2D/3D Registration of TEE Probe from Two Non-orthogonal C-Arm Directions

Markus Kaiser[1,2,3], Matthias John[3], Tobias Heimann[4], Alexander Brost[4], Thomas Neumuth[1], and Georg Rose[2]

[1] Innovation Center Computer Assisted Surgery (ICCAS), Leipzig, Germany
[2] Otto von Guericke University, Magdeburg, Germany
[3] Siemens AG, Healthcare Sector, Forchheim, Germany
[4] Siemens AG, Corporate Technology, Imaging and Computer Vision, Erlangen, Germany

Abstract. 2D/3D registration is a well known technique in medical imaging for combining pre-operative volume data with live fluoroscopy. A common issue of this type of algorithms is that out-of-plane parameters are hard to determine. One solution to overcome this issue is the use of X-ray images from two angulations. However, performing in-plane transformation in one image destroys the registration in the other image, particularly if the angulations are smaller than 90 degrees apart. Our main contribution is the automation of a novel registration approach. It handles translation and rotation of a volume in a way that in-plane parameters are kept invariant and independent of the angle offset between both projections in a double-oblique setting. Our approach yields more robust and partially faster registration results, compared to conventional methods, especially in case of object movement. It was successfully tested on clinical data for fusion of transesophageal ultrasound and X-ray.

Keywords: 2D/3D registration, X-ray & Ultrasound fusion.

1 Introduction

2D/3D registration is a key technology for image-guided medical interventions [1]. The ability to combine pre-operative clinical volume data sets and live fluoroscopy from a C-arm supports physicians during interventions and paves the way for novel procedures and workflows [2]. Usually, a CT or MRI volume is registered to C-arm X-ray images to provide additional anatomical information. Recently, different 2D/3D registration based systems were introduced, e.g. the registration of a transesophageal echocardiogram (TEE) ultrasound probe to X-ray images to track the device and to use it as indirect registration for the other live imaging modality [3]. Our presented registration framework targets the same clinical application. We adapted the approach of [3], combined it with a new method for parameter estimation and a new TEE probe prototype (Siemens AG, Healthcare Sector, Mountain View, CA, USA), shown in Fig.1.

In general, 2D/3D registration is an iterative process, where the six spatial parameters S of a 3D volume (translations (t_x, t_y, t_z) and rotations yaw, pitch

P. Golland et al. (Eds.): MICCAI 2014, Part I, LNCS 8673, pp. 283–290, 2014.

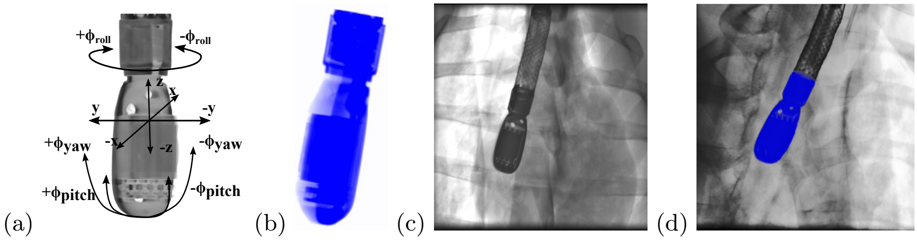

Fig. 1. (a) CT volume of the TEE probe prototype with object axes. (b) DRR of the TEE probe volume. (c) TEE probe under fluoroscopic X-ray. (d) Registered TEE probe with overlayed DRR from another C-arm angle.

and roll (ϕ_y, ϕ_p, ϕ_r)) are estimated by an optimizer until the projection of the 3D data is correctly aligned with the current image. A digitial reconstructed radiograph (DRR) is generated after each adaptation of the parameter set. This DRR is compared with the X-ray image by a similarity measure. Due to the projective characteristic of a C-arm system, S can be separated into in-plane and out-of-plane parameters. In-plane parameter transformation (t_x, t_z, ϕ_y) is parallel to the detector plane (i.e. the projected image). Therefore, a change in such a parameter can cause a significant image change and is easier to estimate. Changes in out-of-plane parameters like depth (t_y) or pitch (ϕ_p) and roll (ϕ_r) cause an object shift perpendicular to the image plane, which is more difficult to identify. Typically, there are two ways of registering multi-plane images.

