Accuracy of 3D Scanning Technologies in a Face Scanning Scenario

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Abstract

In this paper, we will review several different 3D scanning devices. We will present a method for empirical accuracy analysis, and apply it to several scanners providing an overview of their technologies. The scanners include both general purpose and face specific scanning devices. We will focus on face scanning technique, although the technique should be applicable to other domains as well. The proposed method involves several different calibration faces of known shape and comparisons of their scans to investigate both absolute accuracy and repeatability.

1. Introduction

3D scanning devices are now available from a number of commercial sources, and address a variety of target applications. Knowing the accuracy and limitations of these devices is imperative to picking the best device for a given application. This choice is not simple, as many factors are involved. We focus our efforts on biometrics as a target application and 3D face scanning as a particular problem of interest. However, our methodology should prove applicable to hand and ear shape biometrics as well as other applications of 3D scanning, since several of the scanners reviewed are general purpose scanners not designed specifically for faces. Other scanners could use the methods discussed here.

The environment, and the object to be scanned, affect scanner accuracy and impose limitations on scanning. The material, geometry, or many other factors in the scanned object can cause decreases in accuracy or prevent successful scanning completely. For example, specular materials are difficult to scan with lasers and discontinuous surfaces can yield scanning errors around edges. For this reason, it is difficult to define a single measurement to characterize accuracy. By focusing on a specific type of object (in our case, faces), we can provide a more detailed analysis for that specific type of object. The limitation of this approach is that for the reasons discussed previously, different objects may exhibit different image artifacts and errors. Further, faces themselves are rather complex with nontrivial geometry. As a result, they are a good test object to consider for different applications.

When attempting to determine the best scanner to use in a face recognition application, there are several factors to consider. There are accuracy levels in a scanner (one micron for example) that are not necessary because faces can change several millimeters or more over time. However, we will not explore that limit here since the majority of the scanners have accuracies in approximately tenths of a millimeter.

There are two different, but equally important notions of accuracy that are of interest in our application. *Absolute accuracy* (the accuracy of the scanner with respect to a physical reference object) is most important if one is implementing a large system with numerous different types of scanners. *Repeatability accuracy* (the degree of consistency between scans) is more important if one plans on a smaller scale system using a single type of scanner. In this case, the relative accuracy of the scans with respect to one another is the most important factor.

In this paper, we give an overview of the operation and limitations of several scanners and present an empirical analysis of the accuracy of these scanners using custom produced synthetic 3D face masks with known ground truth.

2. Previous Work

There is little previous work on this topic. Some groups have proposed metrics for measuring accuracy but usually they measure only one aspect of accuracy and have a rather small scanner test data set. Further, (as pointed out in [1]) no method for accuracy analysis has yet emerged that is generally accepted.

Goesele *et al.* [2] compared the accuracy of two laser scanners using a slanted edge modulation transfer function. They scanned a cubical object and assessed the scanners performance on the edges and planar

faces. While this is an interesting test, the need for more complex shapes and materials is apparent in order to determine the accuracy of general-purpose scanners.

Workshops examining the accuracy of environmental scanners (such as those made by Cyrax [14]) are not uncommon [3] [4] [5] [6] [7]. These scanners have measurement errors orders of magnitude larger than we are dealing with in biometrics, and are therefore not applicable.

Others have examined different versions of customized VLSI opto-sensors for 3D vision to demonstrate how different VLSI methods can enhance 3D vision, but did not compare different technologies [8].

Genex manufactures a scanner for faces and have published an accuracy analysis for their system [1]. They did not do perform any comparisons with other systems, and employed planar surfaces for accuracy assessment. They state an accuracy of 500 microns for their scanner while scanning planar objects.

We were unable to locate any previous independent work that analyzed and compared different scanners in the accuracy range appropriate for face scanning.

3. Scanner Overview

We will examine five different scanners from different companies utilizing different technologies. We explore scanners from 3DMD, Konica Minolta, Polhemus, and two companies from the face recognition market (names are left anonymous and referred to here as FR1 and FR2). We leave these vendors anonymous because the sensor models tested are no longer available and hence do not represent the companies' current technology. We will briefly discuss the technologies used but do not intend for this to be a comprehensive overview.

