Merging Visible and Invisible: Two Camera-Augmented Mobile C-arm (CAMC) Applications

N. Navab and A. Bani-Hashemi
Siemens Corporate Research
755 College Road East
Princeton, NJ 08540, USA
{navab, ali}@scr.siemens.com

M. Mitschke
Siemens AG Medical Engineering
Henkestr. 127, 91052 Erlangen, Germany
Matthias.Mitschke@med.siemens.de

Abstract

This paper presents the basic concept of Camera-Augmented Mobile C-arm (CAMC) and a set of its possible applications. A CCD camera is attached to a mobile C-arm fluoroscopy X-ray system. Both optical and X-ray imaging systems are calibrated in the same coordinate system in an off-line process. The new system is able to provide X-ray and optical images simultaneously. This system was first used for on-line estimation of X-ray projection geometry for low cost mobile C-arms, which do not guarantee the reproducibility of their motion [8]. The CAMC framework has great potentials for medical augmented reality.

In this paper we introduce two new CAMC applications. They are quite different and could be subject of two separate detailed papers for a medical conference. Here we only aim at briefly introducing these two new concepts to the Augmented Reality (AR) research community.

The first application aims at merging video images with pre-computed tomographic reconstruction of 3D volume of interest. This is a logical continuation of our work on 3D reconstruction using a CAMC [8]. The second approach is a totally new CAMC design where using a double mirror system and an appropriate calibration procedure the X-ray and optical images are merged in real-time [1]. This new system enables the user to see optical image, X-ray image, or an augmented image where visible and invisible are combined in real-time.

The paper is organized in two more or less independent sections describing each of the above. Experimental results are provided at the same time as the methods and apparatus are described for each section.

1 Overlay of pre-computed 3D reconstruction volume and optical images

1.1 Introduction

Many clinical procedures are guided by X-ray imaging: commonly under X-ray fluoroscopy. Even if a 3D CT reconstruction is computed off-line, often X-ray fluoroscopy is used as interventional image-guided modality. However, the success of the procedure depends on the ability of the surgeon to mentally recreate the spatio-temporal intraoperative situation from two-dimensional fluoroscopic X-ray images. Recently there has been a considerable effort in replacing fluoroscopic guidance with an interactive display of 3D bone models created from preoperative CT studies and tracked in real time [9, 3]. The basic motivation for proposing the Camera-Augmented Mobile C-arm (CAMC) in [8, 7] was to enable a mobile C-arm itself to provide 3D reconstruction results. This can eliminate the need for a pre-computed CT reconstruction for many applications.

Since the same mobile C-arm is also used for intraoperative guidance, the registration between the 3D data and 2D fluoroscopic images is much easier. In this paper, we show that the CAMC can also be used to combine optical images with 3D reconstruction results. In fact, using the optical camera and its associated markers, which are transparent to X-ray, one can estimate the projection geometry of the X-ray C-arm without taking an actual X-ray image. The 3D reconstruction can then be viewed from the same viewing angle. This can be considered as a simulated X-ray image. The clinician can then move the C-arm freely and observe the simulated X-ray images from different viewpoints. Once the system is at a desired position, the clinician may take an actual fluoroscopic image to make sure that the projection geometry is correctly computed. In this case the simulated X-ray image will be continuously combined with real-time video. This has many advantages. For example the surgeon can position and orient a needle relative to a deep seated target, as it is usually done under fluoroscopic guidance, but with reduced X-ray radiation for both patient and clinician.

In this section, we first present some results of 3D reconstruction using a Camera Augmented Mobile C-arm (CAMC). We then show that CAMC can provide new possibilities for augmented reality through registration and superimposition of the reconstructed 3D volume and patient's optical images. This is done by estimating the camera projection parameters in the same coordinate system in which the 3D reconstruction is computed. The 3D data is then projected onto the optical camera, in order to create an X-ray projection image which is registered with the optical image. The "enhanced reality display" [4] and image overlay system for medical imaging [2] present excellent techniques for combining patient images with different medical imaging data. However, in both cases external sensors are used for registration and tracking. Here we propose a new mobile X-ray system which is able to provide real-time enhanced reality images with no need for external equipment or multiple registration procedures. If equipped with a camera, the mobile C-arm, which is often readily available in medical environment, will be able to provide X-ray images, 3D reconstructed data, optical images and finally combined X-ray/optical images.

