Registration of Arbitrary Multi-view 3D Acquisitions

Camille Simon Chane\textsuperscript{a,b}, Rainer Schütze\textsuperscript{b}, Frank Boochs\textsuperscript{b}, Franck S. Marzani\textsuperscript{a}

\textsuperscript{a}le2i, Université de Bourgogne, B.P. 47870, 21078 Dijon, France
\textsuperscript{b}i3mainz, Fachhochschule Mainz, Lucy Hillebrand Straße 2, 55128 Mainz, Germany

Abstract

To register 3D meshes of smooth surfaces we track the acquisition system using photogrammetric techniques and calibrations. We present an example digitizing a 800 mm $\times$ 600 mm portion of a car door. To increase the tracking accuracy the 3D scanner is placed in a cubic frame of side 0.5 m covered with 78 targets. The target frame moves in a volume that is approximately 1100 mm $\times$ 850 mm $\times$ 900 mm to digitize the area of interest. Using four cameras this target frame is tracked with an accuracy of 0.03 mm spatially and 0.180 mrad angularly. A registration accuracy of 0.1 mm and 2 mm is reached. This method can be used for the registration of meshes representing featureless surfaces.

Keywords: 3D imaging, close-range photogrammetry, 3D registration, multi-view registration

1. Introduction

We are interested in the registration of 3D range maps provided by fringe projection 3D digitization systems. These systems are composed of a projector and one or two cameras. The projector illuminates the surface under study with a series of predetermined patterns. The deformation of the patterns is acquired by the cameras and used to evaluate the shape of the object. Widely used commercial systems include those by Breuckmann [1] and Gom [2].

Such systems are very flexible: changing the camera, lens or other modules changes the acquisition system field of view and resolution, which can thus easily be adapted to the current context. These systems are also quite practical since a single shot digitizes a full area. By comparison, TOF (Time of flight) laser scanners require the user to manually sweep the full surface of interest with a scan line of approximately 10 cm. This is both time consuming and tedious. Furthermore, the regularity of the resulting mesh can depend on operator skills.

\begin{footnotesize}
\begin{flushleft}
Email addresses: camille.simon@u-bourgogne.fr [Camille Simon Chane],
rainer.schuetze@geoinform.fh-mainz.de [Rainer Schütze],
frank.boochs@geoinform.fh-mainz.de [Frank Boochs], franck.marzani@u-bourgogne.fr [Franck S. Marzani]
\end{flushleft}
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A drawback to fringe projection systems is that the multiple acquisitions necessary to digitize but the smallest object must somehow be registered. Typically this is done by adding targets to the surface of the object to enable a precise registration based on corresponding points. ICP or one of its variants are the most commonly used algorithms. These additional targets are necessary because many objects do not have a sufficient number of natural well-resolved features. Industrial objects tend to be smooth or composed of regular surfaces.

Unfortunately, there are many drawbacks to using targets. Not only is it time-consuming to place and remove targets from the multiple objects that we want to digitize, but there is always the possibility that a target covers a defect that we want to detect. Also, there may be cases in which we fear damaging the surface or fragile coating with the targets.

There have been recent developments in automatic 3D digitization by robot arms. In this case the known position of the robot arm guides the registration, though the object must be placed on a turntable.

Hand-held TOF laser scanners increasingly rely on optical tracking to create an accurate 3D model either using photogrammetry or using a laser tracker. A similar setup has been used to guide the registration of colored 3D data from a high precision scanner by fixing spheres to it and tracking it with a second scanner.

Photogrammetry is an accurate technique that is widely used in industrial settings, yielding a measurement precision of up to 1:200,000. In this context, the study of manufacturing processes has been based on digitizations by multiple cameras. Stereo vision has been used to measure 3D displacement and strain, based on digital image correlation. Increased accuracy is obtained using multiple stereo pairs and a bundling algorithm that takes into account the weighted uncertainty of the target detection.

Optical tracking using photogrammetric techniques has also been used to dynamically calibrate robot arms on factory floor. Two setups are possible: either a camera is fixed to the robot and observes the scene which has been covered with targets, or the robot itself is covered with targets and observed by a set of fixed cameras. It is this second setup that is better suited to be adapted to the tracking of an acquisition system for registration purposes.

We present a registration method suitable for featureless 3D data issued from fringe projection digitization systems. Our method is based on the photogrammetric tracking of the acquisition system and does not require the positioning of targets on the surface of the object under study. Our goal is to register 3D datasets with an accuracy better than half the scanner resolution.