3.1 3DMD

3DMD [15] sells several different types of scanners. We chose to use the Qlonerator, a stereo scanner designed specifically for scanning faces. The current market emphasis for 3DMD is in medical imaging, especially facial surgery planning and assessment. Other models using similar technologies exist for other types of biometrics. It uses four cameras along with a protected texture pattern in order to acquire the data in two milliseconds once the flash is fully charged (a process that takes about 10 seconds). It also uses the data acquired to produce a high quality color texture map that is registered with the 3D data. The captured shape and texture data typically extends from ear to ear, providing a texture-mapped mesh with greater coverage than a raster-structured scanner. The subject is not required to hold still but does need to position the head within the volume of overlap the cameras require, as the scanner has a focal range of approximately one foot. To the subject the scanning process is comfortable, and passive other than a camera flash, which is approximately the same brightness as a standard camera flash.

3.2 FR1

The scanner from our first anonymous vendor, FR1, uses a projected infrared pattern and a single camera in order to capture 3D data in real time and does not provide color optical images associated with the 3D data. The design of the scanner is for face scanning and from a subject standpoint is very comfortable. The projected pattern is not visible to the human eye. Their scanner has a limited fixed focal range, but is the least sensitive to ambient light variations of all of the sensors examined.

3.3 FR2

The second anonymous vendor, FR2, uses three cameras and an LCD stripe pattern from a projector to capture the 3D image. The scanner is designed for face scanning and because of the three cameras, it can capture a color image texture map as well. It is the least comfortable scanner from a subject standpoint because it flashes a series of bright patterns at the subject over the course of approximately 20 seconds during scanning and requires the subject to sit still during that time. It also requires very specific lighting conditions in order to capture a scan, and has a small focal range.

3.4 Konica Minolta 910

The Vivid 910 scanner from Konica Minolta [16] uses a single camera and laser stripe, and acquires 3D data using triangulation. This scanner is not designed specifically for faces. The scanning process is comfortable, although subjects can see a quick flash of red when the laser stripe crosses the pupil. The laser is eye safe so the subject's eyes can remain open during scanning. The scan takes approximately 2.5 seconds and the subject must remain motionless during that time or a poor scan will result. There are three different zoom lenses available and an automatic focus system that allows scanning at a wide variety of distances from the camera (there is a tradeoff between image resolution and standoff). It is somewhat sensitive to lighting conditions, but generally operates well indoors away from sunlight.

3.5 Polhemus

The Polhemus FastTrack scanner[17] includes attachments specifically for faces, but the scanner is a general-purpose device. It uses a handheld wand that has a fixed camera and laser to triangulate a 3D stripe.

The system uses a magnetic tracking system to track the wand location in 3D as the operator moves the wand over the subject/object. It is possible to attach an additional tracker to assist in scanning the head of the subject. However, the expression must stay the same throughout scanning. The sensing range is 3-6 feet depending upon the power of the magnetic field generator used by the tracker. The wand must be 2-4 inches away from the object during scanning.

The scanning time for a particular face varies by operator since using this scanner is an acquired skill. In general scanning should take 30 seconds or less depending on the desired quality of the resulting scan. Subject comfort is comparable to the other scanners reviewed. The laser used is also eye safe.

A summary of the scanners assessed in this paper appears in Table 1.

Scanner	Scan Time	Color Image	Focal Range	User Comfort	Desgined for Faces
3DMD	<1s	Yes	Low	Medium	Yes
FR1	<1s	No	High	High	Yes
FR2	20s	Yes	Medium	Low	Yes
Minolta	2.5s	Yes	High	Medium	No
Polhemus	~30s	No	Low	Medium	No

Table 1: Scanner Overview

4. Assessment Method

In order to be able to analyze the scanners, we need to know the shape of the object we are scanning. Since scanner accuracy is object dependant and we are interested in the accuracy of the scanners for face recognition, we chose to use human faces as our test objects. However, using human faces is problematic because the human face is deformable. No matter how much a person may try to keep the same face from one minute to the next, it can change significantly. Therefore, we constructed 3D face masks from real subjects in order to test the scanners. Since we were manufacturing the synthetic faces, we knew the ground truth values for them. In order to get the most realistic accuracy values possible, we produced ten faces consisting of five male and five female subjects. We varied the races to include four Caucasians, two Asians, two Asian Indians, and two African-Americans.

