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Verification and Acceptance Tests for High Definition 3D Surface Scanners

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Abstract

High definition three-dimensional (3D) surface scanners, based on structured light or laser light section techniques, have found a wide range of applications, especially for technical and industrial applications (mostly for measuring and inspection tasks). Since about 10 years, systems adapted for the requirements of arts and Cultural Heritage (CH) support 3D digitization of art objects. Although the use of digital 3D models in CH is rapidly growing, many of the users are not yet completely familiar with terminology and all details of technical specifications. As most of the users are practitioners there is sometimes only little experience with terms as data quality, accuracy, resolution, measurement uncertainty, especially because these terms are used in very different ways, in manuals and brochures of scanner manufacturers as well as by authors of scientific papers. Moreover, the objective of many applications is digitization instead of measurement; therefore, many users are not even aware, that they nevertheless have to care about metrology issues such as verification and acceptance tests of the used equipment to get a reliable scanning result. In its first part, the paper will give an overview the fundamentals of data acquisition and data processing, presenting also advantages and benefits, limitations and drawbacks as well as correlations between different performance parameters of high definition 3D surface scanners. Our goal is also to rectify a number of typical misunderstandings and to clarify related terms and definitions. In its second part, the paper will concentrate on verification and acceptance tests of high definition 3D scanners, reviewing the German guidelines VDI/VDE 2634/2 and proposing some preliminary extensions required to cope better with the CH domain.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Digitizing and scanning

1. Introduction

3D scanning systems are on the market since around twenty years, but general knowledge on terminology and specifications is still not very well disseminated. Users tend to consider a scanning device as a black box, ignoring most of the technical concepts and internal architecture design. Therefore, taking decision on the base of a comparative evaluation is not easy for standard potential users. Moreover, the quality of commercial data sheets does not help users, since device producers often use different terminologies making the cross evaluation of alternative systems a complex task. The goal of this paper is therefore to give an overview of the basic concepts which characterize short-range 3D scanning technologies, to propose a common terminology and to evaluate the available approaches for verification and acceptance tests of 3D scanners. Most of the concept presented are also valid for long-range 3D scanning devices, but for the sake of conciseness we do not present those technologies in detail.

2. State of the art

The verification of 3D scanners performance parameters is a topic that has been not very frequently studied (among pioneering papers, we would cite a work by the Canadian NRC [BEHB95]). In the ideal world, we need first to define a general evaluation procedure for measuring the performances of 3D sampling devices. This procedure should be as much possible representative of the scanning difficulties that users will face in their activities, going much beyond the simplistic approach used frequently (e.g., sample a planar surface with an average, uniform diffuse reflection). More-

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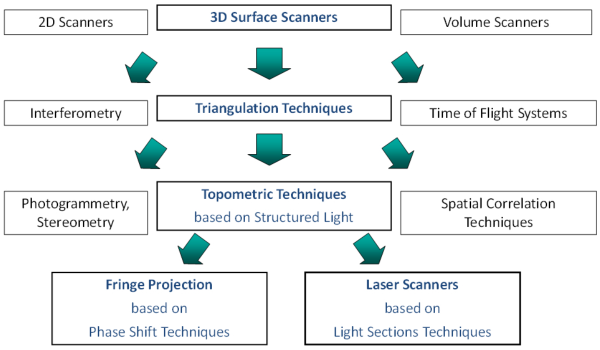

Figure 1: *Classification of optical scanning technologies.*

over, frequent sampling of current technologies is needed, possibly operated by an independent player, to monitor the evolution of technologies.

One of the more comprehensive approaches to verify the quality and performances of 3D scanners was proposed in [BVM03, i3M10]. This work focused on medium and long range scanners (thus, encompassing time of flight (TOF), phase modulation and triangulation devices). Authors defined some specific setups to evaluate scanner performances taking into account: angular and range accuracy, resolution and capability to recover from edge and surface reflectivity effects. We will describe and comment the approaches proposed in [BVM03, i3M10] in Section 6.