Section first presents the principle of our technique and the current experiment. Then the materials in used are described in section while section details the necessary calibrations and the data processing. Section presents the achieved accuracy for the individual calibrations, the target-frame tracking and the full registration. Finally, we conclude in section with a few perspectives.
2. Materials and Methods

2.1. Principle

Figure 1 illustrates the principle of our technique: a set of photogrammetric cameras observe an acquisition system while it digitizes a surface. A target frame is fixed to the acquisition system to enable the precise tracking of its’ position and orientation during the measurements. Careful calibration of all the materials in use is necessary for an accurate tracking of the target frame which enables the precise registration of the data acquired by the acquisition system.

We have performed simulations to predict the accuracy with which we can track a target frame in two configurations [20]. The scope of this experiment is first to validate the results from these simulations and second to show that this setup can be used to register 3D acquisitions provided by an acquisition system fixed to the target frame. The object under study is a car door that measures approximately 1100 mm × 600 mm. Since the simulation configuration was optimized for an area of 400 mm × 800 mm, we only digitize a portion of the car door measuring approximately 800 mm × 600 mm. We slightly modify the tracking setup, compared to that defined during the simulations, to accommodate this larger area of interest. If we can reach the target tracking accuracy in this larger configuration, then there will be no difficulty reaching it in the smaller, original simulation configuration.

The smooth surface of the car door makes it a good test object: there are few salient features and this is typically the type of object where conventional registration algorithms fail. We cover the car door with un-coded photogrammetric targets that are used to evaluate the accuracy of our registration procedure. These targets are not use to guide the tracking nor the registration.

2.2. Materials

All 3D digitizations were performed using a commercial fringe projection digitization system by Gom, the Atos III. The system can be built in different field-of-view/ accuracy setups. For this study we use a 500 mm × 500 mm field of view, yielding a resolution of 0.24 mm. In this configuration the measuring distance between the Gom Atos III and the surface under study must be 760 mm. This entails that our registration accuracy goal of half the acquisition resolution is 0.12 mm spatially and 0.158 mrad angularly (the angular accuracy is calculated from the spatial accuracy and the fixed distance of 760 mm between the Atos III and the surface under study).

The characteristics of the materials used for the tracking procedure were optimized through several simulations [20]. The four 5Mpx AVT Stingray tracking cameras and are used in conjunction with an 8 mm Pentax lens. The target frame is an aluminum cube of edge length 500 mm. It is covered with 78 coded targets (see figure 2) scattered on the five faces that can be seen by the tracking cameras. Only the face through which the acquisition system acquires the surface is target-free. A hexagonal headplate is attached to the bottom of the frame so that it can be fixed to a tripod. A hexagonal plate holder inside the
cube on the bottom face is used to fix the acquisition system to the frame. An additional camera, a Nikon D300, is used for certain calibration procedures.

2.3. Calibrations

To ensure a precise tracking, all optics and objects in play must be carefully calibrated. We introduce the following coordinate systems, linked to the materials in use and illustrated figure 2:

- $C_S$, $(O_S, \vec{x}_S, \vec{y}_S, \vec{z}_S)$ is the coordinate system linked to the 3D scanner.
- $C_F$, $(O_F, \vec{x}_F, \vec{y}_F, \vec{z}_F)$ is the coordinate system linked to the target frame.
- $C_{Ci}$, $(O_{Ci}, \vec{x}_{Ci}, \vec{y}_{Ci}, \vec{z}_{Ci})$ are the coordinate systems linked to each tracking camera. $O_{Ci}$ is the optical center of the camera, $(\vec{x}_{Ci}, \vec{y}_{Ci})$ define the image plane, $\vec{z}_{Ci}$ is collinear to the optical axis.
- $C_0$, $(O_0, \vec{x}_0, \vec{y}_0, \vec{z}_0)$ is the world coordinate system.

We now describe the necessary calibrations and how they are performed. The following notations will be used throughout this section: $A|_{C_U}$ are the homogeneous coordinates $(x_A, y_A, z_A, 1)$ of point $A$ in coordinate system $C_U$. We define $T_{C_U,C_V}$ the transformation matrix between two coordinate systems $C_U$ and $C_V$ such that $A|_{C_V} = T_{C_U,C_V} \cdot A|_{C_U}$.
Figure 2: Target frame is an aluminum cube covered with 78 coded targets. The acquisition system is fixed inside the cube. The car door we digitize is visible in the background.

