

MicronMapper's Accuracy

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Abstract

We start by discussing how best to usefully characterize the accuracy of photogrammetry devices, and surveying published scientific papers on the accuracy of such systems. We then suggest, based on several considerations, that RMSE below 50 μ m and maximum error below 100 μ m will enable obtaining a passive fit in close to 100% of clinical cases.

We designed and performed a set of benchmarks to characterize MicronTracker's accuracy across the full range of operating conditions that may be encountered in actual usage. The results of the benchmarks were:

- Repeatability: 5 μ m, 0.05° RMSE
- Accuracy (typical): 20 μ m RMSE, 30 μ m MAX.
- The following factors do not significantly degrade accuracy:
 - a. Warmup of camera (after 1 minute since power on)
 - b. Ambient temperature up to 32°C/90°F
 - c. Ambient lighting (darkness to full sunlight)
 - d. Scan body screw tightening torque (≤ 15 Ncm)
 - e. Steam sterilization of scan bodies at 134°C
 - f. Blood staining (any staining disables detection)
 - g. Mechanical handling in regular usage (not major shocks).

We conclude that MicronMapper meets its clinical accuracy requirements with a substantial "safety margin".

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Purpose of this document

Describing and comparing accuracy characteristics of a dental photogrammetry system is a complex and often confusing subject. While prospective buyers would like the accuracy to be described as a single number, eg, “15 microns”, there is currently no standard, verifiable, process for producing such a number. The same photogrammetry system can produce a wide range of different “accuracy” values, depending on the design of the experiment being performed, the circumstances in which the experiment was conducted, the quantities being measured, and the statistical functions used to reduce the data collected to that single number. Since potential buyers rarely have the knowledge and means to perform a thorough accuracy evaluation of competing systems, vendors of metrology systems are tempted to provide numbers that grossly underestimate real-life measurement errors. Without a detailed description of how that number was measured and computed, and how well it reflects actual clinical usage, it cannot be fairly and meaningfully used to evaluate and compare accuracy.

The purpose of this document is to describe MicronMapper’s accuracy performance in a manner that will provide prospective buyers and users with the information needed to make better informed decisions. It is our hope that vendors of competing systems will provide similar documents, enabling researchers to evaluate the veracity of the results by replicating the experiments.

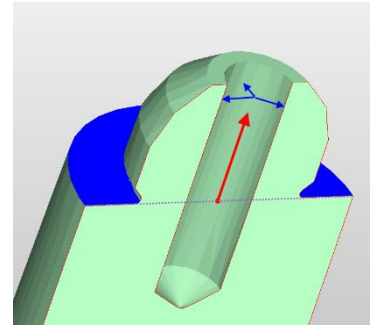
The accuracy benchmarks were all performed using MicronMapper software and hardware release 1.0, scheduled for release in March 2023. Subsequent releases may provide better results.

Characterizing accuracy

The goal: passive fit

MicronMapper’s main purpose is to measure the relative positions and orientations of multi-unit abutments (MUAs). The measurements are used to design a screw-retained dental prosthesis that will be coupled to these abutments. Ideally, the prosthesis should have a perfect (“passive”) fit with the abutments such that the screws, when fully tightened, should not result in any sustained force applied to the implants and the prosthesis. The fit can be interactively assessed by very lightly tightening all the screws, then tightening them fully while counting the number of screw tightening turns where noticeable resistance is felt prior to their final fully tightened position. However, this test is impacted by the accuracy of the prosthesis fabrication process, not only that of MicronMapper, making it unsuitable for evaluation of MicronMapper on its own.

Since the prosthesis interfaces to the MUAs, accuracy should be evaluated in relation to the MUA surfaces engaged with the prosthesis, i.e., the rim, and the screw thread (blue region/arrows in the illustration on the right). Representing the thread by its rotation axis, and the rim by the plane it lies on, the MUA's position and orientation can be concisely represented as an arrow (shown in red in the illustration) with its position at the intersection of the rim plane and the thread's axis, and its direction pointing along the thread's axis towards the prosthesis.



As the prosthesis is pressed against the abutments, the amount of force the prosthesis and the implants apply to each other is proportional to the amount of relative movement that occurs when all the retaining screws are tightened. That movement consists of local displacement and rotation at each abutment. Correspondingly, accuracy measurements should estimate the magnitude of this movement in these two aspects: distance in microns and rotation in degrees (in any direction).

Referring to the above illustration, the error magnitude is the difference between the reported and true pose (position and direction) of each MUA arrow. However, positions and directions are always specified in a reference 3D coordinates frame, and there is no natural coordinates frame for either the reported or the true poses of the MUAs. Therefore, an evaluation of pose differences between an MUA mapping output and a reference "ground truth" pose data (or between two mappings) must first bring the two coordinate frames into alignment using a mathematical process called *registration*.