Evaluation of TOF scanners for the acquisition of architectures was presented in [BPPU01], while the very specific domain of face acquisition was the subject of a paper evaluating the performances of short-range scanning devices [BF05].

Finally, a very peculiar approach was proposed in [GFS03] to evaluate the accuracy of short-range scanners, based on an approach frequently used to characterize standard 2D cameras. Goesele and colleagues defined a set up to measure the spatial frequency response of a scanning device: they acquire a simple cubic block that presents a slanted edge in the device view, derive from this acquisition a super-resolution edge profile and use it to evaluate the frequency response of the acquisition camera.

3. Fundamental of Structured Light Techniques

Optical scanning techniques can be classified according to the scheme in Figure 1. Since most of the high-definition, short range surface scanners are based on triangulation techniques using structured light (fringe projection or laser light section), we will concentrate in this paper on these techniques.

Figure 2: *Stereoscopic images.*

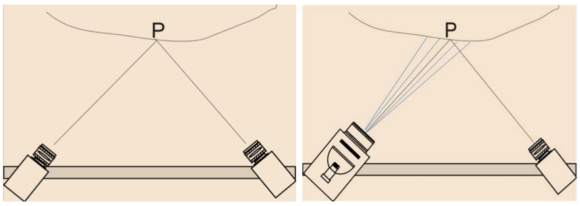

Figure 3: *Technical realization of a stereoscopic set-up with two digital cameras (left); principal set-up of a fringe projection system (right).*

Most people are familiar with the concept of optical triangulation, because the human vision system with its two eyes is based on a stereoscopic set-up (see Figure 2). A technical realization replaces our eyes by digital cameras (see left-most image in Figure 3) and an image processing system to correlate the stereoscopic images. However, there are very different objectives between the requirements of a technical vision system and the human one: humans have an extraordinary system for pattern recognition and feature extraction; technical systems do not even begin to compare with the complexity and versatility of the human visual system. On the other hand, our visual system is only a qualitative one with a strong subjective component. Technical vision systems, on the other hand, should guarantee a quantitative and objective recording of our surroundings. Moreover, metrology requires high accuracy, reliability and repeatability. Therefore, homologous points in the stereoscopic images must be correlated with sub-pixel accuracy, typically in the range of 1/10 of a pixel. To overcome the many problems of correlating stereoscopic images just by image processing techniques, most of the 3D surface scanners are based on a structured light approach, using one of the three options:

- *random patterns*;
- *laser light* (usually beam or plane shaped);
- *fringe projection*.

The most simple configuration of such a topometric system is to replace one camera of the stereoscopic set-up by a projection unit (see right-most image in Figure 3). This allows to create an unambiguous indexing of all object points and a reliable and quantitative calculation of 3D data (see

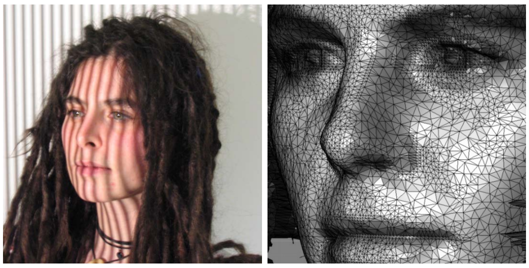

Figure 4: *Left: object with projected fringes; right: 3D-data reconstructed by triangulation.*

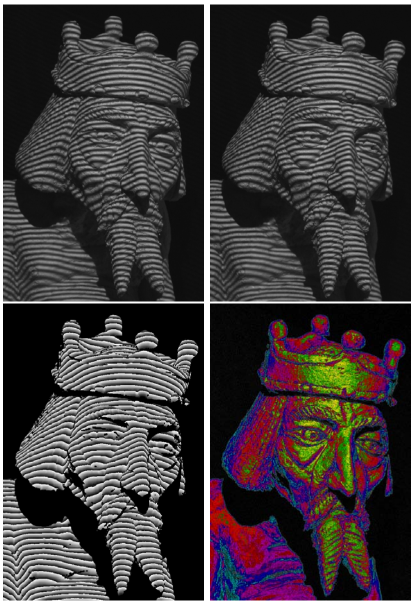

Figure 5: *Fringe projection: two phase shifted images (above); computed phase map and contrast (below).*

Figure 4). Some advanced topometrical systems are using a two camera set-up with an additional pattern projector.

