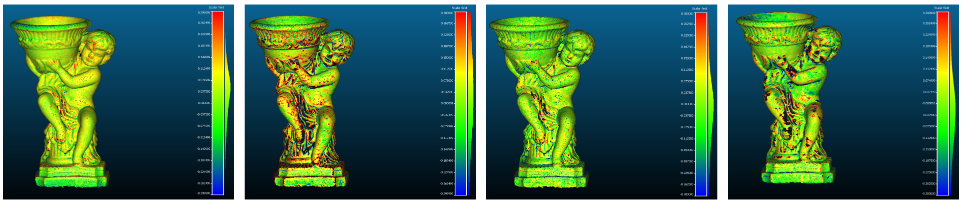
Table 2: Processing time in seconds for each of the six objects by the tested software solutions. Models which contain problems like missing sides, broken parts, floating noise, etc. are marked with red. Models which could not be reconstructed are given an N/A notation.

Program	**Angel**	**Bird Bath**	**Owl**	**Sea Vase**	**Plastic Vase**	**Black Vase**
ContextCapture	2820 sec	3600 sec	N/A	3780 sec	3060 sec	N/A
Memento Online	4860 sec	4920 sec	5160 sec	4440 sec	4260 sec	5340 sec
PhotoScan	4020 sec	4500 sec	3780 sec	4560 sec	4740 sec	3480 sec
RealityCapture	5220 sec	6480 sec	N/A	6720 sec	2820 sec	N/A
3DF Zephyr	3720 sec	4440 sec	4140 sec	4860 sec	3060 sec	4680 sec
Pix4D	4140 sec	3240 sec	N/A	4860 sec	3960 sec	3720 sec
Memento Offline	11520 sec	9360 sec	7140 sec	10320 sec	7980 sec	N/A

All packages, except Memento offline have comparable processing times, which depend on the complexity of the reconstructed object. Memento online, PhotoScan and 3DF Zephyr could reconstruct all objects, while ContextCapture, Reality Capture and Pix4D experienced the most problems. The coarse visual inspection is followed by a more qualitative inspection, using the ground truth scanner data for comparison. The idea suggested by Schning and Heidemann [17] is used for this part of the test scenario. In their paper they conclude that each tested program produces 3D models and point clouds of different density, which also may contain parts of the background or noise particles. Therefore, it is better to use the reconstructed models as reference and compare the ground truth data to each, noting the difference. In addition their idea of using the



(a) ContextCapture (b) Memento Online (c) PhotoScan



(d) Reality Capture (e) 3DF Zephyr (f) Pix4D (g) Memento Offline

Fig. 3: Pseudo color distance maps between the ground truth and the reconstructed objects. Red colors indicate distances above the ground truth, blue colors indicate distances below the ground truth and green colors indicate where the surfaces coincide.

meshes for comparison is used, as opposed to using the point cloud. This gives the possibility to test signed distances using the model's pre-calculated normals.

The comparison between the reconstruction and the scanned data is done using the free open source software *CloudCompare* [7]. The reconstructed models are scaled to the absolute scale of the ground truth and registered to it using an iterative closest point algorithm (ICP) by Besl and McKay [18]. Once the models are registered the distances between the triangles of the reconstructions and the ground truth is calculated. Using the normals of the meshes the distance is calculated as signed. These distances are visualized as pseudo color heat map. The pseudo color maps for the angel statue can be seen in Figure 3. The maps are filtered removing distances outside the interval of $[-0.3mm; 0.3mm]$, for easier visualization. From the distances, the mean and standard deviation of the distance distribution for the whole object are calculated. A Gaussian normal distribution is assumed for the modelling of the distance distribution between the ground truth and the reconstruction. The mean and standard deviation are given in Table 3 for the easy to reconstruct objects - angel statue, bird bath and sea vase, together with the Gaussian distributions for them in Figure 4. For the hard to reconstruct objects - the plastic vase, owl and black vase the data is given in Table 4 and Figure 5, respectively.

The initial speculation dividing the objects into easy and hard ones is proven by the amount of reconstruction failures. Both the black vase and the owl statue, experience much higher number of failures, compared to the other objects. The plastic vase fairs better, but because of its symmetrical featureless and dark surface, the reconstruction suffers from improperly placed geometry. This can

Table 3: Mean value (μ) in mm and standard deviation (σ) in mm^2 of the distance metric for each software solution for the three objects selected as easy to reconstruct

	Angel	**Bird Bath**	**Sea Vase**
	Mean/Variance	Mean/Variance	Mean/Variance
ContextCapture	-0.024/0.703	-0.030/0.588	-0.245/2.016
Memento Online	-0.089/0.438	-0.039/0.382	-0.408/2.277
PhotoScan	-0.109/0.805	0.034/0.175	-0.463/2.321
RealityCapture	-0.038/0.486	-0.006/0.143	-0.481/2.421
3DF Zephyr	-0.040/1.020	-0.045/1.537	-0.911/3.514
Pix4D	-0.194/1.124	-0.060/0.668	-0.425/2.419
Memento Offline	-0.080/0.569	-0.046/0.40	-0.255/2.983