Rigid registration and residuals

Approximating the physical process of fitting a prosthesis to the MUAs, registration involves computing the parameters of a coordinate transform between the coordinate frames of the metrology device's output and the reference "ground truth", such that the discrepancy between the coordinates of corresponding pairs of locations would be minimized when each is transformed from one frame to the other (such transforms can be applied in both directions). When the mapping parameters allow only rotation and shift (not scaling, skewing or elastic distortion), the alignment algorithm is called *rigid registration*, since it simulates aligning two rigid objects by moving and rotating them relative to each other.

Due to measurement inaccuracies, after applying the registration mapping, the mapped positions do not match their corresponding positions exactly. The 3D difference between each reference and registered (aligned) measured position is called the position's *residual vector*. Residual vectors are illustrated in the right picture of a jaw model in yellow. The length of each residual vector represents a 3D shift in position, which is a proxy for the amount of strain applied to the prosthesis at that location when the mounting screw is fully tightened at that MUA location.



Reducing registration residuals to a single accuracy value

Since we are interested in minimizing strain on the prosthesis, and strain is proportional to the length of the residual vector at that MUA location, we can compute an overall accuracy value by averaging the lengths of all the residuals. This approach has a drawback in that it gives equal weight to small and large strains, while we are more concerned about larger strains since they are more likely to cause prosthesis failure. So, we chose to instead use another common method of combining many errors called Root Mean Squared Error, or RMSE. In this method, the squares of the residual lengths, not the lengths themselves, are averaged, and then a root is taken of the average.

RMSE gives more weight to the larger errors, and ends up always being larger than the average or median. For example, suppose the errors in microns for 4 abutments were 20, 20, 20, 20. Their average, median and RMSE would all be 20. Supposed that, instead, they were 10, 10, 50, 10. The median would be 10, the average would be 20, and, because one of the measurements is much larger than the others, the RMSE would be 26.5.

A simpler approach would be to just pick the largest error, i.e., the maximum deviation. While this value would be useful in assessing the accuracy of a single mapping, it is not a reliable statistical value when looking at errors of multiple mappings. This is because (1) the more experiments we do, the higher the maximum error is likely to be, and (2) it “noisy” since only a single measurement in each mapping is being used while the others are completely ignored.

The approach we have taken in assessing MicronMapper’s accuracy is to use RMSE for evaluating overall accuracy and changes in accuracy due to changes in measurement conditions (drifts), and to add the maximum residual length in assessing the accuracy of individual experiments.

Angular errors

Angular errors in measuring the axis of the MUA may also lead to strain on the prosthesis. With a typical outer rim diameter of 5mm, an error of 1 degree translates into a significant gap of $87\mu\text{m}$ ($5,000\mu\text{m} * \sin(1^\circ)$) on one side of the rim when the other side makes contact with the prosthesis’ base. The angular error at each MUA is computed as the angle between the measured axis vector rotated by the registration transform and the reference axis vector. The individual angular errors can be combined by computing the angular RMSE in the same way position errors are computed.

Accuracy of other photogrammetry systems

To get a sense of what is good or bad accuracy, we reviewed all the published scientific papers we could locate on the accuracy of commercially successful dental photogrammetry systems. Here is a brief summary of the published accuracy values and how they relate to our measurement method.

iCam4D by iMetric 4D Imaging

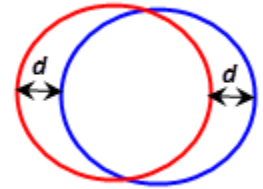
1. [Comparison of conventional, photogrammetry, and intraoral scanning accuracy of complete-arch implant impression procedures evaluated with a coordinate measuring machine](#)
iCam4D outputs were compared to CMM reference measurements by computing the lengths of the registration residuals (called “distortions” in the paper). The averaged 3D errors

reported were $77.6\mu\text{m}$ with a large inter-quartile range (IQR, the difference between the 25th and 75th percentile deviations) of $300\mu\text{m}$ in each of x and y axes (roughly aligned with the occlusal plane). Angular precision was 0.6° computed as IQR separately for each projection on the XZ and YZ planes.

2. [Accuracy of photogrammetry, intraoral scanning, and conventional impression techniques for complete-arch implant rehabilitation: an in vitro comparative study](#)

iCam4D STL outputs of 10 successive scans were compared to a reference surface scan made by a lab scanner with a specified accuracy of $4\mu\text{m}$. The comparison included a setting for surface deviation tolerance of $20\mu\text{m}$ (no explanation of what this means were provided). The iCam4D accuracy results were listed as $2\mu\text{m}$ median/mean and $0.85\mu\text{m}$ SD. These results, which appear to indicate that the test is much more accurate than the ground truth reference, are practically and mathematically impossible, and are likely grounded in some fundamental methodological or mathematical error and should be ignored.

It is important to note that calculating the error using inter-surface distances cannot be translated to registration residuals using registration residuals. In most circumstances, the inter-surface average error will be much smaller than the part's position distance. For example, in the illustration on the right, the red and blue circles are shifted by distance d , but that distance is equal to the distance between the boundaries of the two circles only in the two marked two locations. The rest of the locations are closer, some are even 0 distance!