Since **random patterns** are analyzed by spatial correlation techniques, which results in a strong low-pass filtering (smoothing) of the calculated 3D data, they do not offer highest spatial resolution. On the other hand, these techniques are instantaneous, because the data acquisition can be based on the recording of only a single image.

Laser light section systems usually sweep a plane of laser light onto the object surface and thus draws a laser line over the intersected section. Data analysis is based on simple feature extraction techniques to detect the centers of the projected line section. Although the laser can be focused onto the object, this results in a small low-pass filtering of the calculated 3D data.

Figure 6: *Process from single scans to merged polygonal mesh.*

Fringe projection techniques are mainly based on the phase shift technology [Cre88, Mal89, Bre93] (see Figure 5). Instead of recording only one image, a sequence of fringe patterns is projected and recorded. The main advantage of this technique results from the fact, that it allows a very accurate calculation of the fringe positions (phase map) and thus of the 3D coordinates for each camera pixel, completely independent from all adjacent pixels. Moreover, phase-shifting techniques allow to separate the projected light structure from the texture of the object. They also provide a contrast image which can be used for estimating the reliability of the calculated data. The main disadvantage of fringe projection techniques is the number of patterns, typically about 10, that must be projected onto the object and recorded. These techniques offer the highest spatial resolution, however, they are not sharp in time.

4. Measuring Reality and Processing Sampled Data

To fully capture an object, or rather to create its watertight 3D model, several individual measurements from different angles are usually needed. Arranging the scanner and planning the scan overlay requires careful preparation, especially for objects featuring many concave and hidden parts [BVM03]. As a consequence, digitized data from different viewing angles are available, representing portions of the object surface and lying in different coordinate systems. To create a merged polygonal mesh (i.e. a complete model representing all object surface in a non-redundant manner), all scan data have to be transformed in a common coordinate system (see Figure 6). This processing phase is called *registration* or *alignment*. To guarantee the best possible alignment of scan data for each application, or rather for each measured object, various alignment strategies can be applied:

- Direct alignment by means of the object geometry; this approach is usually based on, first, a manual selection of an approximate transformation, followed by an automatic fitting based on the Iterative Closest Point (ICP) algorithm

[BM92, LR01, Pul99]. Fully automatic solutions have also been proposed more recently [FPC*05, AMCO08];

- Using an highly accurate positioning system (e.g. linear axis for scanning paintings) [LPC*00];
- Alignment by means of index marks or reference spheres positioned in the scanning scene (but positioning elements in the scene is often complex, time consuming and not robust);
- Using *photogrammetry* to have precise locations of a few feature points which can be easily located in the scanned raw data; this is a common approach in the acquisition of architectures with long-range scanning systems and has also been applied to check the accuracy of software range maps registration in short range scanning [TCG*01];
- Adding a tracking system to the scanning unit (e.g., an optical tracking systems or a magnetic tracking).

The listing above shows that exist multiple measuring and registration strategy on the market. In the context of CH applications we need both very accurate alignment and easily deployable systems that could be moved on the field without loosing the sensor calibration [BW08]. Therefore, the more practical and frequent solution is geometry-based alignment through ICP, i.e. using the object geometry for aligning scans; to a lesser extent, positioning systems as well as optical tracking systems are also used.

Once we have aligned the range maps, we obtain a very redundant representation (many surface sheets overlapping each other). Therefore, we usually apply a reconstruction algorithm to produce a single (usually triangulated) surface, where each surface parcel of the sampled object is represented by one single digital element (a triangle). The digital surface can be reconstructed adopting one of the many reconstruction solutions proposed in literature and available in the different range data processing systems. We cannot describe here, due to space limitation, the most diffuse reconstruction algorithms. It is important to clarify here that the reconstruction is often a resampling process, where the geometry and topology of the digital model are reconstructed to approximate (or interpolate) the sampled data. The resampling process usually works on a very dense and redundant sampling. Therefore, when this reconstruction is implemented with a proper solution, it could also improve the quality of the output surface with respect to the raw sampled data. As an example, consider the random noise that could be contained in the sampled data: if in the reconstruction process I am able to characterize the quality of the samples and to make a keen average between nearby samples, I am usually also able to reduce the impact of this random noise on the reconstructed model.