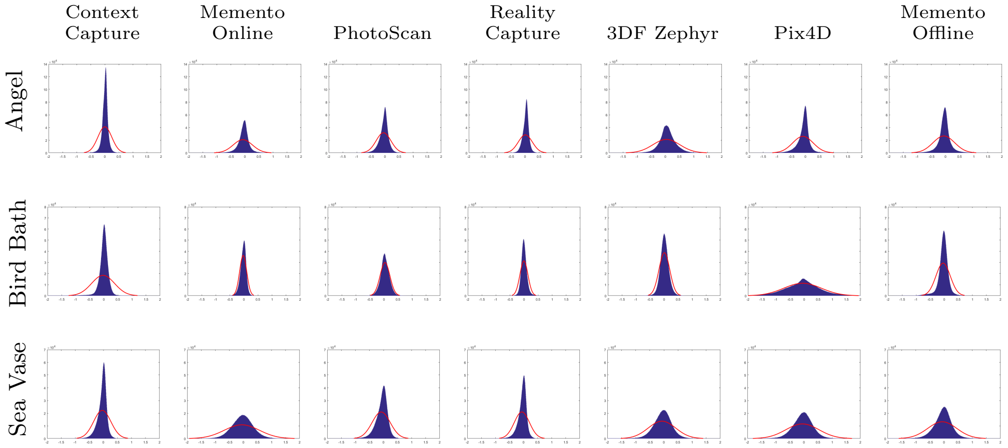


Fig. 4: Histograms of the Gaussian distribution characterizing the distances between the ground truths and the three easy objects. All the histograms are scaled the same.

Table 4: Mean value (μ) in mm and standard deviation (σ) in mm^2 of the distance metric for each software solution for the three objects selected as hard to reconstruct

	Plastic Vase	**Owl**	**Black Vase**
	Mean/Variance	Mean/Variance	Mean/Variance
ContextCapture	-2.512/10.601	N/A	N/A
Memento Online	-3.450/6.697	-0.937/3.318	-4.549/5.886
PhotoScan	-3.791/7.027	0.371/6.806	-4.331/5.758
RealityCapture	-4.395/7.222	N/A	N/A
3DF Zephyr	-4.814/7.471	0.169/3.191	-4.035/5.933
Pix4D	-3.782/7.187	N/A	-4.794/6.027
Memento Offline	-5.074/7.429	-0.929/0.977	N/A

also be seen from the Gaussian histogram distributions in Figure 5, where the distributions for both the black vase and the plastic vase are much wider, showing larger divination distances from the ground truth. The owl statue has less noisy

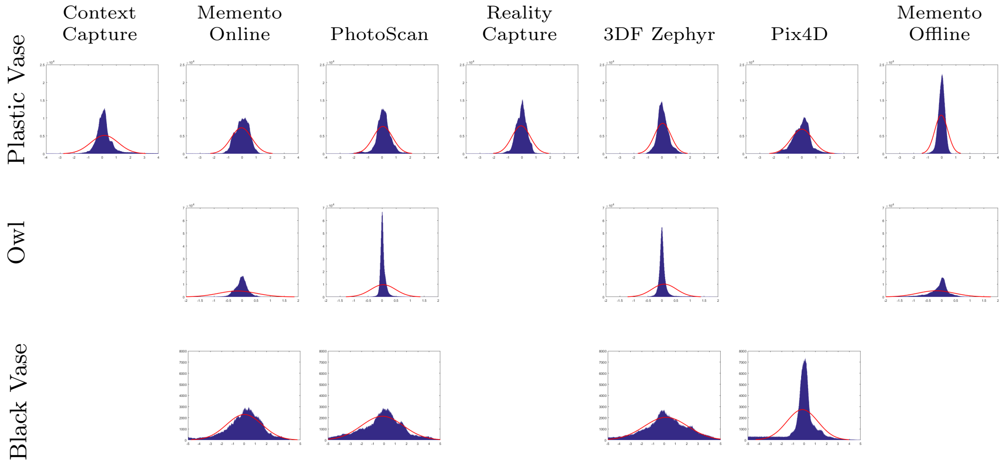
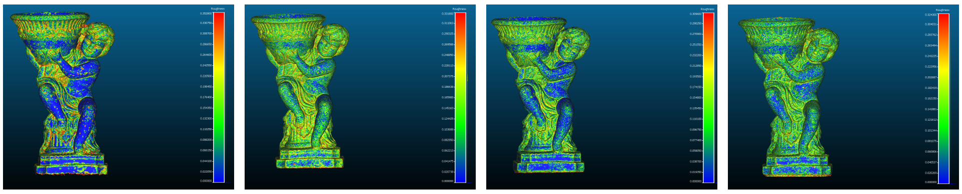


