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Evaluation of Geometric Registration Methods for Using Spatial Augmented Reality in the Automotive Industry

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Abstract

Spatial augmented reality is especially interesting for the automotive industry, because in the production process of a car a lot of virtual content and also real objects are used. Therefore, the virtual content can be directly projected onto the real object to combine the advantages of the real and virtual world. One important issue for the usage of spatial augmented reality in automotive processes and applications is that the virtual content has to be projected with a very high accuracy onto the real object, because decisions are made on the basis of the projection. Therefore, we present in this article a new method for the evaluation of geometric registration techniques which align a projector to a real object. Additionally, we use this proposed method to evaluate existing geometric registration techniques. Furthermore, we present a new application where a projector is used to support the design process of a new car.

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.3]: Picture/Image Generation Image Processing and Computer Vision [I.4.8]: Scene Analysis Image Processing and Computer Vision [I.4.9]: Applications

1. Introduction

The automotive industry uses a lot of virtual content for designing, developing and assessing new components of a car. This virtual content is traditionally viewed on a standard monitor or projection wall. However, real objects are still used and preferred in many steps of the production process. The reason is that real objects are somewhat more intuitive than a presentation on an ordinary display. The user can walk around the object and can focus or concentrate on different aspects of the object with the eyes.

Especially, when a new car is designed, then a real object made of clay is used to create the shape. The created shape of the car is compared to virtual content which can represent different components of the car like front lights, the engine or a virtual 3D model of the shape. This is an important step in the production process of the car, because the comparison is used to see e. g. if specific components fit into the designed shape or a collision occurs with the surface. The results are used to adjust specific components, so that all components fit together. This is done by measuring the real object with structured light techniques or a laser scanner. The measured shape is then compared to the virtual content by computing the distance between the real and measured data. The results are visualized in so-called difference plots. An example for such a plot can be seen in figure 1(b,c). One problem in this procedure is that the computed difference plots are viewed on a monitor and thus, it is time-consuming to exactly identify for every point of the plot the corresponding area on the real object.

Nowadays, it is also possible that projectors are geometrically aligned to a real object and are used to project the virtual content directly onto the surface. Thus, the difference plots can be directly viewed on the real object. One important issue for this projection is that the virtual content is projected with a very high accuracy, so that the difference plots lie on the correct positions of the real object. This is a very important aspect, because decisions are made on the basis of the projected virtual content.

1.1. Related work

There is a lot of related work which discusses the geometric registration of a projector to a real object. An

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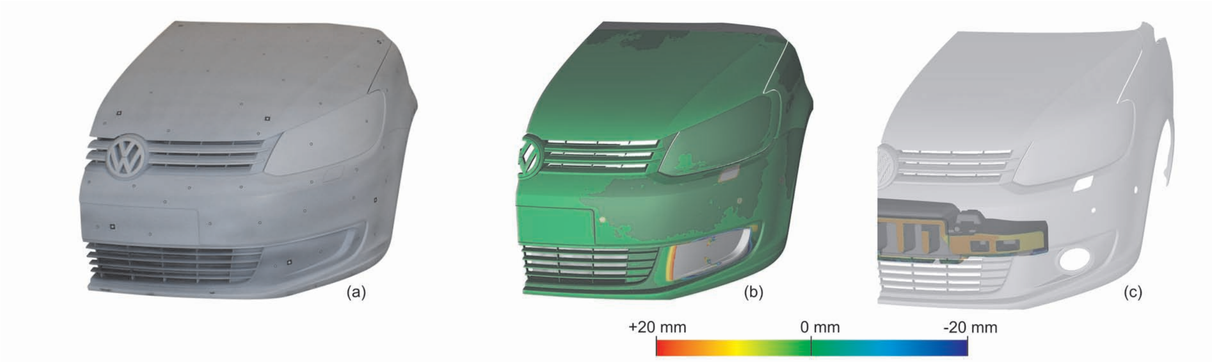