It is also important to clarify that most of the reconstruction methods apply some sort of convertion to a regularly sampled space subdivision (first, distribute the sampled data on a regular 3D grid, e.g., by computing a discrete distance field; then, reconstruct a small surface patch for each cell of this grid). Thus, the selection of the resolution of this reconstruction grid is a critical decision, since it has a direct impact on the quality and accuracy of the reconstructed model with respect to the sampled data. A good rule of thumb is to use a reconstruction resolution (i.e., size of the elementary grid cell) which is more or less identical to the inter-sampling distance used while scanning the surface. A coarser grid will allow faster processing and a less dense reconstructed surface, but will also wash out high-frequency detail. A reconstruction grid denser than the inter-sampling distance will only increase reconstruction time and size of the output mesh, without increasing the detail or the accuracy.

5. Specifications, Correlations and Limitations

A spectrum of 3D-surface scanners is available for digitizing CH artifacts [Be09, BVM03, BMV09] and the selection of the more proper device depends on the specific user experience and on the application requirements. Table 1 gives an overview of typical specifications of 3D scanners used for CH applications; the specifications for one commercial high-end scanner are also listed in the same table. Scanning systems are often designed to fulfil the needs and specifications of different application domains, e.g. to be adopted in the field of product design and development (inverse engineering and rapid prototyping) or quality control (mould making and tooling). Enlarging the spectrum of utilization is of paramount importance in a market that is still very small in terms of units sold per year. There are also some specific applications that require ad hoc solution, but also offer a market sufficiently large to recover the design and specialization effort (dentistry applications are an example). As shown in Table 1, the user analysis and decision process is complicated, since existing systems differ in most of the parameters, such as available FOV, triangulation angle and resolution. Moreover, terminology is still not uniform and some of those terms and concepts are rather obscure for many users that have no idea of the internal processes and see the scanner as a black box. Between all these different parameters there are always correlations. To facilitate decisions concerning sensor configurations and to clarify some typical misunderstandings, some of these important correlations are explained further in the following.

Camera resolution. The number of samples acquired in a single scan depends on the resolution (number of pixel) of the camera(s) used in the sensor unit.

Field of View (FOV). The FOV determines the space subset that one can sample with a single scan of the instrument. One should choose a system adequate to the average size of the artifacts to be scanned. Some systems offers the possibility to have several, adjustable FOVs (e.g., by changing the lenses of the sensor). A wider FOV has some negative effects (usually, a coarser sampling is produced; if a larger FOV is obtained with the same emitter-sensor configuration,

	Typical specification ranges	Example of a commercial 3D scanner
Camera:	CCD/CMOS device, color or black/white	CCD, color
Digitization:	0.3 to 6 MPixel	2 x 5 MPixel
Light source:	Laser, LED, halogen or discharge lamps	250 W halogen
Field of View:	about 20 mm to 2 m	300 mm
Data acquisition time:	0.5 sec to minute per single scan	1 sec / scan
Operating distance:	200 mm to 2 m	1 m
Sensor weight:	1 to 10 kg	4 kg
Triangulation angle:	5 to 40 degree	30/20/10 degree
Point (inter-sampling) distance:	5 μm to mm	100 μm
X/Y resolution:	10 μm to mm	150 μm
Depth resolution:	2 μm to 200 μm	10 μm
Accuracy:	5 μm to mm	15 μm, probing error according VDI/VDE 2634/2