We produced the synthetic faces from range images of subjects scanned by the Minolta Vivid 910. While the resulting faces, once processed, may not be 100% accurate to the actual subject, the resulting scans remain within the range of a possible human face. We ran the initial scans through the cleaning function and applied a low level of additional smoothing in Raindrop Geomagic [9]. The cleaning function description, provided by the vendor, follows: "The Smooth Clean function strives to improve the mesh quality by optimizing the shape of triangles. This means that each triangle should be roughly equilateral (60 degrees at each vertex), and the number of triangles around a vertex should be roughly 6. To achieve this, an iterative algorithm is applied that prioritizes triangles in terms of poor shape, and attempts to iteratively improve their shape by applying one of three techniques: locally repositioning (relaxing) a vertex, contracting an edge, or flipping an edge. The best technique is chosen for each poor triangle depending on the local geometry." It appears to improve the mesh for small triangles and apply a very low level of smoothing. After this step, the scans were processed to fill holes and suppress large spikes near the eyes, using Geomagic's [9] sandpaper function (the translucency of the eyes can cause spikes when using a laser scanner).

We created molds from the surfaces employing .STL files we generated through the process described previously. We manufactured the molds on a 3D Systems Thermojet rapid prototyping machine [10]. The Thermojet has a 300 X 400 X 600 DPI resolution with a maximum build size of 254 X 190.5 X 203.2 mm. It uses "inkjet-like" technology to build the 3D object from layers of polymer dots. Because the resulting part from this machine is rather fragile, we made masks from the molds produced on the ThermoJet using a two part plastic polymer. The polymer is durable and does not deform over time or from contact.

Inaccuracies in the masks could exist due to the manufacturing and molding processes. Therefore, we felt it necessary to attempt to verify the accuracy of our physical models. First, we wanted to consider the claimed accuracy of the prototyping machine. Assuming the polymer voxels laid out by the Thermojet are perfectly accurate, the longest diagonal of a voxel is approximately 0.11mm. That means that we should be able to be confident of each point to be within half of that, or approximately 0.057mm. However, that is the extreme case. Most of the object will be more accurate than this. We estimate that the model is most likely accurate to around 0.03mm, half of that value.

To confirm this accuracy claim independently, we used a Roland PIX-30 tactile scanner [11] to scan the masks. Tactile scanners are an established scanning method with more known limitations due to the physical process involved. The Roland scanner uses a ball needle with a tip diameter of 0.08mm to scan the object. This means that it can only produce a scan accurate to within 0.04mm of the original. The error is

only this large when comparing two points taken on exact opposite sides of the needle. Since most of the points are not on opposite sides of the needle, the average error is probably substantially less than the maximum 0.04 mm discussed above. However, that error does not take into account mechanical errors in the motor/sensing systems. Even with the mechanical errors in mind, the average error of the resulting models is most likely less than 0.04 mm.

We scanned all 10 synthetic faces on the tactile scanner. Each face took an average of 3 weeks to scan because we scanned at a high resolution. The resulting scans had an average of 1.5 million points each in a grid pattern with 100 microns posting in x and y. On