1. Full 3D: all six spatial parameters are registered simultaneously along the object axes like in [3]. The optimizer will not distinguish between in-plane and out-of-plane parameters.
2. Subdivided in-plane: The decoupling of in- and out-of-plane parameters can be of major importance, particularly when registering on multi-plane system. The objects' in-plane parameters are registered alternately between both imaging planes. One can dramatically increase accuracy and capture range while registering only the in-plane parameters for each plane [4][5].

In a common biplane setup, the detector planes have a rotational offset of 90 degrees. Therefore, in-plane parameters of the first image become out-of-plane parameters in the second image and vice versa. Only one rotational parameter will always remain out-of-plane. In this work, we do not necessarily refer to a biplane C-arm system, but use images from a monoplane system from two angulations acquired consecutively. Since the TEE probe is in a fixed position for longer periods, performing imaging from a second angulation is a reasonable workflow, in particular for small angle offsets. Due to space constraints in hybrid operating rooms and catheter labs, orthogonal multi-plane imaging can be difficult to achieve. This leads to projection angle differences smaller than 90 degrees. The position of a C-arm system is defined by two angles, one for left-anterior-oblique and right-anterior-oblique given as α, and the second one for cranial-caudal as γ. The indices $_A$ and $_B$ are used to indicate the two

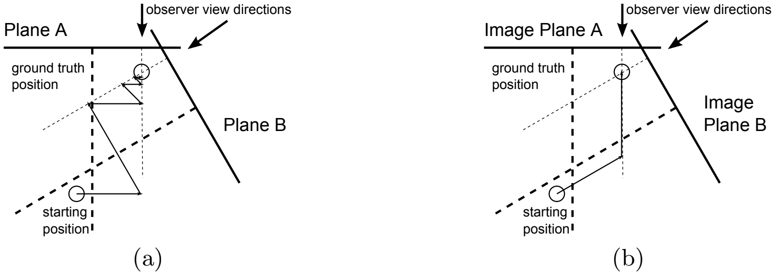

Fig. 2. (a) illustrates the in-plane approach and (b) the planar approach

different C-arm angles. If only one angle is changed between two images, this refers to a mono-oblique, otherwise to a double-oblique setting. In this work, we are considering the setup given by

$$\forall \alpha, \gamma : |\alpha_A - \alpha_B| \leq 90^\circ \wedge |\gamma_A - \gamma_B| \leq 90^\circ. \quad (1)$$

The drawback of a non-orthogonal setting is that the in-plane registration strategy results in an iterative process like in Fig. 2(a). Depending on the projection angles, this can have a significant influence on registration accuracy and runtime.

To resolve this issue, we improved the in-plane strategy to a planar approach. This approach keeps in-plane parameters invariant to the registration on the other image plane and establishes a one-step movement like illustrated in Fig. 2(b). The main idea is to transform the 3D object without disrupting previous in-plane registration results. For each view, only in-plane parameters t_x, t_z, ϕ_y are changed, while out-of-plane information is used from the other plane.

We employed the method in an automatic multi-plane image-based 2D/3D registration system for fusion of TEE ultrasound and X-ray. Our approach, which was basically introduced for manual registration in [6], is not limited to this application and could be used for various purposes.

2 Methods

Our approach is object-centerline-driven which initially lies in the cranial-caudal direction. Therefore, the rotation ϕ_r around the centerline c remains out-of-plane from both views. Aligning the other parameters correctly along the centerline will reduce the search space for ϕ_r.

In our setup, we have two image planes I_A and I_B, which are the detector planes of the C-arm in two different views. All object translations and rotations in one image are bound to the spanning plane of the other image. See Fig. 3 for an illustration. Considering I_A for example, every transformation is restricted by the plane P_B spanned by the focus eye_B and the centerline c. P_B is defined by its normal vector n_B as

$$n_B = (eye_B - m_{p_B}) \times (eye_B - c_{p_B}). \quad (2)$$

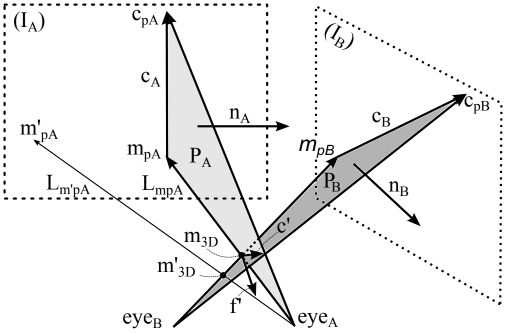

Fig. 3. Schema for multi-plane transformation

If the object is moved on I_A from image coordinate m_{pA} to a new one m'_{pA}, the new 3D position m'_{3D} of the object is determined by plane-line-intersection of plane P_B and line $L_{m'_{pA}}$. This ensures that the position of the object is changed for I_A, but is not influencing the independent translational in-plane parameters in I_B.

