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Localization of endovascular tools in X-ray images using a motorized C-arm: visualization on HoloLens

<https://doi.org/10.1515/cdbme-2020-0029>

Abstract: C-arms are medical devices widely used for image-guided minimally invasive endovascular procedures. This technology requires considerable experience for the physicians to position the C-arm to obtain X-ray images of the endovascular tools. In addition, this image-guided therapy is based on two-dimensional images which lack depth information. The purpose of this study was to develop a system that controls the C-arm movements based on the previous position of the tip of a guide wire and the vessel information, and also displays the estimated tip position (specifically, the virtual line that would join the X-ray source and the projected tip in the flat-panel detector) on an augmented reality device (HoloLens). A phantom study was conducted to evaluate the system using intraoperative cone-beam computed tomography scans to obtain the reference tip position. The mean distance between the tip position (ground truth) and the virtual three-dimensional line was 1.18 mm. The proposed system was able to control the C-arm movements based on the position of the tip of the guide wire. The visualization on HoloLens also allowed a more intuitive understanding of the position of the endovascular tool related to the patient's anatomy during the intervention.

Keywords: aneurysm; augmented reality; guide wire; motorized C-arm; stenosis; X-ray images.

Introduction

Abdominal aortic aneurysms (AAAs) and peripheral arterial diseases (PADs) are common vascular diseases. The endovascular procedure to treat these diseases consists in inserting guide wires/catheters along the artery to the aneurysm/stenosis through a small surgical incision. Then, a stent graft is placed in the diseased vessel to cover the aneurysm/stenosis and re-establish physiological blood flow.

A preoperative computed tomography (CT) scan is typically performed to confirm the diagnosis and to provide the three-dimensional (3D) information of the vessel to plan the treatment. Intraoperative two-dimensional (2D) fluoroscopy and conventional digital subtraction angiography are commonly used to guide and evaluate the stent graft placement during the intervention. However, these image modalities are 2D projections thus not providing depth information. Cone-beam CT (CBCT) scans are not acquired throughout the intervention due to radiation exposure and limited field of view (FOV). To acknowledge the 3D nature of the anatomy, the C-arm used to acquire those 2D images must be repeatedly repositioned during the intervention to provide the required projections. This is a time-consuming process, increases radiation exposure to the surgical team and the patient, and requires considerable experience of the physicians to adjust each joint to move the C-arm [1].

Augmented reality (AR) is a technology that provides virtual content superimposed onto the user's vision of the real world. AR allows a more intuitive visualization of 3D models than that provided from standard 2D screens at fixed positions.

The objective of this study was to develop a system that controls the C-arm movements based on the previous position of the tip of an endovascular tool, specifically a guide wire, and the vessel information, and also displays the position information in an intuitive way with AR glasses, specifically Microsoft HoloLens (first generation). A phantom study was conducted to evaluate the system

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using intraoperative CBCT scans to obtain the ground truth of the tip position.

Materials and methods

System description

C-arm: A Ziehm Vision RFD 3D C-arm was used in this study. This motorized C-arm is equipped with a 3D scanning mode to acquire CBCT scans and a fluoroscopy operating mode to acquire X-ray images. The FOV of the CBCT scan is $16 \times 16 \times 16 \text{ cm}^3$. The matrix size of the projection is $1,024 \times 1,024$ pixels while the pixel size is $0.291 \times 0.291 \text{ mm}^2$. The nominal distance between the X-ray source and the center of the flat-panel detector ($d_{\text{Source-FD}}$) is 1,074 mm.

The motor drives on this system enable movement for the vertical direction (d_1), horizontal direction (d_3), angulation (θ_4) and orbital rotation (θ_5), (Figure 1). However, users can only swivel (θ_2) manually because joint 2 is not motorized.

Since joint 2 does not have any encoder, θ_2 was set to 0° . In this case, the pose (position and orientation) of the flat-panel detector with respect to the base coordinate system (${}^0M_{FD}$) is defined using forward kinematics as follows:

$${}^0M_{FD} = \begin{bmatrix} C_4 & S_4 S_5 & -C_5 S_4 & a_5 S_4 S_5 - a_4 S_4 - d_{FD} C_5 S_4 \\ 0 & C_5 & S_5 & d_{FD} S_5 + d_3 + a_5 C_5 \\ S_4 & -C_4 S_5 & C_4 C_5 & d_1 + a_4 C_4 + d_{FD} C_4 C_5 - a_5 C_4 S_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where C_i denotes $\cos \theta_i$, S_i denotes $\sin \theta_i$, a_4 and a_5 are offsets (Figure 1), and d_{FD} is the distance between the origin of the coordinate system S_E and the center of the flat-panel detector (origin of the coordinate system S_{FD}). In the case of the X-ray source, its pose with respect to the base coordinate system (${}^0M_{\text{Source}}$) is obtained by replacing d_{FD} with $-d_{\text{Source}}$ in Eq. (1), where d_{Source} is the distance between the origin of the coordinate system S_E and the X-ray source (Figure 1). The offsets a_4 , a_5 , d_{FD} and d_{Source} were computed with the transformation matrices ${}^{BKS}M_{Iso}$ and ${}^{Iso}M_{FD}$, and the transformation vector ${}^{Iso}V_{\text{Source}}$ (data provided from Ziehm company and saved in the

