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PHOTOGRAMMETRY AND 3D SCANNING: ASSESSMENT OF METRIC ACCURACY FOR THE DIGITAL MODEL OF DONATELLO'S MADDALENA

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ABSTRACT

The deployment of 3D optical scanning technologies for measuring three-dimensional shapes of sculptures of high morphological complexity, have seen recently a development so noticeable that it emerges as one of the most promising methods for the analysis and preservation of the Cultural Heritage. In spite of an undoubted richness of information produced with this technique, the method for generating a digital model from single 3D acquisitions involves errors propagation that may deteriorate the actual metric accuracy attainable with such procedure. The activity reported in this paper describes a recent experiment in 3D scanning of a highly complex sculpture: the wooden statue "Maddalena" by Donatello, kept in the museum of the “Opera del Duomo", in Florence. The acquisitions, taken with a commercial system based on fringe projection, give a local measurement uncertainty of about 70µm, but when the complete model is generated by automatic alignment of the raw 3D images in a common coordinate system, possible scale variations might be involved, especially along the height of the statue. With this preliminary work, the authors want to verify the metric reliability of the three-dimensional model, obtained through iterative alignments of single 3D acquisitions. For this purpose, a measurement over well-identified features of the sculpture have been performed and the distances between couples of significant points have been calculated with photogrammetric operations. By repeating the same measurements on the 3D model, a corresponding set of point-to-point distances have been evaluated and compared with the photogrammetric results.

1. INTRODUCTION

The need to acquire information about historical works of art can be satisfied on different levels: on the one hand, to promote enjoyment and appreciation of art; on the other, for purposes of study and subsequent conservation. In both cases, technological developments have modified the methods used and the wealth of detail of the information that can be gathered. If the “history of art for the last hundred years, as soon as it is out of the experts’ hands, is the history of what can be photographed” (Malraux 1947), it has been photogrammetry which has made possible the study, measurement and representation of art. When one approaches the question of the enjoyment of plastic works, whose originals had a three-dimensional existence, the limits of the static, frontal representation characteristic of the photograph, are immediately evident: the logical outcome is the need to acquire the third dimension, in line with what the spatial-temporal visual experience of a person looking at the work would be. If, instead, what one is interested in is analysis and study, the need to approximate the surface as well as possible, eliminating subjective interpolations, becomes indispensable.

With the advent of digital technology, we have witnessed the transfer of visual culture onto new electronic supports and into new channels of diffusion as well as a change in the methods with which the form and substance of works of art can be transmitted.

This patrimony is waiting to be transformed into multi-media language for the world of knowledge, while at the same time it continues to contribute in substance to the development of the very means of expression that shape that knowledge. In another sense, the language of the multi-media is the natural outlet for access to those aspects of an original work that would otherwise be accessible only in reproduction. Universities, research centres and museums began some time ago to digitalize research sources and instruments and to transmit them via Internet. Digital models

are, unlike those of the past, dense, full of information and reticular connections; they possess a surplus value that derives from the possibilities of hyper-media links, superimposition on other descriptive elements.
In this scenario, the availability of new procedures for acquiring and processing numerical data capable of thoroughly describing the three dimensionality of works of art opens up opportunities for use which were formerly inconceivable. The following is a list of some examples of the many fields in which 3D numerical models, each oriented towards a specific end, can be used.

- In the field of documenting and cataloguing our artistic patrimony, the faithful representation of the morphological-dimensional characteristics of a work so that it can be studied from the historical/artistic viewpoint. A three-dimensional model obtained in this way can be combined with video and photographic information so that it becomes possible to create a data bank for accurate comparative evaluations of different works.
- For verifying the state of conservation of an artwork, in order to evaluate the dynamics of the process of deterioration, the repetition in time of such accurate measure makes it possible to monitor the changes occurring, which facilitates planning effective maintenance strategies.
- Simulation of possible restoration work and the documentation of previous restorations. Virtual recomposition of fragments can be used for pedagogical objectives and research and also serve as the basis for cost estimates needed to evaluate the feasibility and correctness of restoration work.
- Making moulds and replicas when it becomes necessary to replace sculpture and plastic works situated in the open because conserving the work entails removing it from its original location.
- Reproducing models on different scales for sale to tourists in bookstores and museum shops.
- Producing supports for packaging works of art that minimize the risks of damage when works are moved.