The vectors c_A and c_B that determine the in-plane yaw are obtained directly in the 2D image plane when projecting the centerline vector c of the object onto the image plane. Every yaw rotation ϕ_y is carried out in 2D by calculating the vector between the projected object center point m_p and the projected object point in center line direction c_p as

$$c_p = m_p + [sin(\phi_y), 0, cos(\phi_y)]. \tag{3}$$

The center line vector c' is thus defined by the intersection of planes P_A and P_B, which ensures that the yaw in I_B stays fixed even when the yaw in I_A is changed. The angle ϕ_p is not changed by the optimizer, but determined via n_B from I_B. The plane normal n_A determines the objects' 3D yaw rotation. The new rotation matrix R of the object is now built with the base vectors n_A, f', c' which are given as

$$c' = n_B \times n_A \tag{4}$$
$$f' = c' \times n_A. \tag{5}$$

The rotations ϕ_y and ϕ_p are covered by the matrix $R_{\phi_y \phi_p}$ which is given by

$$R_{\phi_y \phi_p} = \begin{pmatrix} n_{A_x} & f'_x & c'_x & 0 \\ n_{A_y} & f'_y & c'_y & 0 \\ n_{A_z} & f'_z & c'_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{6}$$

Finally, the rotation ϕ_r around the centerline c' is given by the rotation matrix R_{ϕ_r}, which is build with the common Euler angle representation. The overall rotation matrix is then given by

$$R = R_{\phi_y \phi_p} \cdot R_{\phi_r}. \tag{7}$$

2.1 2D/3D Registration Framework

We employed our approach within a 2D/3D registration system for TEE probe registration. We use a Powell-Brent minimizer as optimizer. This algorithm is well understood and produces good results for non-linear optimization. It was also successfully employed in similar registration problems [3].

The optimization is multi-scale/multi-resolution driven. We use the regularized normalized gradient fields (NGF) [7] as similarity measure, which is based on gradient directions and magnitudes. We use it in the following configuration

$$NGF(I_1, I_2) = \frac{1}{2} \sum_{x \in I} \langle n_\epsilon(I_1, x), n_\epsilon(I_2, x) \rangle^2, \tag{8}$$

which evaluates the dot product between all gradients in the X-ray image (I_1) and the DRR image (I_2). Each pixel gradient n_ϵ is calculated as

$$n_\epsilon(I, x) = \frac{\Delta I(x)}{\sqrt{||\Delta I(x)|| + \epsilon^2}}, \tag{9}$$

where ϵ is the regularization condition to suppress gradients coming from image noise. For the X-ray image, we set ϵ to the mean value over all image gradients and $\epsilon = 0$ for the DRR, because there is no noise in the DRR.

2.2 In Case of Object Motion

The presented approach can also be used to overcome the influences of slight object movement caused by breathing or heart motion. This can result in wrong offsets between objects in the consecutively acquired X-ray images. Also uncalibrated C-arm projection matrices can cause differences between two views. It follows that one could not achieve a 3D position that correctly matches both 2D positions in the projection images. To solve that issue, we decouple the translation of both views. Therefore, in-plane translation parameters t_x, t_z of A and B are registered independently. The depth t_y is still obtained from the intersection point m'_{3D}. For our data, we recognized that the object motion causes a translational shift but only insignificant errors for rotation. Therefore, the rotation is still combined on both images.