In summary: The single clear study of iCam4D we were able to locate used a similar registration residual methodology to one we are using in MicronMapper. It suggests RMSE of about $100\mu\text{m}$ (with maximums exceeding $300\mu\text{m}$) and 1° . These are poor results, which may have been improved by design changes since that study was undertaken.

Pic Camera by Pic Dental

3. [Trueness and precision of complete-arch photogrammetry implant scanning assessed with a coordinate-measuring machine - ScienceDirect](#)

The Pic Camera's accuracy was evaluated by the same group which wrote paper 1 above, using a similar methodology. The median of the 3D error was $20\mu\text{m}$ and the 75th percentile was $38\mu\text{m}$. The median of the angular errors' projections on each axis was about 0.25° . The median position accuracy of the conventional (analog) method was similar, at $18\mu\text{m}$, with a more accurate 75th percentile at $22\mu\text{m}$. The 75th percentile of the angular error with the analog method was, however, worse at 0.46° .

4. [Accuracy of Implant Level Intraoral Scanning and Photogrammetry Impression Techniques in a Complete Arch with Angled and Parallel Implants: An In Vitro Study \(mdpi.com\)](#)

An all-on-4 cast scanned by a desktop surface scanner was used as reference. Angular deviations were measured directly by fitting cylinders to scan bodies, and averaged 0.7° . Distance deviations were calculated using surface-surface distances and its average was reported as 0.078μ which is obviously incorrect. The authors admitted the value doesn't make sense but didn't provide a satisfying explanation for it. It may have been 0.078mm , but one cannot be sure.

5. [Comparison between stereophotogrammetric, digital, and conventional impression techniques in implant-supported fixed complete arch prostheses: An in vitro study - Journal of Prosthetic Dentistry \(thejpd.org\)](#)

This study was done by the same group which did the previous one (#4), with the 3D deviations measured as surface-surface distance and reported as being impossibly small ($0.002 \pm 0.001 \text{ mm? } \mu\text{m?}$ – they don't even provide units for the values).

6. [Comparative study of the accuracy of an implant intraoral scanner and that of a conventional intraoral scanner for complete-arch fixed dental prostheses - ScienceDirect](#)

A comparison between the Pic Camera and a CMM measured reference data acquired from a 6-implants jaw. The accuracy was computed by comparing the 15 inter-implant distances and angles, rather than by using registration residual. Since the distance comparisons are 1-D and the residuals are 3-D, the errors reported are likely to be significantly smaller than in the residuals approach. Furthermore, the averaging of the individual distance errors used signed values, which does not reflect absolute errors. The bar graphs show linear errors that range between $-200 \mu\text{m}$ and $200 \mu\text{m}$. SD values were in the 32 and $65 \mu\text{m}$ for the two model jaws (one with parallel, the other with angled implants).

7. [Comparison of the accuracy between conventional and various digital implant impressions for an implant-supported mandibular complete arch-fixed prosthesis: An in vitro study](#)

The average deviation measured with the Pic Camera was $49 \mu\text{m}$.

8. [In Vivo Complete-Arch Implant Digital Impressions: Comparison of the Precision of Three Optical Impression Systems](#)

Uniquely, this was an in-vivo study to compare the full-arch accuracy of 2 IOSs (Trios and True Definition) and Pic Camera in mapping 8 implants each in the lower and upper jaws of a single patient. Rather than using registration residuals, the accuracy evaluation involved comparing the 28 inter-MUA distances and 7 relative angulations (between each MUA and the first one). Following a review of the literature, the authors decided that the tolerances for ensuring a passive fit are $75 \mu\text{m}$ and 0.6° . Note that these tolerances are for 1D distances and MUA-MUA angulation, not 3D registration residuals, which are likely to be significantly larger. Also note that, since no "ground truth" reference was available, deviations reported are actually deviations within the measurement sets, or precision, and thus under-estimate the true error values.

The results show the Pic Camera distances varying by as much as $108 \mu\text{m}$ and 0.5° from their average value (in 5 measurements). Overall, 95|99% of the Pic Camera scans in the lower|upper jaw fell within the set tolerance. This compared very favorably with 68|78% for the Trios and 80|90% for the True Definition IOSs.

In summary: The data presented suggests that the Pic Camera has an RMSE in the $30\text{--}75 \mu\text{m}$ and $0.3\text{--}0.5^\circ$ range. It occasionally has errors exceeding $100 \mu\text{m}$.