Figure 3: Coordinate systems defined for the tracking procedure.
Internal orientation (I.O.) of the photogrammetric cameras. The calibration of the tracking cameras is performed by taking close to a hundred images of a calibration plate from various points of view. The calibration plate is covered with coded and uncoded targets and two distances are precisely known. From this we can measure the internal camera parameters such as focal length, principle point offset and lens distortion. The four tracking cameras are placed side by side and observe the same area so that they can be calibrated together. Previous experience has taught us that the internal orientation can stay stable for over a week if the cameras are handled with care during this time frame. We thus perform the interior orientation a few days before the acquisitions.

Internal orientation of the acquisition system. It is also necessary to know the distortions introduced by the acquisition system. In the case of the Atos III there is a specific calibration procedure to perform and the output data is automatically corrected by the acquisition software.

Calibration of the target frame. The calibration of the target frame is performed by taking over one hundred images of this cube surrounded by a scale bar and additional targets. We can then define $C_F$ and know the position of each coded target in this coordinate system.

Orientation of the acquisition system with respect to the target frame. To know the position of the acquisition system in the system defined by the target frame, we proceed in three steps:

1. Fix the acquisition system to the target frame.
2. Use the acquisition system to digitize another target-covered 3D object.
3. Take over fifty photos of the target frame and the additional 3D object.

We associate a coordinate system $C_{temp}$ to the 3D object. Step 2 provides us with $T_{S, temp}$, which describes the position and orientation of the 3D object in $C_S$. Similarly, step 3 provides us with $T_{F, temp}$, the position and orientation of the 3D object in $C_F$ previously defined.

We can thus easily calculate the transformation between $C_S$ and $C_F$:

$$T_{C_F, C_S} = T_{C_F, C_{temp}} \cdot (T_{C_S, C_{temp}})^{-1}. \quad (1)$$

Exterior orientation (E.O.) of the photogrammetric cameras. Once the tracking cameras have been positioned to observe the area in front of the surface under study, we can measure their relative position and orientation. This is done by acquiring approximately eighty images of a scale bar in various positions and orientations, simultaneously by the four calibrated cameras.

The position and orientation of the other three cameras are measured with respect to the first. We define the world coordinate system as the coordinate system of the first tracking camera to be the world system: $C_0 = C_{C1}$. 

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2.4. Data processing

We now have the necessary data to register the meshes. Each acquisition provides us with the coordinates of a group of surface points in the sensor system, $A|_{C_S}$. The simultaneous tracking provides us with $T_{C_0,C_F}$. The known interior orientation of the tracking cameras and their relative orientation ensures that $T_{C_0,C_F}$ is sufficiently accurate.

We can thus calculate $A|_{C_0}$, the coordinates of the surface points in the world system using:

$$A|_{C_0} = T_{C_0,C_F} \cdot T_{C_F,C_S} \cdot A|_{C_S}.$$  \hspace{1cm} (2)

Tracking and calibration software. All photogrammetric processing relies on two pieces of software: Tritop Deformation Software [21] and i3AxOri, a lab-developed software based on the AxOri photogrammetric bundle adjustment library [22][23]. This library is often used for high precision photogrammetric bundle adjustment [24][25]. Tritop is used to recognize the coded and uncoded points in the images and to compute a first assessment of the position of the cameras. This data is then exported to i3AxOri in which we have more flexibility and control on what we want to compute given our input parameters.

Evaluating the registration accuracy. The Gom Atos III acquisition software recognizes any coded or uncoded target present in the scene. In our case the full surface is covered with over 48 uncoded targets of diameter 6mm. They are manually numbered and recognized in each mesh. This step would have been unnecessary if we had used coded targets, but such targets are larger and we wanted to minimize the disruption these targets incurred on the digitization of the surface. 8 to 16 targets are visible in each mesh. It is possible to export the list of the targets visible in each mesh. We thus have $A_{ij}|_{C_S}$, the coordinates of target point $j$ from mesh $i$.

Using equation (2), we calculate $A_{ij}|_{C_0}$ for all targets of all meshes. For every target $j$ we now calculate

$$D_{(i,k)j} = A_{ij}|_{C_0} - A_{kj}|_{C_0}$$  \hspace{1cm} (3)

for every pair of meshes $(i,k)$ where target $j$ is visible. If the registration were perfect, the result of this subtraction would be a null vector. Since the registration is imperfect, the $D_{(i,k)j}$ provide us a measure of the accuracy of the registration.