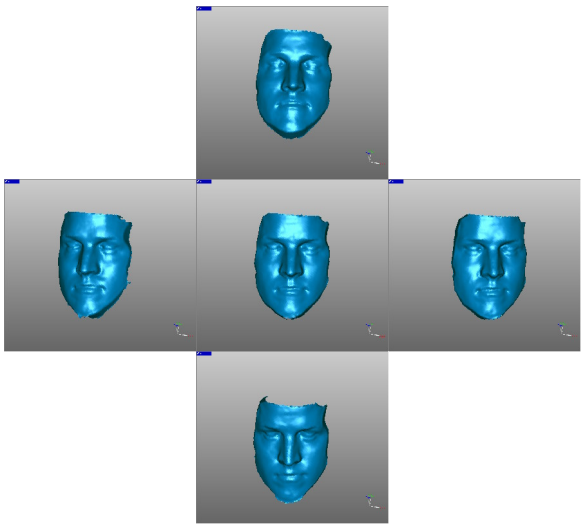

Figure 1: Sample Pose Variations

average, the scans from the tactile scanner were accurate to 0.058 mm of the ground truth. If we assume that the tactile scanner is only accurate to within 0.04mm as discussed above, then the actual models are accurate to within 0.018 mm. This is very close to our believed accuracy of the prototyping machine (0.028mm). The actual accuracy of the models is probably somewhere between these two numbers.

Since we have managed to crosscheck the accuracy of the prototyping machine with a highly accurate tactile scanner, we have evidence that the error of our models is less than 0.028mm (believed accuracy of the prototyping machine) with respect to the ground truth. For the rest of this paper we will assume that the models are within 0.023 mm of the shape, which is half-way in between the accuracy measured by the tactile scanner and the accuracy of the prototyping machine.

After having our test faces manufactured and confirming their ground truth, we performed six scans of each face on each scanner with the exception of the Polhemus, where only one scan per face was obtained. We adjusted the conditions to allow for each scanner's ideal lighting or distance. We took the first two scans with the face looking directly at the scanner without any changes made between scan 1 and 2. There were no changes in the environment or the object between scans 1 and 2. These two scans should produce an identical shape. For scans 3, 4, 5 and 6 we varied the pose by approximately 10 degrees of yaw and pitch in order to asses scanner accuracy for a nonfrontal face presentation. Thus, we took a total of 60 scans for each scanner, 6 for each face. Examples of these scans appear in Figure 1.

After taking the scans, we coarsely aligned them manually to one another and to the ground truth. We treated each scanner the same way in the data processing and performed some manual editing of the data in order to retain just the face from each scan. The 3DMD, FR1, Polhemus, and Minolta scanner required little manual post-processing but the FR2 required more manual post-processing in order to remove outlier data from around the faces.

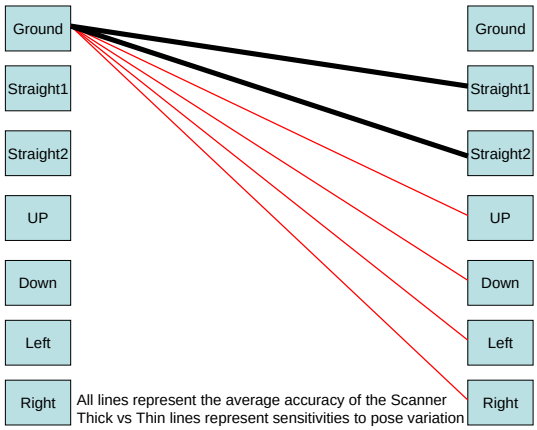

Figure 2: Absolute Accuracy Comparisons

Then we applied Geomagic's [9] cleaning function to the scans, as discussed in the previous section. We applied this processing because different scanners internally already apply some 'cleaning' to their data. Since the internals of the scanners assessed here are proprietary, there is no way to determine what processing is done between the capture and reporting of the data. By allowing them all to have some of the same processing applied, we hope to ensure a fair comparison by not penalizing the scanners that do little or no pre-processing to the data. Also, for the companies that have already done some processing this function has a very small effect. While ideally we would like to be able to get the 'raw data' from the

scanners without processing, since this is not possible we feel this is the next fairest way to perform the comparison. We repeated this process for each scan, and saved the resulting six scans and ground truth to a file for analysis.