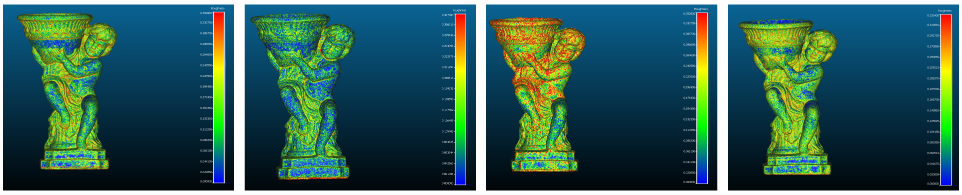
Fig. 5: Histograms of the Gaussian distribution characterizing the distances between the ground truths and the three hard objects. The missing histograms are programs which failed to reconstruct the object. All the histograms are scaled the same.

histogram, but it suffers from holes in the reconstruction. ContextCapture and Reality Capture demonstrate the overall smallest mean and variance deviations from the ground truth for the easy objects, but both programs completely or partially fail when the surfaces are not optimal. 3DF Zephyr, Memento Online and PhotoScan on the other hand are much more consistent and have a more graceful degradation of performance, but tend to miss smaller details and have an overall high variance in the distance distribution. From here another observation can be made - the programs can be roughly divided into ones that capture a lot of small detail at the price of noise and easier failures - Context Capture, Reality Capture, Memento Offline and the ones that are more consistent and robust, but fail to capture details - Memento Online, 3DF Zephyr, PhotoScan. Pix4D is mainly aimed at aerial photos and this clearly shows, as the program is much noisier in all instances.

To determine the amount of noise and over-smoothing of features in the reconstructions compared to the ground truth, a second metric is introduced. The local roughness of both the reconstructions and the ground truth is calculated using the Gaussian curvature of the models, which is normalized to give proper weights to rough patches and smooth patches near edges. The method is introduced by Wang et al. [19] for assessment of mesh visual quality. The method is useful in the case of our paper as it generates an accurate roughness map, which can give both visual and more quantitative information for the success of the reconstruction. The roughness map is also visualized as a pseudo color map, which is given in Figure 6.



(a) Ground Truth (b) ContextCapture (c) Memento Online (d) PhotoScan



(e) Reality Capture (f) 3DF Zephyr (g) Pix4D (h) Memento Offline

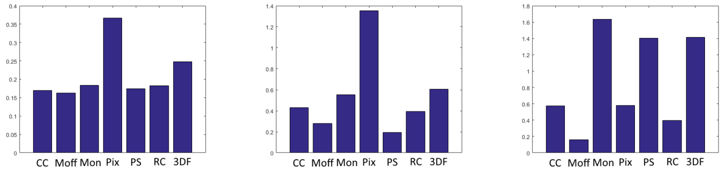
Fig. 6: Pseudo color roughness maps of the ground truth and reconstructed meshes. The colors go from red to blue through green, depending on how rough the surface is.

From the local roughness map, the histograms of both the ground truth and the reconstructions is calculated. Using these histograms the Kullback-Leibler distances [22] between the ground truth and reconstructions are calculated. This gives a measurement of the similarity between the two, which penalizes deviations from the roughness of the ground truth both caused by introduction of noise in the reconstructed mesh and in over-smoothing details in it. Figure 7 has the results from the roughness histogram distances, where smaller values give more faithful reconstructions, roughness-wise.

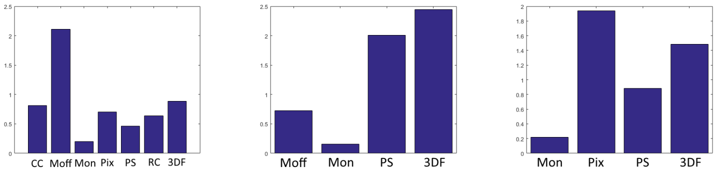
The results from the roughness metric support the division of the programs. Pix4D introduces a lot of noise and smooths details. This can be seen in both Figure 6 and Figure 7, where it has clear disadvantage in many of the cases. Figure 6 also shows that Pix4D, Memento Offline and Reality Capture have introduced a lot of noise on the smoother parts of the angel, compared to the ground truth, like the stomach and legs, while Memento Online, 3DF Zephyr and PhotoScan have smoothed out small features in the face and hair of the angel. Memento Offline, Reality Capture and PhotoScan manage to capture most of the detail on the easier to reconstruct objects like the angel and the bird bath, without introducing too much noise as evidenced by the smaller histogram distances. However they fail on the smoother objects like the plastic vase and the owl, where they introduce uncertainty noise. Memento Online and 3DF Zephyr tend to over-smooth the surfaces as evidenced by the bar chart of the sea vase.