Figure 1: *Real Object and computed fictional difference plots: (a) Real front of the Touran (b) Fictional difference plot to a virtual shape; (c) Fictional difference plot for a front element of the car which collides with the measured shape.*

overview about projector-camera systems and different geometric registration techniques was presented by Bimber et al. [BIWG08]. The geometric registration of a projector to a real object without a camera was introduced by Raskar et al. [RWLB01], where a projector was used to augment real objects with virtual content. For this purpose, the 3×4 perspective projection matrix was computed, which describes the relation between the projector and the real object. The correspondences for the computation of the projection matrix are determined by finding the projector pixels which illuminates known 3D coordinates on the real object (Raskar et al. [RWLB01], Bimber et al. [BGWK03]). For this purpose, a cross-hair, with the center at a specific pixel of the projector, is displayed onto the real object. The center of the cross-hair is then moved till the corresponding 3D coordinate is illuminated. A very similar technique is used by Low et al. [LWLF01] , but instead of determining the pixel of the projector, which illuminates known 3D coordinates, the coordinates from certain illuminated projector pixels are measured with a tracking device. The techniques, just mentioned, do not consider optical distortions of the projector, which can be computed by projecting e. g. a checkerboard pattern onto a known geometry from different views. The estimated distortion parameters can then be used to compute a displacement map, which predistorts the projection image before the perspective projection matrix is computed (Menk and Koch [MK10]).

Other approaches use a camera to determine the geometric relationship between the projector and the real object. In this case, the camera is aligned to the real object and then the transformation from the camera to the projector is computed. This transformation can be described by a rigid 3D transformation (Raskar et al. [RBY*99]) or a 2D mapping between camera and projector pixels. The 2D mapping can be described e. g. using linear transformations (Chen et al. [CSWL02]), a piecewise linear approach (Yang et al. [YGH*01]), a piecewise approach with second order polynomials (Grossberg et al. [GPNB04]), bezier-patches (Bhasker et al. [Bha07]) or detecting every projector pixel in the camera image (Chang [Cha03]). The correspondences can be created by projecting circles with a gaussian distribution of intensity, a checkerboard pattern or structured light e. g. gray-coded patterns. An overview about different codification strategies for structured light was presented by Salvi et al. [JPB04].

1.2. Our contribution

The geometric registration of a projector to a real object is discussed by the authors mentioned in the last section, but there are no statements about the overlay accuracy which is achieved by the different methods on the real object. Particularly, it is not clear if a projector should be geometrically registered with or without a camera or non-linear distortions of the projector should be taken into account. Additionally, there is no method proposed, which can compare the different techniques to each other.

For this purpose, we present a new method for the evaluation of different geometric registration techniques. This method uses the projector to display coded markers directly onto the real object. The positions of the projected markers are then measured and their deviations to the correct virtual positions can be compared between the different geometric registration techniques.

We use this method to evaluate existing geometric registration techniques and show which ones are suitable for a scenario in the automotive industry where a projector displays virtual content onto a real object. Additionally, we use suitable techniques in a new application to visualize difference plots directly on a real object.

Section 2 presents the geometric registration techniques and their implementation, which are used for our evaluation. Then, the proposed method for the evaluation of the different techniques is described in section 3. The results of our evaluation are discussed and presented in section 4. Additionally,

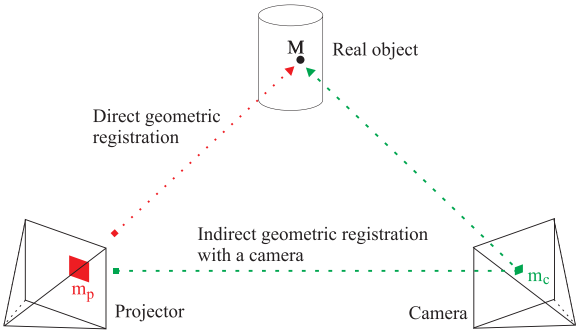


Figure 2: *Direct (red) and indirect (green) geometric registration of a projector to a real object.*

these results are then used for a new application in the automotive industry (section 5). Conclusions and possible future work is described in the last section 6.