Within the scope of the larger problem of surveying plastic works, the study of wood sculpture assumes particular significance when referred to the non-linear ways this material behaves, given the physical nature of wood fibre, which is not homogeneous and is particularly sensitive to thermo-hygrometric variations. As is known, in order to unequivocally correlate the analysis of the causes of deterioration with the definition of adequate operative intervention, it is vital to have information gathered from interdisciplinary investigations on registration of the work's form, documentation of its consistency, and identification of the static, dynamic and climatic parameters to which it is normally subject. The elaboration of this type of data requires obtaining volumetric measurements which are accurate to a fraction of a millimetre and integrating a variety of survey techniques and investigative methodologies, as has been shown by examples developed in the D.I.C. photogrammetry laboratory in Florence, which concern problems specific to the restoration of works of art made of wood (Ostuni, 1989; Chiaverini-Ostuni, 1995).
The work presented intends therefore to verify through photogrammetry the results obtained in the modelling of structured-light projection techniques in order to refine the procedures used for acquiring digital models that will allow us to obtain global accuracy coherent with that which is consistent with the instrumentation used.

2. MEASUREMENT METHODS

Three-dimensional acquisition techniques utilized even before the advent of computer-based technique employed analogue procedures (construction of moulds), and are therefore not always applicable with objects of great value or ones, which are in an extremely poor state of conservation. Correct spatial determination was, moreover, verified on a limited number of points, making use of the principle of triangulation while everything else was left to subjective interpretation.
It is for this reason that photogrammetry, initially analogical and then numerical, has for some time represented the only survey method capable of satisfying these requirements and at the same time guaranteeing the necessary degree of accuracy of measurement.

2.2 Photogrammetry

The data derived from this type of metric investigation have all the advantages of the numerical model: profiles, contour line and DEM are obtained without contact with the work of art. The points surveyed can be interpolated by surfaces using modelling software while maintaining a distinction between acquired data and processed data. From the application of analytic photogrammetry to the surveying of sculpted surfaces (Monti, 1994), to the automatic and semi-automatic processing characteristic of digital photogrammetry (Kludas et al., 1996) is but a short step.
The problem of acquisition has been resolved with digital cameras and high-resolution scanners. The optimisation procedures used in the photogrammetric process doubtless represent an outstanding achievement in surveying works of art. For example, starting from the radiometric and geometric calibration of the unit of acquisition, inner and relative orientation, algorithms of autocorrelation to full and sub pixels, actual restitution via automatic DEM extraction and the production of orthoimages are now completely automated. However the difficulties still inherent in working with objects of this sort should lead to new considerations and suggest other perspectives. The natural evolution of

photogrammetry, to some extent thanks to the refinement of semiautomatic and automatic triangulation techniques, seems to be headed towards the total elimination of the subjective phase of representation, replacing it with assisted three-dimensional exploration within a photogrammetric block (Migliari, 1997; Dequal et al., 1999). The stereo-photographic model which has emerged makes it possible for us to move within this type of three-dimensional reality and read its coordinates directly from whatever point is collimated. Considering that this sort of model is composed by the set of oriented **images**, which make up the photogrammetric block, the process for its construction is limited to the phases of image acquisition and orientation, with significant reductions in time and expense. Although a product of this type satisfies some of the requirements listed in our premise, the need for 3D models that are ever closer to reality, shifts the focus of attention to new modes of acquisition, which have already proved useful in other sectors of application.