DICOM file of the projections in the 3D scanning mode). Ziehm defines BKS as the base coordinate system of the C-arm when neglecting the link length between each joint. Iso corresponds to the isocenter when acquiring CBCT scans. The Iso coordinate system is not shown in Figure 1 because it depends on the CBCT acquisition. To calculate the previous offsets, the base coordinate system S_0 (Figure 1) was set to be the same as the BKS coordinate system defined by Ziehm company so that Eq. (1) is equal to ${}^{BKS}M_{FD} = {}^{BKS}M_{Iso} \times {}^{Iso}M_{FD}$. The first three elements of the last column in Eq. (1) $(p_x, p_y, p_z)^T$ corresponds to the center of the flat-panel detector in the BKS coordinate system.

Preoperative – intraoperative registration: The matrix ${}^{pre}M_{BKS}$ to transform the BKS coordinate system (or intraoperative coordinate system) into the preoperative coordinate system is calculated by means of a marker-based registration. Several lead markers (Suremark SL-10, 1.0-mm lead ball) are attached surrounding the region of interest.

The markers in the preoperative CT scan (3D markers) are automatically segmented by means of intensity thresholding method and considering the marker size. The 3D coordinates of each marker are calculated as the centroid of its segmentation mask.

The 3D coordinates of the markers in the intraoperative coordinate system are estimated from two X-ray images with an angular difference of approximately 30° between C-arm poses. First, each marker is segmented in each projection by means of an adaptive intensity thresholding (threshold computed automatically from windows of 80×80 pixels) and a user-defined marker size. The 2D coordinates of each marker are calculated as the centroid of its segmentation mask. Next step focuses on finding out the right 2D–3D correspondence of the markers for each projection. The C-arm is considered as a pinhole camera model. The camera intrinsic matrix is defined with $d_{\text{Source-FD}}$ and the image center of the detector, both in pixel scale. The camera extrinsic matrix is estimated by means of solving perspective–n-point (PnP) problem according to the set of 3D coordinates of the markers in the CT scan and the set of 2D coordinates of the markers in that projection (function solvePnP, iterative method, Python package opencv-python). The minimum estimated reprojection error of all the possible combinations of 2D–3D correspondences provides the

Figure 1: Coordinate system of each link for forward kinematics.

right correspondence of the markers for that X-ray image. After that, the 2D coordinates of each marker (with zero z-coordinate) are transformed into the BKS coordinate system using Eq. (1). Finally, the 3D coordinates of each marker in the BKS coordinate system are computed using triangulation with the marker coordinates from both intraoperative X-ray images.

C-arm pose: The computation of C-arm poses is subject to two requirements. First, the y-axis of the flat-panel detector should be parallel to the y-axis of the BKS coordinate system, which means that θ_2 and θ_5 should be zero. For simplicity, angulation θ_4 is also set to zero but this angle can be modified during the intervention. Second, the tip of the endovascular tool (specifically, a guide wire) $M = (m_x, m_y, m_z)^T$ (BKS coordinates) should be at the center of the X-ray image along the y-axis, which means that $p_y = m_y$. Considering both requirements, the C-arm horizontal movement d_3 is determined as follows:

$$d_3 = m_y - a_5 \quad (2)$$

The vertical movement d_1 is determined by setting that the distance between the center of the flat-panel detector and the tip along the z-axis (p_z and m_z respectively) is 0.4 times $d_{Source-FD}$ (to center the vessel between the X-ray source and the flat-panel detector) as follows:

$$d_1 = m_z - a_4 - d_{FD} + 0.4 d_{Source-FD} \quad (3)$$

The tip of the guide wire is identified in the intraoperative X-ray images by means of a marker (Suremark SL-20, 2.0-mm lead ball) attached on its tip. The first pose of the C-arm (specifically, the joint parameters) is computed with the 3D coordinates of the tip in the BKS coordinate system. These coordinates are obtained from two intraoperative X-ray images as described in section Preoperative – intraoperative registration since the guide wire is inserted in the vessel before the registration.

Next C-arm poses are computed with Eq (2) and Eq (3) except for replacing M with M' , where M' is the expected next tip position after moving the guide wire a distance $d_{MM'}$ along the vessel centerline from its current position M . This curve, which the endovascular tool ideally moves along, is estimated with VMTK toolkit (www.vmtk.org) using a vessel 3D model generated from the preoperative CT scan. The vessel centerline is transformed from the preoperative coordinate system to the BKS coordinate system using ${}^{pre}M_{BKS}^{-1}$. In the computation of the next C-arm pose, only one X-ray image is acquired before moving the tip of the guide wire from its current position M to reduce radiation exposure. Therefore, a rough tip position M (3D coordinates) is calculated with that projection as follows. The position of the projected tip (BKS coordinates) is computed as explained in section Preoperative – intraoperative registration with that X-ray image. The position of the X-ray source is calculated with the joint parameters corresponding to that X-ray image as described in section C-arm. The tip position M is then estimated as the closest point of the vessel centerline to the 3D line that would join the X-ray source and the projected tip. After that, the 3D coordinates of the point M' are computed with M , $d_{MM'}$ and the vessel centerline to obtain the next C-arm pose.