2. Geometric registration

Geometric registration determines the relationship between the different components and their corresponding coordinate systems. The projector has to be geometrically registered to the real object for projecting correct aligned virtual content. Additionally, when the geometry of the projection surface and that of the virtual content are different, then the projection has to be shown geometrically undistorted to a specific viewing position. For this purpose, in many applications the viewpoint of a camera is adopted as the later view of an observer (Bimber et al. [BEK05]). In our scenario the difference plot shows the distance from an element to the shape of the real object. This distance is visualized directly on top of the real object. Therefore, it is also sufficient, when only the projector is geometrically registered to the real object and it is not necessary in this case that a viewpoint for an observer is determined.

Every geometric registration technique computes transformations or mappings, so that the relationship between a projector pixel m_p and a 3D point M of the real object can be described. When a camera is used then this relationship can also be described by computing the transformation from a projector pixel m_p to a camera pixel m_c and then the transformation from m_c to the 3D point M, which is shown in figure 2. The next subsections describe the different geometric registration methods and our implementation. Section 2.1 describes the direct geometric registration of a projector to a real object without the consideration of non-linear distortions. This model is extended in section 2.2 where the intrinsic parameters of the projector are precomputed. Section 2.3 describes the indirect geometric registration with a camera using a rigid transformation or a 2D mapping. These methods are then used for the evaluation in section 3.

2.1. Direct geometric registration

The relationship between the real object and the projector is computed by finding the projector's extrinsic and intrinsic parameters without distortion parameters. The projector can be treated as the dual of a camera and therefore the pinhole model can be used (Raskar et al. [RWLB01]). The parameters of this model can be represented by a 3 × 4 perspective projection matrix P, which describes the relation between a projector pixel m_p and the corresponding 3D point M. This is expressed with homogeneous coordinates $\tilde{m}_p$ and $\tilde{M}$ in equation 1, where ρ is the projective scale.

$$\rho \cdot \tilde{m}_p = K \cdot \begin{pmatrix} R & C \end{pmatrix} \cdot \tilde{M} = P \cdot \tilde{M} \qquad \rho \in \mathbb{R}_+ \backslash \{0\} \qquad (1)$$

P consists in this case of a 3 × 3 rotation matrix R, a 3 × 1 translation vector C and a 3 × 3 matrix K, which describes the intrinsic parameters of the projector without distortion parameters. This matrix can be determined with correspondences between pixels of the projector and 3D coordinates of the real object. We determine the correspondences by moving a cross-hair to known 3D coordinates as shown in figure 3(a) and use the *direct linear transformation* (DLT) method for the computation of the matrix P (Hartley and Zisserman [HZ04]).

2.2. Precomputation of intrinsics parameters

The method, just described, does not account for non-linear distortions caused by the optics of the projector. Therefore, equation 1 is extended with a model which accounts for these distortions (Menk and Koch [MK10]). We use the OpenCV library which estimates the coefficients (k_1, k_2, p_1, p_2) of the distortion model described in equation 2 by applying the algorithm proposed by Zhang [Zha00]. $(x,\, y)$ are the projector coordinates before and $(x_d,\, y_d)$ the coordinates after distortion.

$$\begin{aligned} x_d &= x + xc + 2p_1xy + p_2(r^2 + 2x^2) \\ y_d &= y + yc + 2p_2xy + p_1(r^2 + 2y^2) \qquad (2) \\ r &= \sqrt{x^2 + y^2} \qquad c = (k_1r^2 + k_2r^4) \end{aligned}$$

The intrinsic parameters of the matrix K and the distortion coefficients of the used projector are computed from 2D to 3D correspondences. The necessary correspondences are created by detecting the corners of a projected checkerboard pattern on a known geometry in multiple images taken by a calibrated camera, whereas the projector is moved to different positions between the images. These detected points are then transformed to 3D space by estimating the rotation and translation (pose) of the camera and computing a perspective transformation. The camera pose can be estimated with a number of 2D to 3D correspondences and is a common task in computer vision (Hartley and Zisserman [HZ04]).