2.3 3D scanning systems

The system employed to obtain the result described in this article is a commercial product (Opto3D ranger, Optonet Srl, Brescia - Italy) which uses the 3d measurement method based on fringe projection. This triangulation technique previews the projection of various patterns over the measurement area, according to a given sequence, and their acquisition from one television camera angled respect to the projection direction. The deformation of the pattern acquired, after a proper processing, allows gaining one cloud of 3D points reproducing the shape of the illuminated object (Sansoni *et al.,* 1997).
By relocating the optical head with respect to the object it is possible to measure various sights, until all the visible surface of the object is covered. In order to obtain the complete model, the operation of alignment and fusion of the single 3D images can be carried out by a variety of software techniques commercially available. In our case, the software Polyworks (Innovmetric, Québec- Canada) has been used. It uses one of the various point clouds as starting reference, and performs a roto-translation of each adjacent image in order to align them to the reference. The procedure is repeated iteratively until all the images from various points of view are properly aligned.
The following phase is the merge of all aligned point clouds; the duplicated points in the superposition areas between adjacent images are selectively discarded and the remaining points are properly connected through a mesh representing the measured surface. Although an editing step usually follows this part of the processing, once the model has been aligned, any merging and editing does not involve further substantial modifications, so that a dimensional verification can be done just at the end of the alignment step.
The evaluation of possible measurement errors over the 3D model with respect to the true surface is a problem that involves different aspects. First of all an intrinsic error on the single scans is present. Since the evaluation of 3D coordinates is based on optical triangulation, the measurement uncertainty is directly dependent over the distance between the fringe projector and the video camera (baseline), and inversely dependent over the distance of the CCD from the object surface (square function).
During the following step further errors due to the alignment process have to be considered. In the alignment of two images the alignment uncertainty can be roughly considered of the same order of the intrinsic measurement error of each point cloud, if unambiguous three-dimensional features are present and the superposition area is large enough. In general, the error can be also influenced by the peculiar nature of two surfaces. For example two surfaces almost planar, where recognizable reference are lacking can produce large alignment errors, while the presence of bumps or extrusions allow to find much more easily the proper positioning of a view with respect to another one. Therefore, when the alignment involves several 3D images, the error can be propagated in unpredictable way, deteriorating the overall measurement accuracy over the whole model. Such accuracy can be estimated through the 3D modelling software using error histograms and maps as shown in Figure 1. These are generated after the alignment of a few images and can give an estimate of the performance of the system. When the systematic errors are smaller than the random errors, then images should appear interwoven together after alignment. In overlapping regions between images, large areas contributed by the same image are signs of poor calibration.
However, in order to assess the actual overall error in the final 3D model, a complementary measurement method has to be used. As demonstrated by Beraldin (1997), a technique based on a theodolite survey can be employed. Here we chose to operate through a photogrammetric survey as described in the following section.

Figure 1 - Example of a histogram of residual errors after alignment of 2 images: a) best possible calibration, b) poorer calibration.

3. CASE STUDY: THE "MADDALENA" OF DONATELLO (1455)

Within a research program financed by the University of Florence, we experimented the employment of digital 3D scanning for conservation and fruition of the Italian Cultural Heritage with significant 3D features (e.g. sculptures).
The most significant work made up to now, is the digital acquisition of the famous wooden statue of "Maddalena" by Donatello, which can be considered a hard benchmark for the technologies employed.

3.1 Generation of the 3D model

In order to create a "high fidelity" digital model, suitable for conservation of the formal properties of the masterpiece, we decided to acquire the whole statue with a measurement uncertainty of about 70 µm. On the other hand a high number of images would have been critical due to the large size of the data set to be manipulated at once in the post-processing steps. We decided therefore to generate a "skeleton" of the model with a reduced number of images with reduced accuracy (130 µm), to be used as reference for the following high-resolution step. Since in this way we used almost half the spatial resolution, we roughly reduced of 4 times the number of images necessary for obtaining a (even if not complete) closed model, reducing in this way the error propagation. The scanning process, widely described in another paper of this workshop (Beraldin et al., 2001), led in this phase at the acquisition and alignment of about 150 images organized in horizontal strips running around the statue.
The constrain imposed by a closed area such as the one corresponding to a set of images taken by moving the scanner around the object, allowed to generate a set of well aligned "belts" that have been connected vertically to obtain the final 3D model.

a)

b)

Figure 2 - 3D scanning: a) relocation of the 3D scanning system around the statue, b) 3D model