User interface and AR application: The developed Python user interface includes the tools to automatically obtain the 3D coordinates of

the markers in the preoperative CT scan and the 2D coordinates of the markers in the X-ray images to calculate the transformation ${}^{pre}M_{BKS}$ as described in section Preoperative – intraoperative registration. At each C-arm pose, the X-ray image acquired is loaded in the user interface to obtain the position of the projected tip. After that, the 3D line that would join the X-ray source and the projected tip in the flat-panel detector is computed. Then, the expected next tip position M' according to the user-defined $d_{MM'}$ and the joint parameters of the next C-arm pose are estimated as explained in section C-arm pose. The user interface sends the joint parameters of the next C-arm pose to the C-arm via Ethernet. In addition, digitally reconstructed radiographs (DRRs) are also shown to preview X-ray images and reduce the number of image acquisitions (for example, when users adjust angulation in the user interface). A parallel computation with GPU (Numba, Python) generates a DRR (cone beam configuration, same material for the whole CT scan) in less than 2 s.

The AR scene in the HoloLens application (implemented with Unity [<https://unity.com>] and C#) includes the vessel and the patient's skin 3D models for an anatomical reference. These 3D models are generated from the preoperative CT scan with 3D Slicer (www.slicer.org). Two-hand manipulation allows the HoloLens user to move, rotate and superimpose the virtual 3D models on the real object. The line coordinates in the preoperative coordinate system obtained in the user interface are sent via Wi-Fi to the HoloLens (first generation) using gRPC (<https://grpc.io/>) and the virtual 3D line is displayed in the AR scene to indicate the tip position of the guide wire.

Evaluation

A leg phantom, which was designed by the Division of Vascular and Endovascular Surgery (University Hospital Schleswig-Holstein, Lübeck) in cooperation with HumanX GmbH, was used to simulate an endovascular treatment for PAD. Six markers were attached to its surface to calculate ${}^{pre}M_{BKS}$. The guide wire was marked every 2 cm and six C-arm poses were computed after moving the guide wire 2 cm each time. CBCT scans were also acquired at each guide wire position to obtain the tip position of the endovascular tool (ground truth) to evaluate the virtual 3D line that indicates the estimated tip position in the vessel.

Results

Regarding the calculation of ${}^{pre}M_{BKS}$, the fiducial registration error was 0.75 mm. Figure 2 shows two X-ray images acquired according to a calculated C-arm pose. The tip position of the guide wire is approximately at the center of the y-axis in each X-ray image. Figure 2 (right) was acquired after manually setting a different angulation in the user interface so that both vessels were not overlapped. The virtual 3D line obtained according to the position of the X-ray source and the projected tip was displayed on HoloLens (Figure 3). The distance between the tip position (ground truth) and the 3D line was 1.18 ± 0.11 mm (mean $\pm$ standard deviation).

Figure 2: Intraoperative X-ray images with two overlapped vessels (left) and after changing angulation (right). The red arrows mark the tip position of the guide wire in the projections.

Figure 3: Visualization on HoloLens from two points of view.

Discussion

This study presents our preliminary work toward controlling the C-arm movements based on the tip position of an endovascular tool and providing an intuitive visualization of the tip position related to the patient's anatomy (3D) with AR glasses. In Ref. [2], a semi-automatic pre-computation of the optimal C-arm pose was calculated with the vessel information. Our user interface computes next C-arm poses during the intervention based on X-ray images and the vessel centerline. DRRs are also previewed to potentially reduce the number of acquisitions, thus less radiation exposure. Regarding HoloLens visualization, in Ref. [3] volume renderings from a preoperative CT scan and the principal ray of the C-arm were superimposed on the real object. In our case, the estimated tip position is visualized on HoloLens as the region where the virtual 3D line is inside the virtual 3D vessel for a better 3D spatial understanding. Further research will focus on addressing several issues such as the C-arm bending, the use of markers on

patients for a long time period (replacing them with intensity-based 2D-3D registration) and some wrong marker identification in X-ray images (implementing a deep learning approach). In addition, angulation can be automatically computed using the vessel 3D model to avoid a virtual 3D line parallel to the vessel or overlapped vessels in X-ray images, and the virtual content may be automatically superimposed on the real object with surface mapping.

Research funding: Study supported by the German Federal Ministry of Education and Research (grant number 13GW0228) and the Ministry of Economic Affairs, Employment, Transport and Technology of Schleswig-Holstein.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Competing interests: Authors state no conflict of interest.

Informed consent: Not applicable.

Ethical approval: Not applicable.

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