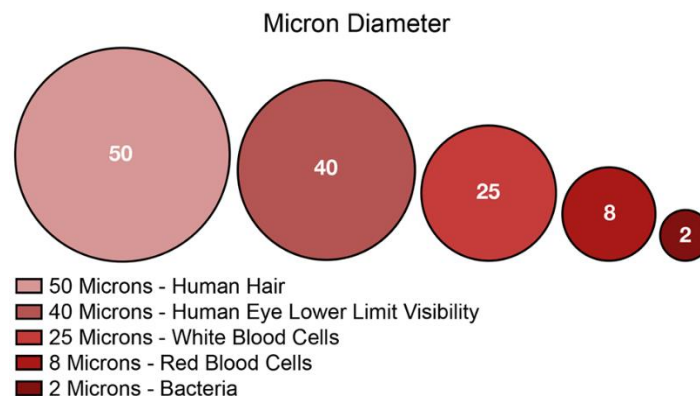
Pass/fail criteria for accuracy benchmarking

The error size where risk of failure to achieve a passive fit becomes significant is dependent on the specific clinical need. Zirconia is about 50 times stiffer than PMMA, and will, therefore, stress much more than PMMA for a given displacement or angular shift. Residual errors in opposite directions at neighboring MUAs that are 8 mm apart will stress the prosthesis much more than residual errors in similar directions at neighboring MUAs that are 25mm apart. Ideally,

MicronMapper will be accurate enough to ensure a passive fit even in the most demanding situation.

Some information relevant to deciding what is accurate enough:

1. [A systematic review of literature](#) (2017) concluded that “The current literature provides insufficient evidence as to the effect of misfit at the prosthesis-implant interface on clinical outcomes of screw-retained implant-supported fixed dentures.” A more recent paper (#5 above) suggests that “Tolerances of 10um to 150um have been proposed as acceptable discrepancies for defining passive fit, with the present consensus for complete-arch FDPs ranging between 50 um and 100 um.”
2. [Manzella et al. studied](#) the effect of the three-dimensional and angular variation of a single implant in a structure with four and six implants. They established limits of 150 μm in the horizontal plane, 50 μm in the vertical, and 1 degree in the variation of the angulation.
3. The tolerance of the processes used in the fabrication of final full arch prostheses, which is typically in the $\pm 100\text{-}200\mu\text{m}$ range (see [this recent paper](#)). MUA measurement errors are combined with production errors to impact the final fit. When two randomly oriented 3D errors are combined, the larger error dominates the resulting error distribution. Since the fabrication tolerance appears to be acceptable for obtaining a passive fit in practice, measurement errors that are 50 μm , half the smaller production tolerance, are likely to add little to the overall fit error and should, therefore, be considered insignificant.
4. Our understanding is that the competitive products, iCam4D and Pic Camera, are considered effective in obtaining a passive fit, and thus their accuracy can be used as a guide to acceptable error level.
5. Our intuition regarding the size of a discrepancy that will matter in fitting a 50+mm long prosthesis on 4-8 supports. It is unlikely that discrepancies smaller than the diameter of a blood cell, or ones that are invisible to the human eye, will matter. Looking at the illustration below, our intuition is that deviations smaller than 50 μ are negligible.



Considering the above, our educated guess is that **RMSE of 50 μm and 0.5°** with maximum errors rarely (no more than 5%) exceeding 100 μm and 1.0° will ensure a passive fit in close to 100% of clinical cases. These will be used as pass/fail criteria in our benchmarks.

Types of measurement errors

Accuracy can be usefully factored into three aspects to be usefully evaluated separately:

1. **Trueness:** The degree to which the size of units used to report values agrees with standard units. In our case, it refers to whether a reported micron is the same size as the standard micron, as used, for example, in the fabrication of the prosthesis. In practice, this involves demonstrating traceability from values used in the reference “ground truth” used in the benchmarks to an international metrology standard.
2. **Repeatability:** The degree of agreement between independent measurements done under the same conditions, for example one immediately after the other without changing the measurement set up in any way. Repeatability errors are considered measurement **noise**. Noise is the results of, for example, random fluctuations in the values of image pixels. They can be reduced by averaging multiple samples. The larger the number of samples, the lower the measurement noise, but the longer the measurement time.
3. **Reproducibility:** The degree of agreement between independent measurements done under different conditions, for example at different temperatures, lighting conditions, viewing directions, scan body autoclaving, mechanical shocks, etc.. The errors induced by varying measurement conditions are termed **Drift**.

Repeatability and reproducibility together are sometimes referred to as **precision**.

Drift errors are the most useful one to benchmark comprehensively:

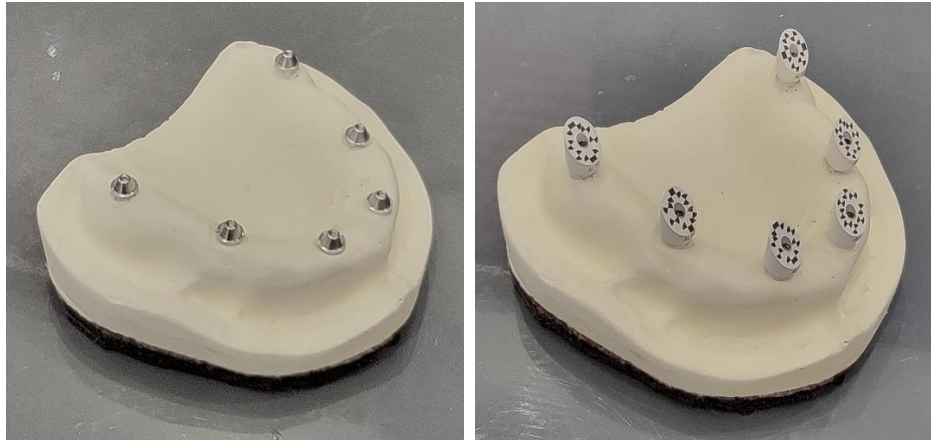
- Systematic drift behaviour can be potentially “calibrated out” of each unit and greatly reduced or eliminated by the system developers.
- Users can use knowledge of drift behaviour to optimize the conditions and the measurement process.
- Prospective buyers and researchers need to be aware of any drift when they select the set of conditions under which to evaluate and compare alternative measurement systems.