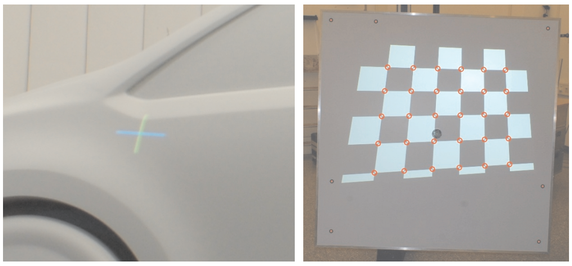

(a) (b)

Figure 3: *(a) Projected cross-hair, which is shifted onto known 3D coordinates; (b) Image with detected points, which is used to determine the intrinsic parameters of a projector, taken by a calibrated camera.*

The correspondences are created by detecting measured reference points on the projection geometry, which is done by an edge detection and an additional ellipse fitting algorithm.

The computed coefficients for the radial and tangential distortion of the projector are then used to derive a displacement map, which is applied as a pixel shader before projection. Figure 3(b) shows an image, which is used for the calibration of the projector. In this image the corresponding detected reference points and corners of the checkerboard are marked.

Note that the projector is again geometrically registered to the real object by shifting the cross-hair to known 3D coordinates. In contrary to the direct geometric registration method described in section 2.1, the projected cross-hair is predistorted with the computed displacement map. Additionally, the intrinsic parameters in the matrix K of equation 1 are known and therefore only the 3×3 rotation matrix R and the 3×1 translation vector C have to be determined, which is done by using the DLT.

2.3. Indirect geometric registration with a camera

The relationship between a projector and a real object can also be established by computing the transformation from a projector to a camera, where the camera is additionally registered to the real object. This is shown in figure 2 and is called indirect geometric registration in this article. Note that we use a calibrated camera and undistort the camera images before the pose of the camera is computed (Hartley and Zisserman [HZ04]). The transformation from the projector to the camera can then be described with a rigid transformation or a 2D mapping, which is discussed in the next subsections 2.3.1 and 2.3.2. The advantage of the geometric registration with a camera is that the necessary correspondences for the estimation of the camera pose and the transformation to the projector can directly be detected in the camera images. Thus, no projected cross-hair has to be manually moved to known 3D coordinates.

2.3.1. Rigid transformation

The rigid transformation can be computed by estimating the rotation R_P and translation C_P of the projector, when the camera has a known translation C_C and rotation R_C or vice versa (Raskar et al. [RBY*99]). Like mentioned above, this can be done with a number of 2D to 3D correspondences. For this purpose, we project a checkerboard pattern to our planar calibration board, which is shown in figure 3(b) and take an image with a calibrated camera. Since the rigid transformation should only consist of a rotation R and translation C, we project a predistorted projection image onto the board. The information for the predistortion are computed as described in section 2.2. These correspondences are then used to estimate the pose of the projector. Additionally, the pose of the camera is estimated with the measured reference points on the board. The rigid transformation from camera to projector is then computed with equation 3.

$$C = C_P - C_C \qquad R = R_P \cdot R_C^T \tag{3}$$

The rigid transformation is then used to compute the pose of the projector when only the rotation and translation of the camera are known. Note that a predistortion of the projection image is still necessary when virtual content is displayed onto the real object.