1.2 X-ray geometrical calibration and 3D volume reconstruction using CAMC

The X-ray projection geometry as well as optical camera geometry is represented by $\boldsymbol{P}$ a 3×4 homogeneous matrix of projection. This matrix represents all the imaging geometry parameters which can be divided into two sets. The first set is called the extrinsic parameters. They define position $\boldsymbol{R}$ and orientation $\boldsymbol{t}$ of the imaging system in a world coordinate system. The second set is called the intrinsic parameters $\boldsymbol{A}$. They only depend on internal parameters of the imaging system such as pixel size, image center, and principle distance (for optical camera) or source to detector distance (for radiographic imaging system). Both X-ray and optical imaging systems are modeled after a simple pinhole camera. The homogeneous matrix $\boldsymbol{P}$ maps 3D points or voxels from the world coordinate system onto the image plane. We have:

$$\boldsymbol{P} \cong [\boldsymbol{AR} \;\; \boldsymbol{At}] \qquad (1)$$

The symbol $\cong$ is used to emphasize that the equality is up to scale.

For a CCD camera with fixed focal length it is reasonable to suppose that the intrinsic parameters remain fixed while acquiring a sequence of images. For X-ray images this is not the case due to minor torsion of the C-arm caused by the weights of both X-ray source and detector. In order to be able to take the motion estimated from a CCD camera and apply it to X-ray geometry we need to fix the X-ray imaging intrinsic parameters. This is accomplished by a plate with a small number of X-ray opaque markers that is attached to the X-ray focus. These markers are projected onto the X-ray image close to the image borders. The marker plate is placed at a fixed position relative to the X-ray source and therefore, its projection onto the image plane only depends on the intrinsic parameters.

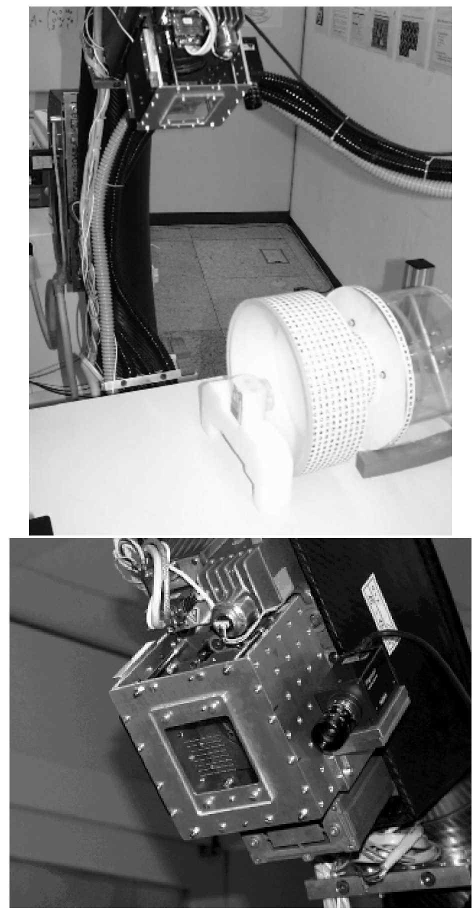


Figure 1. Experimental setup: Our isocentric test system C-arm and the combined X-ray and optical phantom for off-line calibation (top), X-ray source and the attached CCD camera (bottom)

Using the concept of a *virtual detector* plane [8] allows us to treat our C-arm system as a pinhole camera with fixed intrinsic parameters. The virtual detector is an imaging plane of reference corresponding to a set of values for intrinsic parameters of our X-ray imaging system. The definition and use of this cocept is described in details in [8] . The motion of this C-arm imaging system (X-ray source with the virtual detector plane) for a whole image series will then be the same as the motion of a CCD camera attached to the X-ray source. Using the direct motion estimation from consecutive projection matrices as described in [6], we propose a scenario in which we do not need to compute the intrinsic parameters of either our X-ray imaging system or the optical one. The scenario is divided into two steps:

1. *Off-line calibration*: One pair of images (X-ray and optical) is taken. The two projection matrices $\boldsymbol{P}_x$ (X-ray) and $\boldsymbol{P}_c$ (CCD camera) are used as reference for the transformation between X-ray and CCD camera coordinate systems. The image of the marker plate markers on the X-ray image defines the *virtual detector* for the on-line calibration.