By using a representative model as a “ground truth” reference for accuracy, all three types of errors can be quantified to produce clinically meaningful and useful quantities.

Benchmarking tools used

The reference “ground truth”

A stone type IV model of maxilla with 6 MUA analogs, pictured below with and without scan bodies (SBs or “checkers”), was used as the reference object. Replicas of this model, together with the reference data, are shipped with each MicronMapper unit to enable users to perform their own accuracy evaluations (which then include model replication errors).



To obtain the reference measurements, the following process was followed:

1. Using 25.000mm [Gauge Blocks](#) certified to be accurate within less than 1 micron from their nominal length, a thermally stable MicronMapper unit was benchmarked to measure a distance of 50mm between optical markers (of the type used on the SBs) to within 10 μ of their true value in all orientations (along X, Y and Z plus diagonals) at room temperature.
2. That unit was used to perform 20 scans of the model, with the SBs being removed and remounted, with fingertip screw tightening, on different MUAs between scans. This was done to average out errors in the calibration and mounting of the SBs.
3. The MUA poses obtained in the 20 sessions were registered to a common coordinate system, and the registered poses and angles were averaged and saved to form the reference “ground truth” for that model.

The cameras

The production process of each camera includes a series of accuracy benchmarks similar to the ones reported here. This ensures that all units’ performance would be very similar when they leave the factory. To ensure the measurement are representative of clinical usage, we decided not to use new cameras in these benchmarks.

Most benchmarks were performed using camera SN 22901074, which has been used many times for R&D and demo purpose for several weeks before the benchmarks commenced. This unit is known to have been dropped on the floor from a tabletop at least once during that period without being recalibrated afterwards, so it reasonably simulates a MicronMapper system after several months of typical usage.

Several other units have been used during the development of the camera and scan body calibration algorithms and tools, and during the development of the benchmarks. The error values reported by these other cameras were similar to the ones reported below.

The scan bodies

Standard sets of production calibrated scan bodies was used in all benchmarks

Accuracy evaluation software

The key mathematical function used in the benchmarking is RMSE-minimizing registration, which produces a rigid 3D coordinates mapping transform. That function was thoroughly validated and extensively used for over 10 years in many ClaroNav software releases of multiple products. The residual vectors are simply computed by subtracting the transformed coordinates of the measured points from their corresponding reference points. The end-to-end accuracy reporting software has been further validated by introducing deliberate errors (eg, moving one of the scan bodies) and observing the expected effect on reported RMSE and maximum error values.

Repeatability

Static scan repeatability

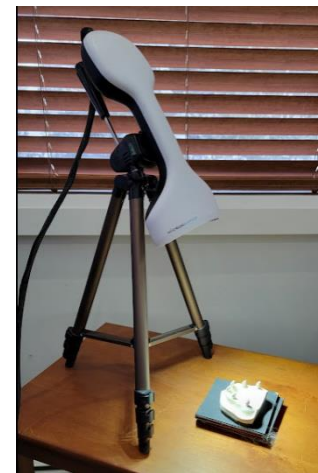
Method: The model was placed about 25cm in front of the camera mounted on a tripod (pictured). 10 scans were made in quick succession.

Results (RMSE/max): 4 μ m/6 μ m, 0.064°/0.166°

Handheld scan repeatability

Method: The model was scanned 15 times in quick succession with the camera held manually and moved in small motions imitating a clinical scan.