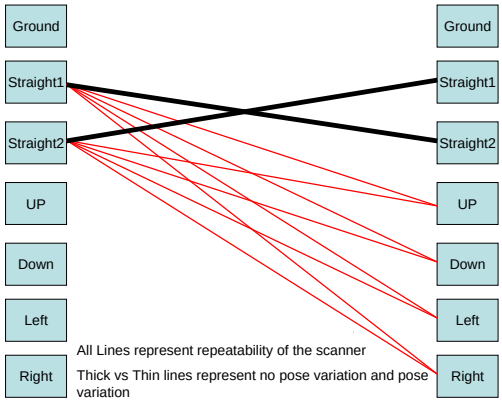

Figure 3: Repeatability

Prior to analysis, we ran the VTK [12] implementation of Besl and Mckay's ICP algorithm on the scans to align them [13]. Then the distance from every point of one surface to the other surface was calculated and averaged over all points. We recorded outlier points, defined as any point with a distance over 20mm, separately along with their quantity. This allowed us to have a primary accuracy, and in addition show the percentage of and average distance of the outliers. In this way, problems such as spikes around the eyes due to translucency in laser scanners are represented in the results. This gives us the result for an individual comparison. We made several such comparisons for each face. The following figures show the comparisons made.

Figure 2 depicts the comparisons used to calculate the absolute accuracy, while Figure 3 represents the comparisons used to compute the repeatability accuracy. We characterize two different classes of accuracy. The first is accuracy under ideal conditions (subject looks directly at the scanner, scan 1 and 2) and with pose variations (subject looks slightly off from the scanner as in scans 3, 4, 5, and 6). The difference between those two averages should tell us the effect of pose variation on the scan accuracy. Looking directly at the scanner should result in better accuracy but different scanner setups such as the three cameras in the FR2 scanner may allow some of those problems to be overcome. This makes both performance measures significant.

Repeatability accuracy is the measurement of similarity between the scans of individual synthetic faces. Those scans should be more accurate in a relative sense than they are to the ground truth, since systematic errors could potentially cancel each other out. We examined the effect of pose variation by comparing the accuracy of the frontal shots to those of the non-frontal shots.

We used these six scans to make 16 individual comparisons. Examining the results should allow us to determine absolute and repeatability accuracy as well as assess the effect of pose variation.

Scanner	Mean Global Accuracy	Mean Repeat Accuracy	Number of Points	Number of Polygons
3DMD	0.106504	0.067726	11000	22000
FR1	0.35859	0.243976	3000	5500
FR2	0.924995	0.606283	50000	100000
Minolta	0.07977	0.014917	92000	185000
Polhemus	0.152945		46000	90000
Ground Truth			70000	140000

Scanner	RMS Global Accuracy	RMS Repeat Accuracy	Number of Points	Number of Polygons
3DMD	0.242287	0.515699	11000	22000
FR1	1.783649	1.564316	3000	5500
FR2	1.21512	1.14467	50000	100000
Minolta	0.181542	0.20415	92000	185000
Polhemus	0.281818		46000	90000
Ground Truth			70000	140000

Accuracy numbers shown are in millimeters

Table 2: Accuracy Summary

5. Results

The accuracy results shown here represent the accuracy of the distance from the points given by the scanner to the ground truth surface. If the scanner provided a small number of points but they were all highly accurate, then the scanner would appear to have a high accuracy rating. It is not possible to represent the detail level of the surface in such a measurement. As a result, it is important to look at the average number of points provided by the scanners as well. Table 2 gives a summary of the results. Also, the RMS (Root Mean Square) accuracy is reported as well as the mean accuracy. The RMS error should cause more inconsistent error distances to become less attractive. However, all of the RMS error reported here seems consistent with the mean, but in some scanners cases this may not be true and is worth mentioning. The Polhemus scanner does not have a repeatability accuracy value because only one scan of each face was acquired (repeatability would also vary by operator for this scanner).