Table 1: *Typical specifications of 3D surface scanners.*

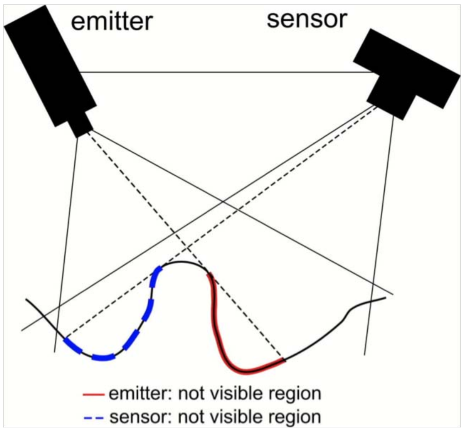

Figure 7: *Any scanning device based on triangulation might produce incomplete samples, since the surface regions effectively sampled by the device are only the surface parcels that are visible to both the emitter and the sensor.*

thus using a smaller triangulation angle for the wider FOV, accuracy of the 3D samples is usually worse), but also some advantages (a reduced number of scans needed to cover the complete surface, a smaller amount of data to be processed). A smaller FOV presents the inverse pro and cons.

Inter-sampling distance. This unit measures the (average) distance of the 3D samples over the sampled surface. This parameter is directly dependent on the camera resolution, the FOV and the depth of the sampled surface inside the FOV. Anyway, it is a very important specification value, to measure how dense the sampling could be on an average surface.

Triangulation angle. Larger triangulation angles result in better depth resolution and S/N ratio, but they may require more scans for complex objects. Larger is the triangulation angle, wider are the potential surface regions that are not seen jointly by the emitter and the sensor (see Figure 7). Those regions will show up as unsampled regions in the scan.

Accuracy. Evaluating the accuracy of a system is an extremely complex task. Commercial datasheets usually present values on the nominal accuracy of the scanning unit. But without giving an exact definition of the term *accuracy* and a procedure (how to measure it), those values are not really meaningful. Moreover, we should also remember that the nominal, ideal accuracy of the scanning unit, however this term is used, is not automatically the accuracy of the final model. For example, the choice of the registration strategy adopted to align the range maps has a strong impact on the overall accuracy, not to forget the calibration of the system which is also very essential to obtain a good accuracy. An improper reconstruction (range maps merging) could also decrease the accuracy of the final model. To give an example of a more familiar situation: the term fuel consumption of a car is not meaningful without defining the conditions and procedure on how to measure it. We need some more information to estimate the real consumption under practical conditions, e.g. how speed and driving behavior influence it. For these reasons we have to point out that values produced in datasheets or even in scientific publications are not easy to compare, since we do not have a common measuring and evaluation procedure. Table 2 gives an overview about different meanings of the term accuracy as used in data sheets and literature. The listed values are typical for a well calibrated high-end scanning unit with a camera resolution of 5MPixel and a FOV of 500 mm. Please note, that only for the values marked with *, there exist a well defined measuring and evaluation procedure. Moreover, usually the listed values are related to very basic material (planar surfaces, painted in light gray, with nearly pure diffuse reflection). Therefore, the results published are in many case much optimistic with respect to the real scanning scenarios the user has to manage. We will comment more in detail on those issues in the next subsection.

Repeatability	1 μm
Bound error of registration	1 μm
Limit of depth resolution	5 μm
S/N-ratio	10 μm
Interpolated spatial resolution	50 μm
Inter-sampling distance	175 μm
Probing error (*)	15 μm
Flatness measuring error (*)	20 μm
Sphere distance error (*)	25 μm

Table 2: *Different meanings of the term accuracy.*

5.1. Limitations of active optical systems

Given the advantages of optical 3D-surface scanners, such as the contact free measurement of a vast number of points within a short time and giving access to color and texture, it always has to be kept in mind that these scanners also have certain limitations. Limitations are often also not mentioned clearly in commercial datasheets, and users should be aware of them. These can be summarized as follows:

- Surface scanning technologies do not give access to volume data (we cannot sample interior surfaces, e.g., the interior of a ceramic vase or of a bronze statue).
- Triangulation techniques have difficulties in capturing deep holes and undercuttings (due to the displacement of the light emitter and the video sensor, see Figure 7).
- The basic principle of active optical techniques, being either structured light or laser-based, is to project light patterns onto the object. Therefore, due to the limited light sources, it is difficult to illuminate large areas; there might be problems due to ambient light conditions, especially for large FOV's (e.g., direct solar illuminations fakes most systems).
- Problems with shiny and (semi-)transparent surfaces: scanning is often possible only with coatings, which are usually forbidden in the CH domain for conservation reasons.
- We have a strong correlation between FOV and resolution: if a dense sampling is requested, a large FOV is often improper.
- Typical inter-sampling distances and depth resolution is in the μm range (the sub-μm range is difficult to reach). But only very few applications really need those extreme dense sampling; the density and accuracy provided by high-end scanner is perceived as adequate by most CH applications.

6. Verification of Optical 3D Scanners

Optical 3D scanners are used as universal digitization or measuring equipment. Every user must be sure that the optical 3D measuring system used does best fulfil the application-specific performance requirements. Both manufacturers and users should be able to check and demonstrate the quality parameters of the measuring system in a simple and clear manner. In the long run, this can only be ensured through: (a) comparable/common verification criteria and (b) verification of the equipment by re-calibrating it at regular intervals. Moreover, in order to check and demonstrate the quality parameters of a system, it should be possible to compare different systems on the market based on the same requirements and considerations. The verification of quality parameters and comparison of different systems, following [VDI02], requires the following points:

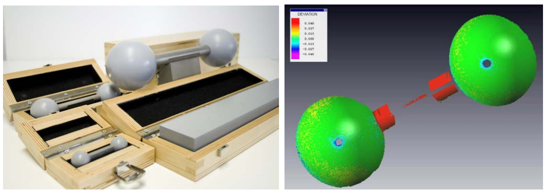

Figure 8: *Dumbbell artefact and measurement result.*

- Definition of the quality parameters;
- Availability of certified artefacts (see Figure 8);
- Measurement procedure;
- Calculation of results;
- Interpretation of results.

The determination and verification of quality parameters must be comprehensible and reproducible. For optical 3D measuring systems providing area-based sampling, the German guideline VDI/VDE 2634 Part 2 [VDI02] gives a practical acceptance test and re-verification procedures to assess the precision of a system. Therefore, the guideline VDI/VDE 2634/2 defines the following *quality parameters*:

- **Sphere spacing error**: it verifies length-measuring capability; given two certified spheres of known radius and distance, it evaluates the difference among measured and calibrated distance of the spheres by finding a best-fitting radius and center over the sampled data (according to the least-squares method).
- **Probing error**: it is the radial distance between the measured points and a best-fit sphere (using the same certified sphere artifact).
- **Flatness measurement error**: given a certified planar artifact, we measure the signed distances of the measured points from the best-fit plane calculated accordingly to the least-squares method.

Most of the high-end systems used for technical applications are meanwhile certified according to this VDI/VDE 2634/2 or a similar guideline. However, in the field of Cultural Heritage many people, either manufacturers or users do not care about the verification of the system parameters; some of them do not even know that there exist any such guideline. Therefore, the specifications for only a very few scanners, e.g. all Breuckmann High Definition surface scanners, has been verified according to existing guidelines, especially VDI/VDE 2634/2.

Moreover, the CH domain opens specific requirements in terms of the evaluation of the different quality parameters. Estimating these values on simple shapes (planar surfaces, calibrated spheres) is already a first step, but it is probably not sufficient to take into account all the complexity of real test cases. The guidelines presented above have been developed focusing mostly on technical applications. In the framework of the 3D COFORM [3DC10] project an activity has been recently started, with the goal of setting up further suggestions for enhanced and application-oriented procedures, to test and verify specifications of 3D surface scanners in the CH domain. Since the results of a verification process will depend heavily on the test target used, the more representative set of test target should be designed to fulfill the specific application needs.