Results (RMSE/max): 5 μ m/6 μ m, 0.034°/0.084°



Accuracy drift

Scanning technique

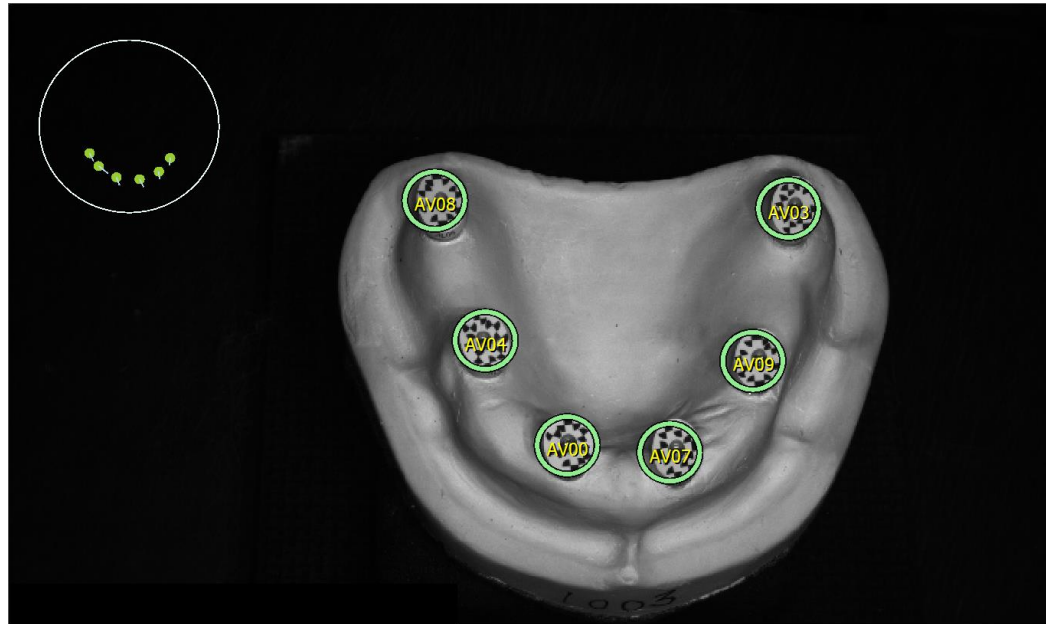
Method: The impacts of distance and viewing angle on accuracy were measured. To reduce the impact of random measurement fluctuations, the average RMSE of 5 similar scans is used at each sample point.

Results:

	RMSE, μ
Distance - at the near end of the circle	13.2
Distance - at the far end of the circle	20.6
Angle - down the SB shafts	14.4
Angle - 45d facing the marked SB surfaces	24.8
Angle - in occlusion plane, moving side to side	18.8

All the accuracy values are well within the PASS range. However, the best accuracy is obtained when scanning at the near (or middle) distance range, with the camera looking down the SB shafts (the “above” view). When the camera is directly facing the flat faces of the SB, accuracy degrades due to strong reflections from the mirror-finish surface which saturate the sensor in some places, leading to increased errors. Scanning from the side, in the occlusion plane, is challenging because the closer SBs occlude the view of the farther ones, requiring moving the camera from side to side.

In conclusion, to get the best results, position the camera to generate this view:

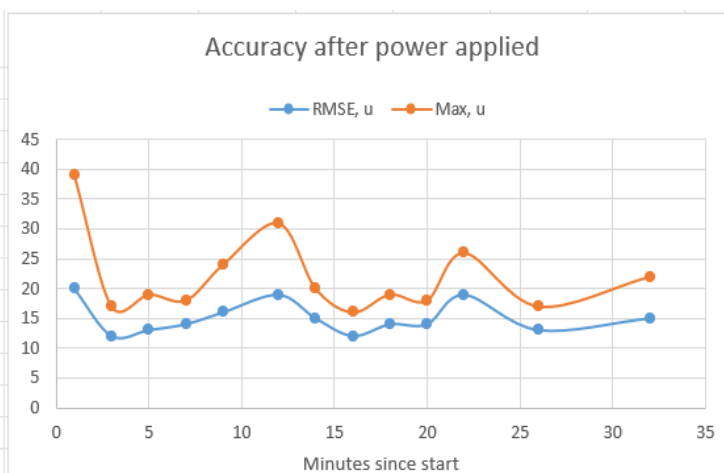


Thermal - warmup

Method: A camera that was left off power for an hour at a room temperature of 22°C was plugged in – both light and USB in quick succession. The application was then started. Scans of the reference model were made manually using the same technique every 3 minutes for 30 minutes. All other conditions, such as scan body seating and lighting, were kept constant. Accuracy, elapsed time and internal image sensors temperature were recorded, then tabulated and plotted.

Results:

Minutes since start	Internal temp, °C	RMSE, u	Max, u
1	23.9	20	39
3	25.5	12	17
5	29	13	19
7	32.4	14	18
9	35.6	16	24
12	39.2	19	31
14	41.3	15	20
16	43.1	12	16
18	44.5	14	19
20	45.5	14	18
22	46.4	19	26
26	47.8	13	17
32	49	15	22



All the measurements are well within the PASS range below 50/100u (RMSE/max). The error is larger in the first couple of minutes, and there are some fluctuations in the measured accuracy as the camera warms up, but these are as likely to be the result of variations in the scan technique and repeatability noise as the effect of camera warm up.

Note that the max value never reached 2xRMSE value. This suggests that RMSE below 50u can be used as the sole PASS criterion.

Thermal– ambient temperature

Since the camera appears to be accurate throughout the warmup range from a cold start at typical office temperature of 22C, we only need to measure the accuracy at the top end of the ambient temperatures it may be operated in, which we estimate at 30C.