3.2 Photogrammetric measurements

The use of photogrammetry in this context has not led to restitution but has been finalised only toward examining and verifying models obtained using optic scanning. In the survey project, therefore, what was considered was taking the lowest number of photographs possible to frame the entire sculpture and remain within the range of accuracy established in advance with a relationship of base-distance of circa 1:3.
The photographs were taken with a 150mm focal length and thanks to the photogram format used (130 mm x 180 mm), with ten different points and a base of 80 cm, it was possible to cover the object along its entire height. Eight stereo models were derived which, at a distance of 2.50 meters from the object, worked out to an average scale of 1:20. The concatenation of the slightly convergent stereo models, delineates a plan with a sort of ellipse around the sculpture's vertical axis and was produced with control points placed along the sides of the statue using rigid supports aligned on its front to back axis. The collimation targets were printed on transparent acetate so that they could be easily collimated in

counterpoised models and inserted in holes that had been made on four metal panels as shown in figure 3. The accuracy in the determination of control points was ± 0.2 mm.
In every model, the determination of the system of absolute reference was further verified through the collimation, in terms of distance, of targets that had been arranged on an aluminium bar. On the rectangular-section bar, four holes were made, on which precision calibration with repeated measurements (± 0.1 mm) was performed. Circular targets larger than the holes were used to render them more visible and thereby facilitate their identification on the stereo models. The uniform illumination needed while the photographs were being taken was ensured by properly positioning lights. The orientation of the models obtained made it possible to measure the relative distances between fully identifiable key points visible in stereoscopy, which it was possible to compare with the values measured on the model obtained with three-dimensional scanning.

a)

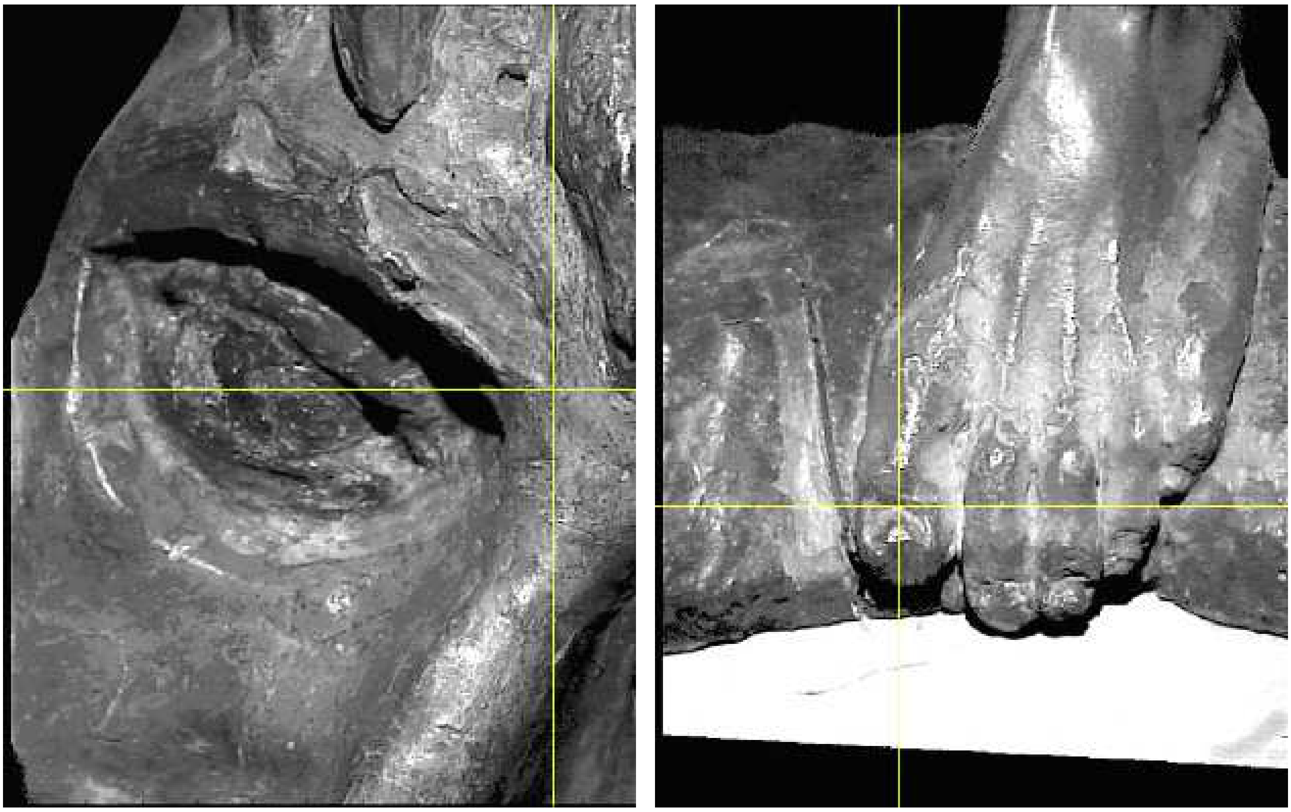
b)