3 Experiments and Results

We evaluated our approach on various multi-plane X-ray sequences acquired during a porcine study and compared it to the two conventional strategies. We

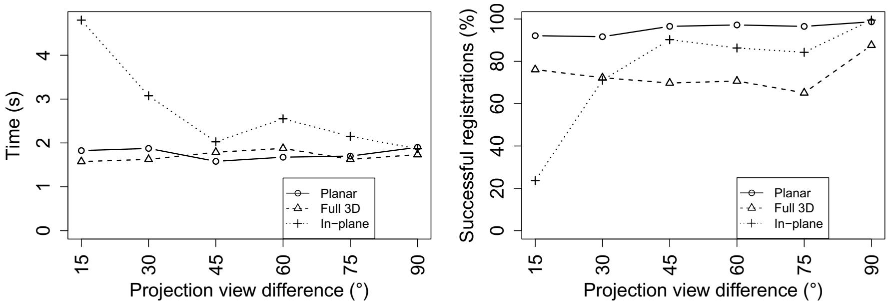

Fig. 4. Detailed registration performances on a mono-oblique system

acquired X-ray images within a wide range of projection angles to achieve different views to the TEE probe. The C-arm angles were in the range of $\alpha \in [-75, 90]$ and $\gamma \in [15, -30]$ degree. This range was limited by environmental constraints of the angiography lab. The probe was fixed to collect data without movement as well. The registration accuracy was evaluated while registering the TEE probe to different multi-plane X-ray image pairs. A ground truth registration was generated manually by careful visual inspection and automatic registration on different views. We tested the registration for a mono- and double-oblique setup, for data with and without movement. In total, we compared a various selection of image pairs from a set of 41 different X-ray scenes, similar to Fig. 1(c)(d).

We evaluated the registration error in terms of target registration error (TRE) [8], which can be seen as the overall 3D error of the registration process. We measured the mean error (mTRE) of 8 corner points of a bounding box around the TEE probe volume which are 5 cm away from the volume center and determined the capture range of the algorithm for each X-ray image pair. For each pair, we initialized 300 uniformly distributed random start positions of the TEE probe within an interval of $[-10, +10]$ mm and $[-10, +10]$ degree. If the final mTRE is below 2.5 mm, the registration is assumed to be successful.

The registration results for mono-oblique data is shown in Fig. 4. The evaluated scenes are merged over the difference between the projection angles. One can see on the left diagram that our approach is close to constant runtime, independent of the projection angle difference. In contrast to the conventional in-plane approach, particularly on small differences. The runtime of the planar and the full 3D approach is comparable, but has a lower success rate. The conventional in-plane method mostly fails on very low angle differences, while it adapts the planar results with increasing angle differences. The results are summarized in Tab. 1. As it can be seen in Tab. 2, the double-oblique views have a negative

Table 1. Results for mono-oblique setup

	Planar	In-plane	Full 3D
success [%]	**95.43**	75.83	73.57
time [s]	1.76	2.74	**1.70**

Table 2. Results for double-oblique setup

	Planar	In-plane	Full 3D
Success [%]	**85.92**	75.45	59.22
time [s]	2.29	1.67	**1.70**

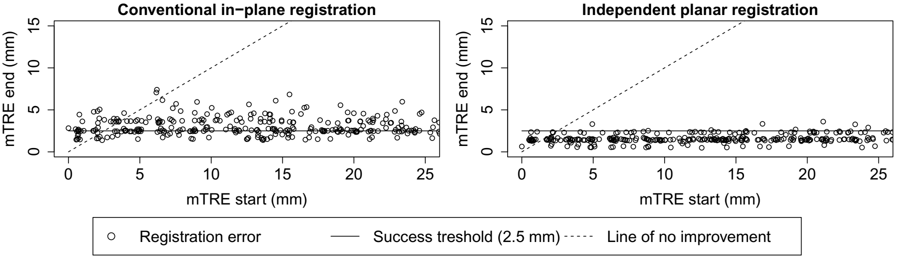

Fig. 5. Example result for registration on data with probe movement

influence on the overall registration accuracy while the planar approach is still more robust than the other. However, an increasing runtime can be observed.

In addition, we tested our approach on data, where we encountered a slight movement of the probe. Usually, the registration algorithm fails because of the varying 2D information. An example is given in Fig. 5. Compared to the independent approach, the conventional in-plane method has a low accuracy and a high variance in the final results. The summarized results in Tab. 3 show that, contrary to the independent approach, both conventional methods have poor results in accuracy. With 14.22 seconds, the runtime for in-plane is very high.