Scanner	Mean Global Accuracy No Pose Change	RMS Global Accuracy No Pose Change	Mean Global Accuracy Pose Change	RMS Global Accuracy Pose Change
3DMD	0.104471	0.242287	0.107521	0.241387
FR1	1.380893	1.783649	0.697045	1.477436
FR2	0.348302	1.21512	0.363734	1.222324
Minolta	0.080002	0.181542	0.079654	0.183537
Polhemus	0.152945	0.281818		

Scanner	Mean Repeat Accuracy No Pose Change	RMS Repeat Accuracy No Pose Change	Mean Repeat Accuracy Pose Change	RMS Repeat Accuracy Pose Change
3DMD	0.016676	0.235932	0.080488	0.58564
FR1	0.231733	0.908968	0.699921	1.728153
FR2	0.060536	0.556052	0.289836	1.291823
Minolta	0.003185	0.051925	0.017851	0.242207

Accuracy numbers shown are in millimeters

Table 3: Repeatability Accuracy with and without Pose change

5.1 Absolute Accuracy

The most accurate scanner here in an absolute sense was the Minolta, followed by the 3DMD and Polhemus as shown in Table 2. The two anonymous scanners were less accurate. The Minolta had the highest accuracy as well as providing a sufficiently large amount of points so that fine detail is easily visible. The 3DMD scanner generated very accurate points as well, but the level of detail is lower and some fine features are not visible in the 3D data. The Polhemus provides a large number of points with good accuracy. The handheld scanner does require some skill to use or else noticeable 'rough' patches of the surface can result.

Finally, our two anonymous vendors came in last. FR1 managed an adequate accuracy level but the number of points provided is low. FR2 returned a large number of points, but with a very low accuracy for those points.

5.2 Repeatability

As would be expected, all of the scanners performed well at repeatability. These improvements are due to two main factors. First, any errors that could have resulted from the production of the mask that would cause its actual dimensions to differ from the ground truth do not affect this portion of the test. In addition, any systematic errors in the scanning process would tend to cancel each other out. The Minolta showed considerable improvement in repeatability over absolute accuracy. As the Minolta is the most accurate scanner in all of our tests, we suspect that the higher absolute error is due to errors produced in the mask production process, but some repeatability errors probably played a role as well.

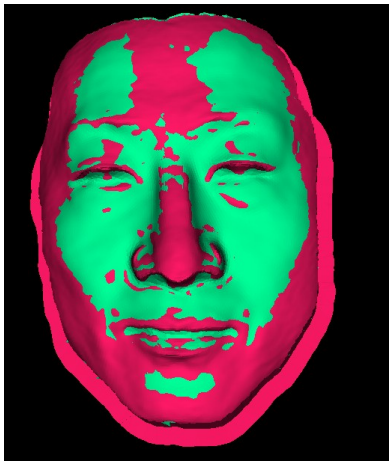

Figure 4: Range Depth Map Comparing Ground Truth Surface to Scanned Surface

Another interesting test in examining the accuracy of these scanners is the results in the "Repeat Accuracy No Pose Change" column of Table 3. We also examined scan consistency with two scans taken in identical conditions and no pose change. These two scans should be identical to each other, regardless of the shape and material used. Higher accuracy in this test identifies scanners with good repeatability and is a good indication of an accurate scanner. In this category, the Minolta managed to be the most accurate with a repeatability of 0.003 mm. The accuracy trends found here is consistent with our other results. This helps to confirm our accuracy hypothesis as the reliability accuracy is not dependent on processing, the object geometry, or method since nothing changes between the two scans.

5.3 Pose Variation

Examining the differences in pose variation data in Table 3 shows us that accuracy is affected by pose. While some change is to be expected, the change in accuracy is relatively small. 3D data has an inherent resilience to pose changes that gives it a significant advantage over 2D biometric sensors. This shows that the advantage can be utilized since the data does not change drastically from pose variation.

5.4 Graphical Depiction of Accuracy

Attempting to determine whether the errors in the scans are systematic (and could be improved) or random is valuable. One way to do this is to examine a graphical depiction of the accuracy of the scans as in Figure 4 and attempt to determine if there are any

patterns. Figure 4 is a sample of the 3DMD scan with the lighter colored surface representing the ground truth and the darker surface representing the scan. All of the 3DMD scans show a similar pattern of error to the one seen here. The error pattern is suggestive of a systematic error due to a slight miscalibration of the stereo rig. The 3DMD obtains the 3D shape of the left and right side of the faces separately (using two stereo rigs) as in Figure 5 and then merges them. If the cameras were slightly mis-calibrated from each other then the two scans would not align correctly and it could cause this systematic error. The error is not large, but if corrected would most likely further improve the accuracy of the system. Analysis of error distribution in the form of error histograms were examined, but these graphs showed that the error percentage quickly dropped to close to zero and stayed there. As such, they were not very interesting and are left absent here.