Figure 3 - Photogrammetry set-up: measurement targets nearby the manufact: a) front view; b) rear view

3.3 Comparison between photogrammetry and 3D model: methods

The experiments performed with both techniques gave two set of measurements defined in a couple of reference systems different between each other. Therefore, in order to avoid the problem of aligning them, we chose to measure some distances between points clearly recognizable on both the 3D images and the metric photographs, employing as targets, features present on the statue's surface such as wood-worm holes.
As the photogrammetric system used in this case is based on manual collimation, we tried to reduce the operator selection error employing 3D scans at resolution higher than that used for the "skeleton" model, such as the metric images at the maximum optical zoom level had a scale similar to the one of the single high resolution 3D images. Also, from the latter set of scans, we chose those taken from the same direction of the photogrammetry.
Since raw 3D images have their own reference system, unrelated to the one of the whole model, we aligned each high-resolution point cloud on the "skeleton" model through the "Polyworks" software, producing in this way a roto-translation matrix for each aligned image, which allows to map the spatial coordinates of the raw image in a common reference system for the whole model.
We developed a specific piece of software to operate a pixel selection on the bitmap image associated to the point cloud, which stores the 3D coordinates and transfer them in the reference system of the model, producing also a bitmap file with a well visible target superimposed on the gray levels image. Once a couple of raw points has been selected (even from different 3D acquisitions), the same software calculates the distance between them in the model reference system. A couple of "stamped" images, as the two in Figure 4, are then passed to the photogrammetry operator for the following manual selection of the corresponding points.
A possible critical aspect in the comparison of the two measurement methods is the operator error made during selection of points. For this reason we performed 10 subsequent distance measurements between two points at the opposite ends of the statue (shown in figure 4), with both methods, obtaining a standard deviation of 0.074 mm with the 3D approach, and 0.266 mm with photogrammetry. Since the deviations obtained are limited, we decided to avoid

repeated measurement on each test point considering that every data collected may intrinsically be affected by such uncertainty.



a) b)

Figure 4 – Images generated by the point selection procedure, specifically developed for comparing 3D scans with photogrammetry: a) detail of the eye; b) detail of the foot

3. EXPERIMENTAL RESULTS AND CONCLUSIONS

All the distances measured through the two systems are described in figure 5 and reported in table 6. Some of those measurements have been repeated for few points near each other when the selection feature was ambiguous or badly defined. In this case the table report a measurement with the same number but with a different index.

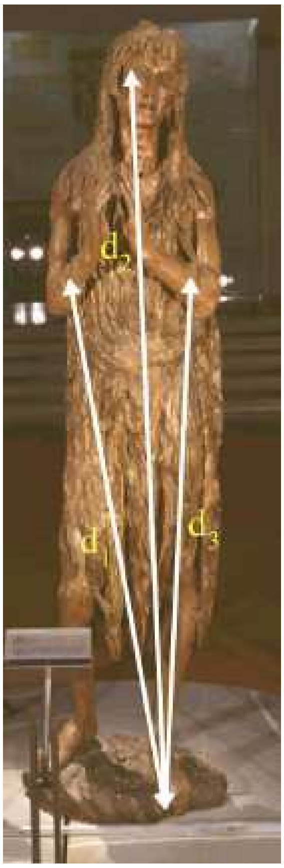
The deviations between photogrammetry and 3D model reported in the fourth column of table 6 (Δ), have been categorized according to its value. All the deviations below three times the standard deviation of the most inaccurate method (0.226 mm), have been considered equal, and the corresponding lines have been highlighted in table 6.

By observing table 6 it is evident that the distance between points belonging to the bust, as the distance between the right eye and the arms (d4 and d6), or the distance between arms (d11), have very similar values with both measurement techniques. Such agreement should be due to a good alignment that was possible thanks to reliable scans as those related with the upper part of the statue, where several well-defined features are present, and the surfaces are mainly convex and with few discontinuities. Hence the related point clouds have no significant gaps. The partial horizontal alignments leading to the upper part of the model, described as "belts" in section 3.1, are therefore precise, and permit a good positioning also along the vertical direction.