2.3.2. 2D Mapping

If the relation from projector to camera is described with a 2D mapping then the intrinsic parameters of the projector does not need to be computed, because the projector pixels are directly detected in the camera image. Therefore, the mapping accounts for the non-linear optical distortions of the projector and a projection image does not need to be predistorted. The correspondences for the mapping are created by detecting the projector pixels in the image plane of the camera. Note that, for this purpose, the transformation between projector and camera does not need to be computed.

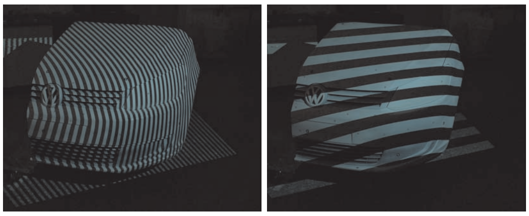


Figure 4: *Projection of two gray-coded patterns which are, besides other patterns, used for the detection of the projector pixels in the camera image.*

As mentioned in section 1.1, there are a lot of methods how the 2D mapping from projector to camera coordinates can be described. The number of used correspondences and the decision for a specific model is a trade-off between accuracy of the geometric registration and computational effort. Since in our scenario a very high accuracy is necessary, we detect all projector pixels and do not use a specific model e. g. a second-order polynomial. The projector pixels are detected by using the LUMA algorithm which uses a gray code to temporally encode the projector pixels in a number of patterns which are captured with a camera (Chang [Cha03]). The detection is started with the coarsest resolution of the captured gray-coded patterns and the position of the projector pixels are computed by taking the average from a number of detected candidates. Figure 4 shows two images taken by a calibrated camera, where the projector displays two of the gray-coded pattern.

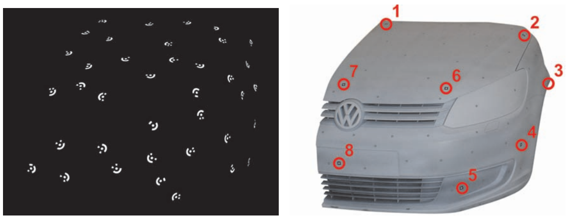
3. Evaluation method

This section describes the evaluation method which is used for the comparison of the different geometric registration techniques. The accuracy for a geometric registration of a camera or projector is often defined in terms of the reprojection error. The reprojection error has the disadvantage that it only describes the deviation according to the references which are already used for the geometric registration. Additionally, when the projector is geometrically registered with a camera, then the reprojection error of the camera gives no clue about the accuracy of the projected virtual content. This can be seen in the results which are shown in section 4.

Therefore, we present a new approach where the different geometric registration techniques are compared by determining positions of projector pixels directly on the real object. Our idea is to project a virtual 3D model, with coded markers at specific positions, onto the real object and then to use an optical measurement system to detect their real 3D coordinates. A projection image of the virtual 3D marker model, as shown in figure 5(a), is rendered according to the corresponding geometric registration technique. Note that the coded markers are virtually aligned on top of a measured 3D shape of the real object and, thus, the measured centers of the projected markers can be directly compared to their virtual position. The deviation between the virtual and real positions are computed and then used for the evaluation. The proposed method has the big advantage that it gives a direct statement about the accuracy of the geometric registration on the real object in millimeters and not in pixels as in case of the reprojection error. The evaluation is carried out with the following geometric registration techniques:

1. Direct geometric registration of projector
    (i) No consideration of non-linear distortions and no predistortion of projection image (section 2.1)
    (ii) Precomputation of intrinsic parameters and predistortion of projection image (section 2.2)
2. Indirect geometric registration with a camera
    (i) Rigid transformation with predistortion of projection image (section 2.3.1)
    (ii) 2D Mapping with gray code (section 2.3.2)

In figure 6 one can see the setup which is used for the evaluation of the different geometric registration techniques. Note that the components do not change their positions for the complete evaluation and only different geometric registration techniques are used. The geometric registration of both the camera and the projector is done with the same reference points, which are shown in figure 5(b). Thus, in case of the indirect geometric registration method, the camera is geometrically registered by detecting the reference points in the camera image. When the projector is directly registered to the real object, then the projector pixels are determined which illuminate the reference points. The next section describes the result of our evaluation where the different geometric registration techniques are compared by our proposed method.