3. Results and Discussion

The bulk of the calibrations were performed the same day as the acquisitions by two people. Only the calibration of the tracking cameras was performed a few days earlier. The order and duration of the calibrations and acquisitions is given in table 1.

In section 3.1 we quickly present the accuracy achieved for the individual calibrations (steps 1 to 4 and 6). Then, in section 3.2, we analyze the accuracy
Table 1: Order and approximate duration of the acquisitions and calibrations.

<table>
<thead>
<tr>
<th>Acquisition or calibration</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Tracking cameras interior orientation (three days in advance)</td>
<td>1</td>
</tr>
<tr>
<td>2. Target frame calibration</td>
<td>0.5</td>
</tr>
<tr>
<td>3. Acquisition system interior orientation</td>
<td>0.5</td>
</tr>
<tr>
<td>4. Target frame to acquisition system orientation</td>
<td>1</td>
</tr>
<tr>
<td>5. Simultaneous digitization of the car door and tracking of the target frame</td>
<td>1</td>
</tr>
<tr>
<td>6. Tracking cameras exterior orientation</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2: Individual calibrations accuracy compared to expected accuracy from the simulations.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Simulations realistic</th>
<th>Simulations best</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking cameras I.O.</td>
<td>0.055</td>
<td>0.1</td>
<td>0.033 pixel</td>
</tr>
<tr>
<td>Target frame calibration</td>
<td>0.015</td>
<td>0.05</td>
<td>mm</td>
</tr>
<tr>
<td>Target frame to acquisition system orientation</td>
<td>0.025</td>
<td>—</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>0.054</td>
<td>—</td>
<td>mrad</td>
</tr>
<tr>
<td>Tracking cameras E.O.</td>
<td>0.017</td>
<td>0.03</td>
<td>0.01 mm</td>
</tr>
<tr>
<td></td>
<td>0.030</td>
<td>0.02</td>
<td>0.04 mrad</td>
</tr>
</tbody>
</table>

with which we track the target frame. Finally, section 3.3 describes accuracy of the global registration. Section 3.4 characterizes the stability of the calibration and the repeatability of the tracking. All accuracy values (simulations and measurements) are given at $2\sigma$.

### 3.1 Individual calibrations

The accuracy of the individual calibrations described in section 2.3 is given in table 2. When available, they are compared with the expected accuracy of the simulations. The simulations were run with two levels of noise: low noise, corresponding to a best-case-scenario and higher noise, corresponding to a realistic situation.

The accuracy of the tracking cameras interior orientation is between the results for the best-case and realistic simulations. Since the interior orientation accuracy directly influences the accuracy of the tracking cameras exterior orientation, it is not surprising that this last value is also between the best and realistic simulation results.

The target frame calibration is performed with much higher accuracy than expected. However, this value does not take into account the deformation that
the aluminum cube may undergo due to temperature variations for example.

The target frame to acquisition system orientation introduces a non negligible amount of errors. A more accurate frame to acquisition system calibration can be performed by performing the calibration with several relative positions of the frame and acquisition system with respect to the calibration target-covered object.

3.2. Tracking the target frame

Thirteen acquisitions were performed with the 3D digitization system. They are numbered M0 to M12 and provided as supplementary material in PLY format. The relative position and orientation of the four tracking cameras and the target frame for each measurement is illustrated figure 4.

This subsection examines the accuracy with which we evaluate the position of the target frame in the world coordinate system for each position. This is described as $T_{C_0,C_F}$ for a given measurement. The accuracy of the tracking of the target frame depends on the accuracy of the tracking cameras interior and exterior orientation calibrations, as well as the target frame calibration. Given the results of the previous section, we can not expect the frame tracking accuracy to reach the levels of the best-case scenario simulations.

Table 3 shows the position and orientation of the frame given by $T_{C_0,C_F}$, as well as the accuracy of these parameters. These accuracy parameters are compared with the simulation results from the realistic scenario in figure 5.
Table 3: Results of the frame tracking. Position and orientation values are given as an indication and significantly rounded.