5.2 Follow Up Test Scenarios

One of the best performing objects - the bird bath is tested in a number of follow up scenarios under different capturing conditions. This is done to deter-



Angel Bird Bath Sea Vase



Plastic Vase Owl Black Vase

Fig. 7: Bar chart visualizing the calculated Kullback-Leibler distances between the roughness histogram of the ground truth and the reconstructed objects. The tested software is denoted with short names - *Context Capture (CC)*, *Memento Online (Mon)*, *PhotoScan(PS)*, *Reality Capture (RC)*, *3DF Zephyr (3df)*, *Pix4d (Pix)* and *Memento Offline (Moff)*.

mine the effect of capturing conditions on the reconstruction results. Five follow up experiments are carried out focusing on different combinations of conditions. First tested condition is the effect of rotating the camera to capture images from different views, as opposed to using a turntable to rotate the object and keep the camera stationary. This test aims to assess if a moving background and completely static lighting will help with reconstruction process, as opposed to the lighting which ”moved” with the object in the case of using a turntable. The second tested condition is using multiple light sources for a more even lighting, as opposed to one directional light. The third condition is using different number of photo positions, combined into bands of photos, with varying height. Five and three bands of photos are created. The first two contain 18 photos each taken in 20^o intervals, the next two contain 9 photos in 40^o and the final one contain 4 images. The setup also aims to test if introducing information from more angles can help the feature point matching algorithm of the tested software solutions. The same analysis pipeline is used as with the main experiment, using the ground truth scans to compare with. The results from the different combination of conditions are given in Table 5.

The tests show that using static lighting and moving background without a turntable yields a higher accuracy, with lower mean and standard deviation values, compared to the turntable results. There is also a difference between using multiple light sources and just one directional one, with the latter introducing more noise, which can be seen by the higher standard deviation in the table above. This shows that if higher accuracy is necessary, a capturing process with-

Table 5: Mean value (μ) in mm and standard deviation (σ) in mm^2 of the distance metric for the bird bath object for each of the tested software solution from the five tested shooting scenarios.

	No Turntable		Turntable		
	Multiple Lights		One Light	Multiple Lights	
	Five Bands	Three Bands	Five Bands	Five Bands	Three Bands
	$(\mu)/(\sigma)$	$(\mu)/(\sigma)$	$(\mu)/(\sigma)$	$(\mu)/(\sigma)$	$(\mu)/(\sigma)$
ContextCapture	-7.167/13.289	-4.147/8.052	N/A	N/A	N/A
Memento	-0.209/2.028	-0.094/1.306	-0.366/2.148	-0.947/3.826	-0.309/2.305
PhotoScan	-0.283/2.312	-0.240/2.685	0.206/1.982	-0.212/2.410	-0.167/1.159
RealityCapture	-0.031/0.284	-0.014/0.689	N/A	0.108/1.710	N/A
3DF Zephyr	-0.039/0.584	0.011/0.411	-0.308/2.035	-0.372/2.712	-0.165/0.922
Pix4D	-0.169/0.407	-0.166/1.911	-5.023/12.401	-0.204/1.520	0.061/1.674
Memento Offline	-0.105/1.355	-0.071/1.118	-1.135/4.253	-0.389/2.262	-0.114/1.552

out a turntable and with uniform lighting and more diverce camera positions need to be used, even if this will cost more time and resources.

6 Conclusion and Future Work

Our paper presents a head to head comparison of the state of the art SfM 3D reconstruction software solutions. As part of the research we tested six programs - ContextCapture, PhotoScan, Memento, Reality Capture, Pix4D and 3DF Zephyr. We tests the programs on both a variety of challenging objects and on images taken from different capturing conditions. Reconstruction results were evaluated against ground truth objects on the basis of distance measurement and roughness comparison.

We demonstrated that programs can be roughly divided in two groups - ones that are more robust to sub-optimal objects and capturing conditions, but do not manage to capture smaller details and ones that can capture high amount of details, but degrade in performace and introduce a lot of noise, once the optimal conditions are not met. Additionally we show that using a turntable can have a negative effect on the accuracy of the reconstructed objects, as well as using a single light source. For optimal capture conditions a moving camera, multiple lights and images taken from multiple locations and angles are recommended.

As an extension to this paper we propose introducing prior information to the programs like - camera positions, feature points, markers, etc., as well as combining multiple software solutions in a pipeline for achieving better results and helping failed reconstruction attempts on hard to reconstruct objects. Testing different cameras is also proposed as an extension to the different environment conditions.

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