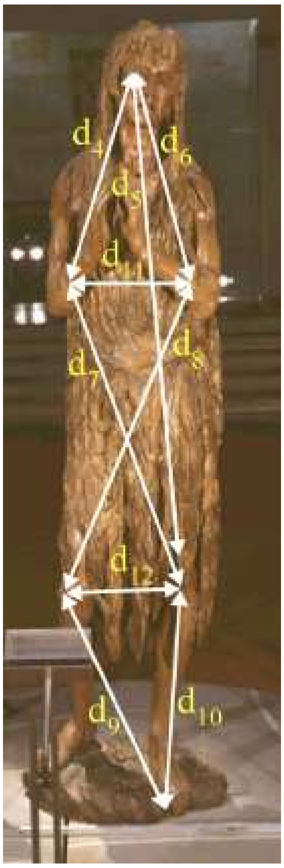
Conversely, the typical discontinuous surface of the lower part of the statue, led to fragmented scans, whose alignment was more complex and involved wider errors although the portion of overlapping surface between adjacent images was of the same order of the other scans. This is confirmed by the measurements from the right eye and the knees and the left foot (d5, d15 and d2), that emphasize a compression of the 3D model respect to the photogrammetric survey.

Another interesting data is represented by the distance between the knees (d12), that on the 3D model is wider than in the reference, probably due to the lack of locking surfaces in that part of the statue, where the two thin legs are separately aligned starting from the upper unique block.

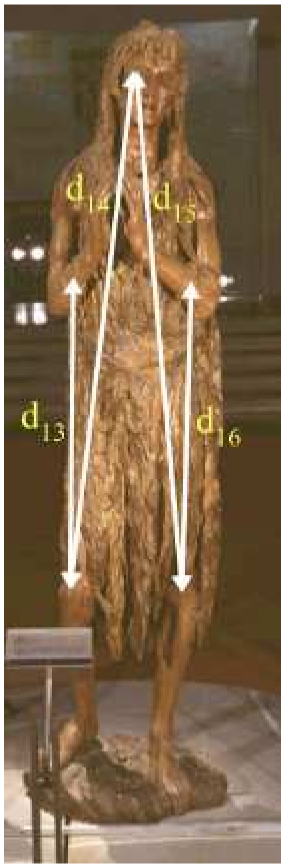
In conclusion, the photogrammetric model has been used as a reference for the 3D model thanks its better overall accuracy, and allowed to detect small dimensional deviations of the final 3D model due to alignment errors.



a)



b)



c)

Figure 5 – Images generated by the point selection procedure, specifically developed for comparing 3D scans with photogrammetry: a) detail of the eye; b) detail of the foot

	Photogrammetry (mm)	3D model (mm)	Δ (mm)
d1	1267.0	1263.6	3.4
d2 (1)	1695.1	1691.9	3.2
d2 (2)	1695.7	1691.4	4.3
d2 (3)	1643.0	1638.8	4.2
d3	1272.5	1270.8	1.7
d4	467.5	467.9	-0.4
d5	1111.2	1106.7	4.5
d6	470.8	470.6	0.2
d7	791.9	789.3	2.6
d8	765.4	764.0	1.4
d9	577.9	576.2	1.7
d10	503.0	504.1	-1.1
d11 (1)	259.0	258.4	0.6
d11 (2)	279.0	279.0	0.0
d12	258.3	262.6	-4.3
d13	717.7	717.2	0.5
d14 (1)	1171.2	1169.6	1.6
d14 (2)	1170.7	1169.3	1.4
d15 (1)	1198.3	1194.1	4.2
d15 (2)	1198.5	1193.9	4.6
d16	745.7	745.1	0.6

Table 6 – Measurement on the photogrammetry and the 3D model. The highlighted items are under the uncertainty threshold. The values with subscript indicate distance measurements repeated on couples of point different each other

On the other hand the high local accuracy attainable with the optical 3D scanning (much better than the one attainable with photogrammetry), seems to be sufficient to maintain a reasonable overall accuracy over the whole model when the scan involves uninterrupted surfaces.
But, when highly complex surfaces have to be acquired, the lack of points due to shadows and other physical constrains, may give worst alignment with significant dimensional errors. Especially in those cases, an integration of the two different techniques appears to be a proper approach for the correct data registration.

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