4 Discussion and Conclusion

In general, the planar approach shows about 25% higher accuracy than the compared methods. The accuracy and runtime of the conventional in-plane approach is limited by its iterative behaviour, Fig. 2(a). This effect can be observed especially for small angle differences. The smaller the angle, the more iterations are needed for convergence. For angles smaller than 15 degree, the error between the iterations is to large and the algorithm tends to converge to a local minimum. Because of the invariant in-plane parameters, the planar algorithm avoids additional iterations. Planar and in-plane methods have the identical behaviour for 90 degrees difference. The invariance of the in-plane parameters provides a better starting position on the respective other plane during optimization and increases the probability to find the correct minimum.

The full 3D strategy success rate is mostly lower. A reason is that the 3D position of the object is changed along the axes of the object which are not necessarily aligned with the image axes. In our implementation, the object is aligned to the in-plane directions of image A which is obviously not true for image B. Therefore, out- and in-plane parameters are mixed and are not separated

Table 3. Mean success and timing results for data with probe movement

	Planar independent	In-plane	Full 3D
Success [%]	**81.4**	38.3	30.1
time [s]	3.44	14.22	**1.59**

during optimization which can cause the optimizer ending up in a local minimum. Except for a 90 degree offset, where the full 3D approach improves significantly.

Double-oblique projection angles have an even bigger influence on the accuracy which can be seen in Tab. 2. This is due to the additional instability caused by the extra rotation of the C-arm. This causes the in-plane approach to make major errors during the iterations.

Our experiments with slight probe movement showed that the independent planar approach is a solution for that issue. As a result of no common 3D position, the conventional approaches try to find a compromise between both 2D image positions, respectively decide for one of the two possible positions. Decoupling the translation fixes this issue. Because of the iterative optimization, the in-plane approach tends to bounce between both positions which results in the increased runtime.

Our novel approach clearly achieves better results for non-perpendicular settings and with its constant runtime facilitates a seamless integration into clinical workflows. The presented approach is specialized on objects that have a "natural" centerline which represents the roll axis. Most technical objects in medical interventions (e.g. catheters, endoscopes) have a distinct centerline as well as anatomical structures like an aorta, vessels or head. That means, our presented approach can be potentially adopted to a various range of registration problems.

Disclaimer: The outlined concepts are not commercially available. Due to regulatory reasons its future availability cannot be guaranteed.

References

1. Markelj, P., Tomaževič, D., Likar, B., Pernuš, F.: A review of 3d/2d registration methods for image-guided interventions. Med. Image Anal. 16(3), 642–661 (2012)
2. Liao, R., Zhang, L., Sun, Y., Miao, S., Chefd'Hotel, C.: A Review of Recent Advances in Registration Techniques Applied to Minimally Invasive Therapy. IEEE Trans. on Multimedia 15(5), 983–1000 (2013)
3. Gao, G., Penney, G., Ma, Y., Gogin, N., Cathier, P., Arujuna, A., Morton, G., Caulfield, D., Gill, J., Aldo Rinaldi, C., et al.: Registration of 3D trans-esophageal echocardiography to X-ray fluoroscopy using image-based probe tracking. Med. Image Anal. 16(1), 38–49 (2012)
4. Brost, A., Wimmer, A., Liao, R., Bourier, F., Koch, M., Strobel, N., Kurzidim, K., Hornegger, J.: Constrained Registration for Motion Compensation in Atrial Fibrillation Ablation Procedures. IEEE Trans. on Med. Imag. 31(4), 870–881 (2012)
5. Miao, S., Liao, R., Pfister, M.: Toward smart utilization of two X-ray images for 2-D/3-D registration applied to abdominal aortic aneurysm interventions. Computers & Electrical Engineering 39(5), 1485–1498 (2013)
6. Kaiser, M., John, M., Heimann, T., Neumuth, T., Rose, G.: Improvement of Manual 2D/3D Registration by Decoupling the Visual Influence of the Six Degrees of Freedom. In: IEEE ISBI, pp. 766–769 (2014)
7. Haber, E., Modersitzki, J.: Intensity Gradient Based Registration and Fusion of Multi-modal Images. In: Larsen, R., Nielsen, M., Sporring, J. (eds.) MICCAI 2006. LNCS, vol. 4191, pp. 726–733. Springer, Heidelberg (2006)
8. van de Kraats, E., Penney, G., Tomazevic, D., van Walsum, T., Niessen, W.: Standardized evaluation methodology for 2-D-3-D registration. IEEE Trans. on Med. Imaging 24(9), 1177–1189 (2005)