One issue that we want to consider is the so-called **edge effect**. CH surfaces are usually not smooth, present a lot of self-occlusions in the view space and we need to define a set of test objects that should be as much as possible similar to the shapes we encounter in real projects. Since the light probe (a laser spot/line or a light stripe) has a certain size, situations where only a part of the probe is reflected by the sampled surface introduce severe errors in the sampled geometry; the situation is even worse when the rest of the probe section is reflected by another, far away surface. Wrong samples are thus produced in the vicinity of silhouettes or of regions with discontinuity in depth. Edge effect has been taken into account in [BVM03] by setting up a specific probing specimen (two planar surfaces, positioned one over the other at a given distance). They also proposed a second probe, where the capability to correctly sample the edge effect was paired to the test of the resolution of the device; this second test was based on a probing box with slots of varying widths opened in the front surface.

Another aspect that is not taken into consideration by the current verification procedures is the texture that is very often associated to a real CH artefact. **Color discontinuities** are common and produce discontinuities in surface reflectivity, either because we have severe patinas or degradation or because surfaces are painted or decorated. The result of an improper design of a scanning system or of its incorrect use (e.g., wrong selection of laser intensity) could originate geometric aliasing in the sampled data. The profile of a color/reflectivity discontinuity can be transformed into a discontinuity in depth of the sampled geometry (e.g., see Figure 9). We should be able to test also the robustness of a specific scanner with respect to surfaces with textures or reflectivity discontinuities. A specific probe has to be designed.

Moreover, when we start considering sample objects with a color texture and those scanning devices able to acquire jointly color and geometry samples, we cannot avoid to consider also the issues concerning the quality of the **sampled color**. The quality of color acquisition is a subject already studied in the image acquisition domain. We could use approaches widely adopted in imaging, for example Machbeth charts, for assessing the accuracy of the color unit of a scanner device and to measure how much the acquired values will differ from the known samples. As much as possible, a uniform illumination should be used, to prevent the creation of shading effects or discontinuities which are not easy to remove from the input images.

Figure 9: *The rendered surface on the right shows some geomertric aliasing due to improper acquisition on the discontinuity border of painted regions, visible on the leftmost image.*

Finally, having a certification of the sampling device is a first step, but it does not solve the global problem. Even the most high quality system can be used in an incorrect manner, and even a very good raw dataset can be processed in an improper manner, producing a low quality digital 3D model. The geometric process is a rather complicated process that can introduce severe inaccuracies or approximation in the final model. Therefore, we need a procedure to evaluate the shape accuracy of the *final model* with respect to the input sampled data. The goal is to define a procedure or a tool that could allow a final customer to evaluate the quality of a 3D model, e.g. the one produced by a service company.
The quality of a final model can be evaluated in a measurable manner by computing the shape difference of the final model with respect to the input data (i.e., the input range maps). This shape difference can be evaluated, as an example, by computing the Hausdorf distance (a generic filter is included, for example, in the *MeshLab* tool [Cig10]). We are designing an evaluation procedure that should work along this path.

7. Conclusions and Future Work

Current high definition 3D-surface scanners, based on the active optical approach and optimized for the requirements of CH applications, allow the 3D digitization of artworks at very high resolution and accuracy. Moreover, the texture and/or color of the object can be recorded, offering a one-to-one correspondence of 3D coordinate and color information. State of the art systems are equipped with digital cameras of up to 5 MPixel, offering spatial resolutions for small fields of view down to 10 μm (according 2,400 dpi for flat surfaces) and depth resolutions of a few μm.

We have presented a brief introduction to existing technology, potentialities and limitations. However, the main goal of the paper has been to help in filling a gap in user perception of the characteristics of those devices, trying to define a common terminology for the principal concepts used in technical specification sheets. Another important issue is the lack of a common evaluation procedure that should allow to evaluate the performances of different systems and to make sound comparisons. We have described the existing guidelines, such as the VDI/VDE 2634/2 that allows the verification of basic scanner parameters on a single scan. In the meantime, a new guideline VDI/VDE 2634/3 is available. However, both guidelines have been developed mainly from the viewpoint of technical applications. We think that there is the need of a major extension of that approach if we want to apply it to the CH domain. This paper is just a first step towards the objective of the definition of an accuracy evaluation policy specifically designed for the CH domain specific needs and requirements.

Acknowledgements

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