(a) (b)

Figure 5: *(a) The virtual 3D model with coded markers which are projected onto the real object. (b) Real object with the eight correspondences which are used for the geometric registration of the camera and the projector.*

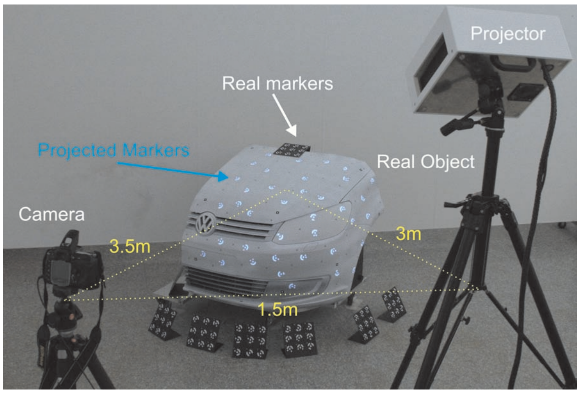


Figure 6: *Setup for our evaluation which is used for determining the accuracy of the different registration techniques.*

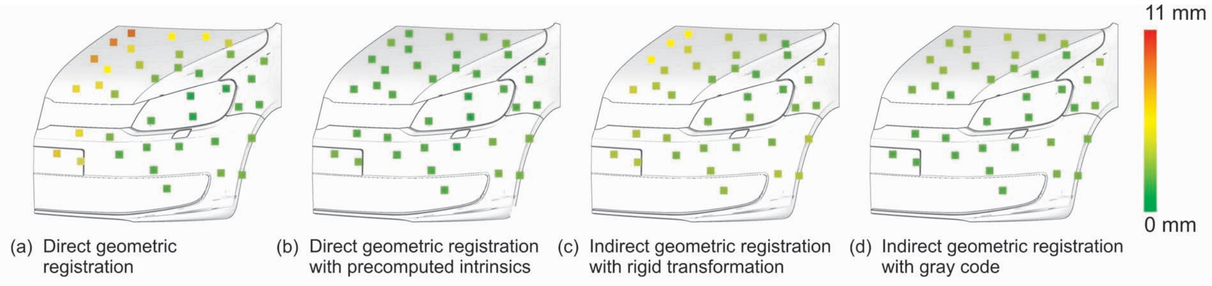


Figure 7: *Comparison between the accuracy of the different geometric registration techniques.*

	Direct geometric registration		Indirect geometric registration	
	No distortion	Precomputed intrinsic parameters	Rigid transformation	Gray code
Average	3.29 mm	1.45 mm	2.86 mm	1.91 mm
Maximum	9.97 mm	2.30 mm	5.73 mm	3.10 mm

Table 1: *Measured deviation between virtual and real positions.*

4. Results

The coded markers, which are projected onto the real object, are measured with the optical measurement system TRITOP from the GOM company. The imprecision of this system is negligible, because the error of the measurement is less than 0.1 mm. Equivalent results are achieved with the GOM ATOS system which is a structured light system and is used to measure the shape of the real object. Therefore, the deviation between the real object and the virtual 3D model of the real object can also be neglected. The real object is painted with a diffuse and grey material as shown in figure 1(a).

We use a Canon Xeed SX7 projector for our evaluation, which has a resolution of 1400 × 1050 pixel and 4000 ANSI lumen. The used camera is a Nikon D200 with a resolution of 3872 × 2592 pixel. The camera is calibrated before the evaluation with the AICON 3D Studio software. All other computations are done with our own software, which uses the OpenCV Library. The projector and the camera are geometrically registered to the object by using the eight measured reference points, which are shown in figure 5(b). The projector displays a rendered image of the virtual 3D marker model as shown in figure 5(a). The projected markers are then measured with the optical measurement system. Afterward, the measured positions are compared to the virtual positions by computing the euclidean distance. The results are visualized in figure 7 and plotted for all projected markers in figure 8. The maximum and average values are additionally listed in table 1.