Method: The camera was placed in a room warmed up to 32C until the camera reaches a stable internal temperature of 58C. The accuracy was measured by averaging the RMSE (relative to the reference model) of 5 scans performed according to the recommended scanning technique.

Results: RMSE at 32C was 16u, which is similar to the RMSE at lower temperatures, and a clear PASS.

Ambient lighting

With its own intense built-in light (25K-50K Lux), MicronTracker is not affected by lower-level ambient light such as that found in clinics and offices, which rarely exceeds 2K Lux. These were the conditions in all other benchmarks reported here. We chose to further benchmark accuracy under the strongest light that can possibly shine into the oral cavity – direct sunlight.

Method: Accuracy was measured 4 times with the scan bodies illuminate by direct morning sunlight (~50K Lux) from several directions.

Results: RMSEs measured were 16u 12u, 21u, 21u, a clear PASS.

Scan body screw tightening torque

Method: Accuracy was measured with the screws in the 6 SBs on the model (1) all torqued by ~5 Ncm, similar to light fingertip tightening, (2) odd positioned SB by 5 Ncm and even positioned by 15 Ncm (maximum allowed), (3) even positioned by 15 Ncm and odd positioned by 5 Ncm, and (4) all torqued by 15 Ncm. The tightening torque control was achieved using an adjustable torque wrench.

Results: The RMSEs for the 4 conditions were (1) 18u, (2) 20u, (3) 17u and (4) 23u. The variations were insignificant, and all errors were easily within the PASS range.

Scan body reseating

Method: Accuracy, including both position and angular errors, was measured 5 times using a similar scan technique with all 6 SBs on the model removed and re-seated using fingerprint tightening on the same MUAs between measurements.

Results: The RMSEs for the 5 measurements were 19u/0.18°, 16u/0.16°, 19u/0.25°, 15u/0.30°, 17u/0.35°. The variations were insignificant, and all errors were easily within the PASS range.

Scan body exchangeability

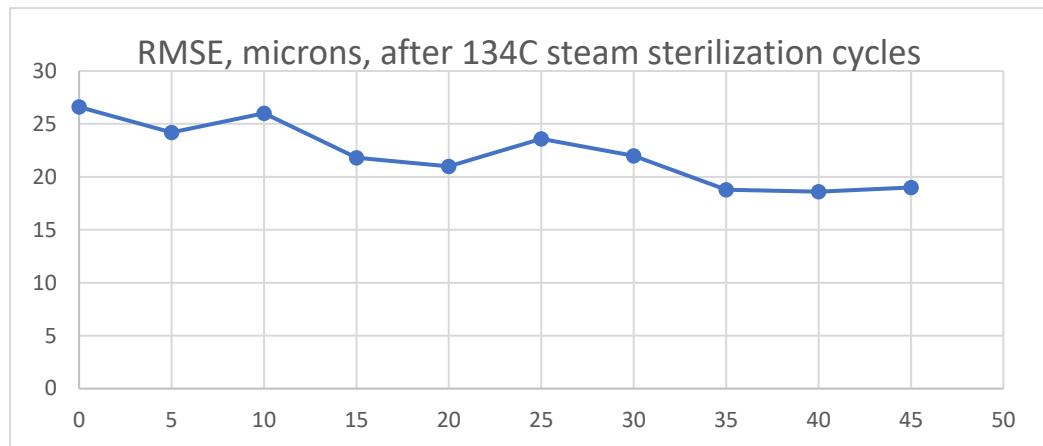
Method: Accuracy was measured 6 times using a similar scan technique, with the SBs rotated one MUA position clockwise between measurements.

Results: The RMSEs for the 6 measurements were: 23u, 23u, 21u, 17u, 22u, 17u. The variations were insignificant, and all errors were easily within the PASS range.

Scan body steam sterilization

Method: A set of 10 scan bodies were mounted on a model for which reference data was available. Initial accuracy was measured by averaging the RMSE of 5 scans and recorded. The scan bodies were then steam-sterilized in the metal container provided for that purpose 5 times at 134°C and the accuracy was measured and recorded again. The process was repeated 9 more times.

Results: The measured accuracy as a function of autoclaving cycles (horizontal axis) is plotted below. Surprisingly, the accuracy seems to improve with more cycles. However, a close examination of the data suggests that what improved was the scanning technique of the tester. The initial sets of measurements produced uneven results, with RMSE values spread between 18u and 33u. They became more consistent over time, with the last three sets varying only between 17u and 21u.



While it is clear that autoclaving the scan bodies does not have an effect on accuracy, a concern was raised that the autoclaving would deteriorate the contrast of the optical markings, degrading the optical scanning process. Follow-up testing, which took weeks to complete, demonstrated that, despite a slight darkening of their color, the scan bodies and the scanning remained fully functional even after 400 cycles (see picture below).



Scan body blood staining

Method: A set of 6 scan bodies were mounted on a model for which reference data was available. Initial accuracy was measured by averaging the RMSE of 5 scans and recorded. All the scan bodies were then the stained by human blood. To simulate clinical usage, the staining was done by a gloved hand touching a blood-stained tissue, then touching the scan bodies. A picture of the stained bodies is shown below. Scanning was then performed on the soiled model, then after gradually wiping the blood off each scan body in turn.