<table>
<thead>
<tr>
<th></th>
<th>Position</th>
<th>Orientation</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X (mm)</td>
<td>Y (mm)</td>
<td>Z (mm)</td>
</tr>
<tr>
<td>M0</td>
<td>133</td>
<td>−95</td>
<td>−1440</td>
</tr>
<tr>
<td>M1</td>
<td>139</td>
<td>−204</td>
<td>−1525</td>
</tr>
<tr>
<td>M2</td>
<td>321</td>
<td>−259</td>
<td>−1440</td>
</tr>
<tr>
<td>M3</td>
<td>267</td>
<td>−404</td>
<td>−1595</td>
</tr>
<tr>
<td>M4</td>
<td>266</td>
<td>−405</td>
<td>−1594</td>
</tr>
<tr>
<td>M5</td>
<td>261</td>
<td>−306</td>
<td>−1515</td>
</tr>
<tr>
<td>M6</td>
<td>250</td>
<td>−108</td>
<td>−1362</td>
</tr>
<tr>
<td>M7</td>
<td>243</td>
<td>95</td>
<td>−1222</td>
</tr>
<tr>
<td>M8</td>
<td>117</td>
<td>−219</td>
<td>−1567</td>
</tr>
<tr>
<td>M9</td>
<td>57</td>
<td>88</td>
<td>−1355</td>
</tr>
<tr>
<td>M10</td>
<td>74</td>
<td>−214</td>
<td>−1590</td>
</tr>
<tr>
<td>M11</td>
<td>117</td>
<td>−258</td>
<td>−1600</td>
</tr>
<tr>
<td>M12</td>
<td>−73</td>
<td>−203</td>
<td>−1687</td>
</tr>
</tbody>
</table>

This figure clearly shows that the spatial accuracy of the results is hardly never as good as expected from the simulation results. The angular accuracy, however, is always better or equal to the value reached during the simulations.

Compared to the target tracking accuracy fixed by our registration goal (0.12 mm spatially and 0.158 mrad), the results are quite satisfying. The target spatial accuracy is always more than three times better than the target value. The angular accuracy is insufficient only for position M7. In this case, the angular accuracy is 10% worse than expected.

It is not surprising that M7 is the least well-tracked position: as figure 4 shows, this position of the frame is slightly off-center compared to the other positions. This position is partially out of the simulation bounds.

Globally, this data validates our realistic simulations for the angular accuracy, which is the critical parameter to reach or target registration accuracy.

3.3. Registration

The full registration of all 13 positions is illustrated figure 6. These registered meshes are also given in PLY format as supplementary material (labeled M0r through M12r). When we interact with the full mesh, the registration seems seamless. Our goal however, is to create a 3D model that is not only visually satisfying, but that can also be used for metrology purposes.

We identify the shared target points between every pair of meshes and calculate $D_{(i,k)}$ from equation 3 for every pair of meshes $(i, k)$ where target $j$ is visible. Table 4 shows the average over $j$ of $\| D_{(i,k)} \|$ for all pairs of meshes. This value varies between 0.097 mm and 2.376 mm with an average at 0.889 mm.
Figure 5: Spatial accuracy (blue squares) and angular accuracy (green circles) of the tracking for all 13 acquisition positions compared to the simulation results of the realistic scenario (red line). The best-case scenario would mandate that the spatial accuracy is better than 0.014 mm and the angular accuracy better than 0.100 mrad.

Figure 6: All 13 meshes registered in a single view.
We reach our target registration accuracy of 0.12mm for only two mesh-pairs: between M0 and M1 (0.10mm) as well as between M4 and M5 (0.12mm). This is partially due to the fact that M0, M1, M4 and M5 are among the most accurately tracked measurements (see figure 5). However, a high tracking accuracy for two positions does not necessarily result in a high registration accuracy. The pairwise registration between M0 or M1 on one side and M4 and M5 on the other size is more than seven times worse than M0 to M1 or M4 to M5.

Table 3 shows that the frame orientation hardly changes between M0 and M1, as well as between M4 and M5, though there is a translation of over 10cm in both cases. This suggests that the accuracy acquisition system and frame are not as tightly fixed as we need them to be: changing the frame orientation slightly changes the position of the acquisition system in frame, resulting in an unprecise registration. The fact that the registration accuracy between M0–M4, M1–M4, M0–M5 and M1–M5 is almost the same (0.86mm or 0.87mm) confirms this interpretation. The bulk of this registration error seems to be a fix error resulting from the unstable position of the acquisition system in the tracking frame.