The results show that the direct geometric registration without the consideration of the projector distortion has the highest deviation with a maximum of 9.97 mm. The deviation gets larger towards the boundary of the projection where the projector has also the highest distortions. Therefore, for a usage in the automotive industry the non-linear distortions of a projector have to be considered, because this deviation is way too large. The lowest deviation with a maximum of 2.30 mm is achieved, when the projector is directly registered to the real object and the intrinsic parameters are precomputed. Additionally, it can be seen in figure 8 that the deviation is for almost all measured markers smaller than the size of a projector pixel on the corresponding position of the real object. Therefore, this method achieves the best possible result and the accuracy can be estimated with the size of the projector pixels on the real object. Note that the accuracy can be increased, when the distance between real object and projector gets smaller, because then also the pixel-size on the real object is reduced.

In contrast to this result, the indirect geometric registration with a rigid transformation does not achieve a good result, because it has a maximum deviation of 5.73 mm. This can be explained with the correlation of the computed camera and projector pose, because the imprecision of the estimated camera pose and the rigid transformation leads to a more imprecise computed projector pose. Note that the camera was aligned with a reprojection error of 0.256 pixel, but this gives no clue about the accuracy of the projected content. The results of the indirect geometric registration with a 2D mapping have a deviation with a maximum of 3.10 mm, which is also an acceptable result.

Altogether, the results show that the direct geometric registration with precomputed intrinsic parameters achieves the best result. Therefore, this method is also used for the application, which is presented in the next section 5, because the virtual content has to be shown with a very high accuracy. Additionally, we also use the indirect geometric registration technique with gray-coded patterns for the application, be-

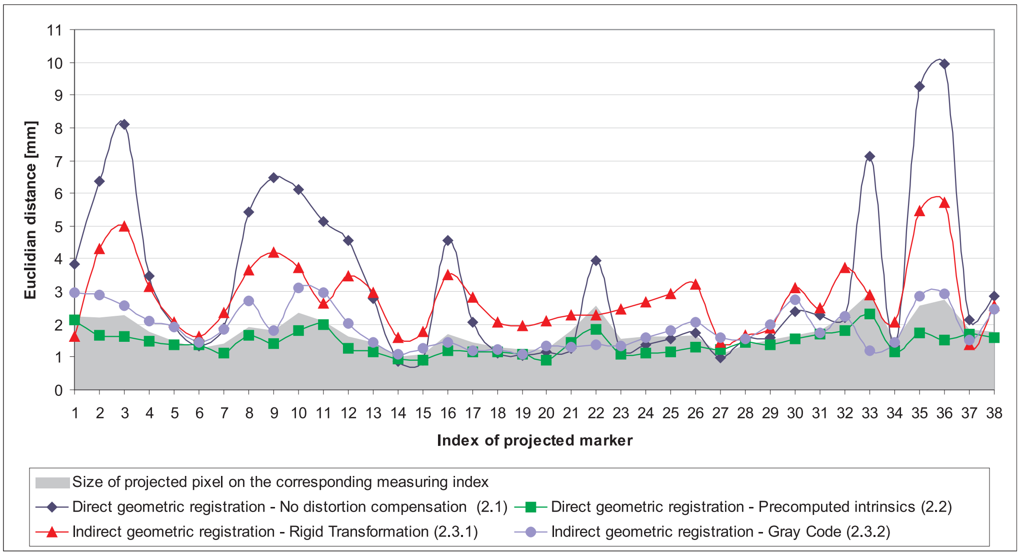


Figure 8: *Plot of the deviations between virtual and measured position of the projected markers. The size of the projector pixels on the real object at the measuring points is drawn as a gray area.*