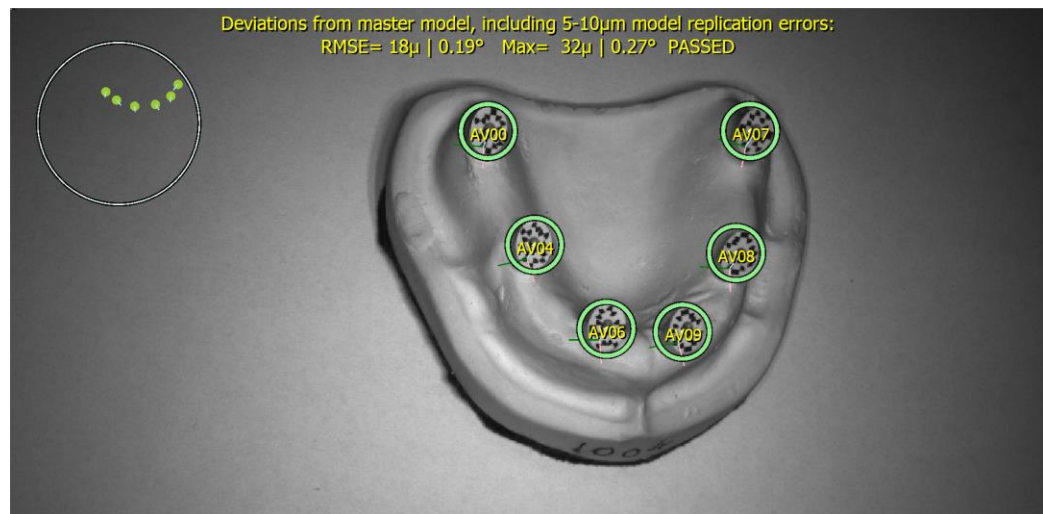
Results: Initial averaged RMSE of the scanned model pre-staining was 10 μm . Following the staining, none of the scan bodies was detected and mapped when there was any trace of blood on its markings. Only when it was completely wiped clean was it detected and mapped. Once all the scan bodies were wiped clean, the averaged RMSE of the scanned model was 9 μm , practically the same as pre-staining.

Accuracy evaluation by users

While the MicronMapper camera was designed to maintain its calibration over many years under normal usage, repeated or strong mechanical shocks may degrade the calibration and reduce the camera's accuracy. To be confident that the accuracy of MicronMapper is sufficient to ensure a passive fit in the next mapping session, users need to be able to perform a short accuracy benchmark on their own.

For that purpose, we have provided a stone model of an edentulous jaw with 6 embedded MUA analogs and an embedded software that, when the model's number, written on its label, is entered as the patient's name, automatically compares the model's scan results to a master model measurements file installed with the software. The master file was created by averaging the measurements of 16 replicas of the master. Since a single master file is used as the ground truth reference for all the replicas, and the replication process has some errors, the reported accuracy numbers are somewhat worse than when the reference was obtained for the individual model, as was done in the above reported benchmarks. We found that the RMSE and max values are typically larger by about 5-10 μm and included those numbers in the on-screen reporting of the result (pictured below).

To help users decide whether the reported values are acceptable, we have labeled the results as "PASSED" when all following conditions are met: RMSE distance < 40 μm , RMSE angular < 0.5° and max distance < 100 μm . Otherwise the results are labeled either "Marginal" or "FAILED". If the results are not labeled "PASSED", we suggest that users examine closely the scan bodies for smudges or damage, ensure they are well seated on the model then try again. If the subsequent benchmarks are not labeled "PASSED", the camera should be returned to the factory for recalibration.



Summary

The best accuracy is obtained when scanning at the near half of the distance range, with the camera looking, to the degree possible, down the SB shafts (the “above” view). The benchmarks suggest the following accuracy values for a MicronMapper used thus:

- Repeatability: 5µm, 0.05° RMSE
- Accuracy (typical): 20µm RMSE, 30µm MAX.
- The following factors do not significantly degrade accuracy:
 - h. Warmup of camera (after 1 minute since power on)
 - i. Ambient temperature up to 32°C/90°F
 - j. Ambient lighting (darkness to full sunlight)
 - k. Scan body screw tightening torque (≤ 15 Ncm)
 - l. Steam sterilization of scan bodies at 134°C
 - m. Blood staining (any staining disables detection)
 - n. Mechanical handling in regular usage (not major shocks).

Review of scientific literature suggests that RMSE below 50µm and maximum error below 100µm will ensure a passive fit in close to 100% of clinical cases. MicronMapper’s is 2-3 times better.

Using the built-in benchmarking function of MicronMapper with the provided stone model enables users to reliably evaluate the accuracy of their unit as needed, for example after the unit is shipped by a carrier, or after a mechanical shock.