This also explains why succeeding measurements generally have a better registration accuracy: the position of the acquisition system has not moved as much in the frame. The exceptions to this are always cases in which the orientation changes significantly between two consecutive measurements (M10 to M11, or M11 to M12).

3.4. Stability and Repeatability

The stability of the calibrations and the repeatability of the tracking accuracy measurements

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Table 4: Mean point to point distance between the measurements in mm. The number of points shared by each pair of measurements is given in parenthesis.

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
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<th>M10</th>
<th>M11</th>
<th>M12</th>
</tr>
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<tbody>
<tr>
<td>M0</td>
<td>0.12</td>
<td>0.59</td>
<td>0.68</td>
<td>0.86</td>
<td>0.87</td>
<td>0.83</td>
<td>0.81</td>
<td>1.64</td>
<td>0.91</td>
<td>1.17</td>
<td>0.58</td>
<td>1.60</td>
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<tr>
<td></td>
<td>(9)</td>
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<tr>
<td>M1</td>
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<td>0.67</td>
<td>0.86</td>
<td>0.87</td>
<td>0.87</td>
<td>0.79</td>
<td>1.59</td>
<td>0.92</td>
<td>1.10</td>
<td>0.68</td>
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<td>(3)</td>
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<td>0.65</td>
<td>0.61</td>
<td>0.47</td>
<td>0.36</td>
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<td>0.99</td>
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<td>—</td>
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<td>0.54</td>
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<td>M4</td>
<td>0.10</td>
<td>0.33</td>
<td>—</td>
<td>0.81</td>
<td>0.51</td>
<td>0.57</td>
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<td>M5</td>
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<td>0.84</td>
<td>0.50</td>
<td>0.57</td>
<td>1.60</td>
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4. Conclusion and Perspectives

We have shown that it is possible to register various independent 3D meshes of a smooth surface by tracking the acquisition system using photogrammetric techniques.

We register thirteen 3D meshes representing a 800 mm × 600 mm portion of a car door. The registration is based on the tracking of the 3D digitization fringe projection system using four cameras. The 3D scanner is placed in a cubic frame of side 0.5 m covered with 78 targets. During the digitization, this target frame moves in a volume that is approximately 1100 mm × 850 mm × 900 mm. It is tracked with an accuracy of 0.03 mm spatially and 0.180 mrad angularly. The final registration accuracy is 0.1 mm and 2 nm. Though there are some improvements that must be performed to ensure the best registration accuracy, the method is promising for the registration of meshes representing featureless surfaces.

The achieved accuracy is highly dependent on the accuracy of the various calibration steps. These calibrations are time-consuming, yet the full setup, calibration and acquisitions can be performed in a single day for on-site measurements. If the acquisitions are performed on factory floor in a fixed setup, these calibrations must only be performed once in a while.

We have shown that it is possible to register the datasets with an accuracy of half our acquisition system resolution (0.12 mm) in very specific cases. To achieve this registration accuracy for all positions, the overall stability of the setup must be improved. In particular, the acquisition system must be more tightly fixed to the target frame. In practice, there is no obvious way to perform this improvement given the acquisition system fixtures.

The current registration could be followed by a content-based optimization step. In the current configuration, the results would be very good, due to the targets, though they were meant only as an evaluation tool. However, in smooth, featureless configurations, this could still improve the registration accuracy until the target frame to acquisition system fixture is improved.

To further improve the tracking accuracy the target frame should be changed. It is currently made of aluminum profiles, which is convenient for rapid prototyping. Since aluminum has a relatively high thermal expansion coefficient, the target frame is sensitive to temperature changes. Now that the technique has been validated, a better target frame made of carbon should be designed.

Since the registration accuracy is independent from the content of the data, there is no need for the for the 30 to 40% overlap necessary in ICP and other feature-based techniques.

This registration technique can be adapted to larger volumes. Simulations and first tests have shown that it is possible to digitize a bigger object (approximately 2m × 1.5m) with comparable tracking accuracy using six tracking cameras instead of four.

The tracking accuracy is independent of the type of acquisition system in use. As such, this technique can also be extended to multi-modal registration. Not only can we register data from various 3D sensors, but using this technique
it is also possible to project 2D data from other optical sensors (thermal, infrared, multispectral) of the 3D meshes. Integrating data from complementary techniques can greatly ease surface inspection.

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