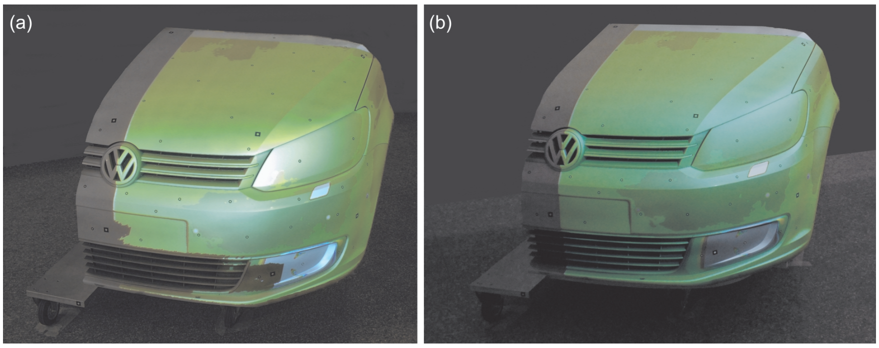


Figure 9: *Images taken with a camera of difference plots which are projected onto a real object: (a) Indirect geometric registration with gray code; (b) Direct geometric registration with precomputed intrinsic parameters.*

cause it has the advantage that it can be combined with the shape measuring system (Chang [Cha03]).

5. Application

As mentioned before, the usage of difference plots is an important step in the production process of a car. Traditionally, these plots are viewed on a standard monitor or a hard copy and the points with a large deviation have to be manually transferred to the real object. In our new approach the complete 3D difference plot is projected onto the real object. Since the 3D plot lies virtually on top of the real object, the projection is independent of the view of an observer. The results from the appliance of the direct geometric registration with precomputed intrinsic parameters and the indirect geometric registration with gray-coded patterns are shown in figure 9.

One problem of the indirect approach is that not all projector pixels can be detected in the camera image, which can be seen in figure 9(a). Note that this problem could be removed with an interpolation of not detected projector pixels. Since this problem does not occur with the direct geometric registration (figure 9(b)), which also achieves a better overlay accuracy, it seems that the direct registration would be the best technique for this scenario. However, one big advantage of the indirect geometric registration with gray-coded patterns is that it can be used, when the pose of camera and projector is known a priori, to measure the shape of the real object. This measurement is a mandatory step in the production process and therefore, when this step is performed with structured light, the correspondences for the computation of the 2D mapping are already known. Note that in this case an additional model has to be applied to compute the positions of the not detected pixels to achieve a better visual result than shown in figure 9(a).

Independently of the used technique, the proposed application has the big advantage that the difference plot can be directly discussed on the real object and the content must not be manually transferred to the real object. Therefore, many people can discuss a problem by pointing directly on the interesting part of the real object. The next section gives a summary of this article and describes possible future work.

6. Conclusions and future work

We presented a new application for using spatial augmented reality in the automotive industry. A projector was used to project difference plots directly onto a real object. The advantage of this method is that the content can be directly discussed on the real object. One important issue for this application is that the virtual content is projected with a very high accuracy. For this purpose, we implemented different geometric registration techniques and proposed a new evaluation method which could then be used to give a statement about the overall accuracy of the implemented techniques. The results of our evaluation show that two of the geometric registration techniques could be used in our proposed application: The direct geometric registration of a projector with precomputed intrinsic parameters achieves the best overlay accuracy, but it is important that the non-linear distortions of a projector are considered. The indirect geometric registration with an additional 2D mapping has the advantage that it can be combined with the measurement of the real object, but has greater deviations in terms of the overlay accuracy.

Future work will address the evaluation of the overlay accuracy for different models e. g. second-order polynomials and other structured light techniques than the one used in this article.

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