Scanner	% Removed	Mean Outlier Removed	RMS Outlier Removed
3DMD	0	0	0
FR1	1.848196	38.06656	47.96688
FR2	0.794525	77.87227	138.4826
Minolta	0	0	0
Polhemus	0	0	0

Accuracy numbers shown are in millimeters

Table 3: Pose Summary

5.5 Outlier Results

As has been discussed previously, any error distance over 20 mm has been considered an outlier and removed from the results discussed previously. However, these outliers are another important factor to consider in accuracy and so we discuss them here in Table 3. While our 3 best scanners have no outliers, our two anonymous scanners have a small percentage of outliers. Also, here we can see the benefit of RMS versus mean. While there is a small difference between the mean and RMS values for FR1 there is a large difference for FR2. This shows that FR1's outliers were all closer on average to the mean and for FR2 there were some smaller and some extremely large values.

6. Conclusions

The most accurate scanner reviewed here in every category is the Minolta, followed closely by the 3DMD, Polhemus, and the two anonymous vendors. The difference in accuracy between the Minolta and 3DMD is small, and with live subjects who can move during the scanning process the 3DMD may be more accurate since it requires only milliseconds to take its scan and the Minolta requires 2.5 seconds to scan. However, the level of detail for the Minolta scanner is significantly higher which we feel to be important for biometrics. For that reason, we rank the Minolta's performance as the highest of all of the scanners reviewed here.

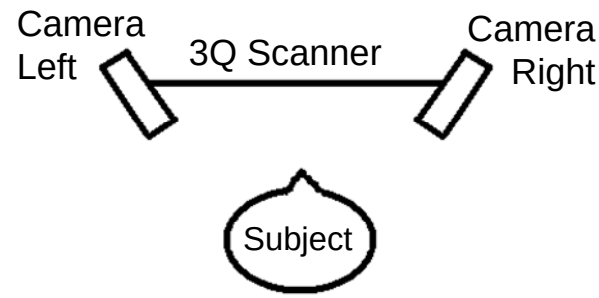

Figure 5: Overhead view of 3DMD scanner arrangement

The 3DMD captures more of the sides of the face than the Minolta because of the use of multiple cameras. Further, it is more subject friendly since it is quicker during capture and does not require the subject to hold still. The points the 3DMD provides are accurate but the sampling is coarser than that of the Minolta.

The Polhemus captures a large number of points, while retaining a good accuracy of those points. It is the smallest of the scanners reviewed here and could perform in a variety of environments the other scanners could not due to its handheld nature. While it is not as accurate as the 3DMD and Minolta scanners, its portability opens other potential uses.

The FR1 scanner managed a competitive accuracy rating, but the number of points it provided is low leaving it with a poor overall assessment. FR2 had the second most points provided here allowing for a high potential level of detail but with a very low accuracy for those points.

FR1 does have the only real-time multi-frame acquisition abilities out of all of the scanners reviewed here and is the most comfortable from a subject standpoint since no visible active elements are used. FR2 has a poor rating from a subject standpoint, and has a high level of detail but very poor accuracy for the points provided.

7. Future Work

In the future, we hope to improve the materials and coloring used in our synthetic masks to more accurately mimic human skin. The white solid material used here scans well, and does not pose the challenges to a scanner that skin does with its translucency.

Further, the faces here are one solid color that is significantly easier to scan than an actual human face. Changes in coloring definitely have the potential to cause errors, especially along color boundaries. As a result figuring out a way to mimic human skin with realistic colors would be a better test for the scanners. The addition of more scanners would also prove interesting since there is an abundance of them on the market.

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