2. *On-line calibration*: For each frame, the motion of the X-ray source relative to its position in the off-line calibration step is computed using the optical camera. This is done by computing the projection matrix for optical camera and estimating the motion without ever computing its intrinsic parameters: $\left([\boldsymbol{R}, \boldsymbol{t}] = f\left(\boldsymbol{P}_c, \boldsymbol{P}'_c\right)\right)$, see [6, 5] for more details on direct motion estimation. We then apply this motion to the reference X-ray projection matrix $\boldsymbol{P}_x$, resulting in X-ray projection matrix $\tilde{\boldsymbol{P}}'_x = \boldsymbol{P}_x \cdot \begin{bmatrix} \boldsymbol{R} & \boldsymbol{t} \\ \boldsymbol{0}^T & 1 \end{bmatrix}$. This provides us with an X-ray projection matrix that projects 3D voxels onto our *virtual detector* plane for each frame. Using the marker plate (attached to the X-ray source) the planar transformation (2D-2D mapping) between the X-ray image and *virtual detector* $\boldsymbol{H}$ is computed. The 3D-2D projection followed by the 2D-2D warping results in a new 3D-2D projection matrix $\boldsymbol{P}'_x = \boldsymbol{H} \cdot \tilde{\boldsymbol{P}}'_x$. This projection matrix, for each frame, provides the final mapping between 3D voxels and 2D pixels on the corresponding X-ray image.

1.3 3D-2D Overlay using CAMC

Once the volume of interest is reconstructed, CAMC provides the real-time registration between the coordinate systems of X-ray imaging system, optical camera and reconstructed volume. If the patient is immobilized, this provides the clinician with simulated X-ray images with no additional X-ray exposure for both patient and clinician. The clinician moves the C-arm to a new position. The optical systems uses the optical markers to compute the position and orientation of the C-arm relative to the initial X-ray and optical calibration. It computes the C-arm's X-ray projection geometry. It then projects the 3D volume and provides a "simulated X-ray image". The clinician can take a fluoroscopic images to check the accuracy of the CAMC calibration of X-ray projection geometry at any moment.

This process can also be used in order to visualize the result of 3D reconstruction combined with the real-time camera images. This is possible since the C-arm geometry and the 3D reconstruction are defined in the same coordinate system as our optical camera. This is done by using the optical imaging parameters as our 3D volume rendering parameters. The overlaid images can be created for each viewing point of the C-arm. Even in a later examination, for instance after surgery planning based on the 3D reconstruction data, the combined optical and X-ray (reconstructed volume) visualization can become quite useful. If the patient is not in the same position relative to the C-arm, additional optical markers attached to the patient can be used to register pre-computed volume data and current C-arm world coordinate system.

1.4 Experimental results

This section very briefly describes experimental results on 3D reconstruction using CAMC calibration process, a more detailed description can be found in [8].

For X-ray and camera calibration, we use a composite phantom which has two distinct but connected parts: one is the X-ray ring phantom, the other one is an optical phantom. The relative position and orientation of X-ray and optical phantom are known in the same coordinate system. X-ray phantom and calibration process are described in [6].

The X-ray and camera projection geometry are computed using an initial frame. The X-ray phantom and calibration procedure is only used for this initial frame. The intrinsic geometry of this X-ray projection is used to define the *virtual detector* plane.

In this experiment the C-arm is rotated about 190 degrees around both calibration phantoms and a reconstruction phantom that consists of two cylindrical objects covered in an acrylic hull (see Figure 2). For each image frame, X-ray and optical images are taken simultaneously. The optical phantom is used for motion estimation during the C-arm motion around the reconstruction phantom. Eighty five pairs of X-ray and optical images are taken during this motion. The C-arm is not able to provide the motion parameters with acceptable accuracy. Therefore, experimental results are primarily validated and compared with regard to the quality of the 3D reconstruction process.

Figure 3 shows CAMC's 3D reconstruction results. These figures show the three orthogonal Maximum Intensity Projections (MIP) of the reconstructed volume. The reconstruction results are quite satisfactory.

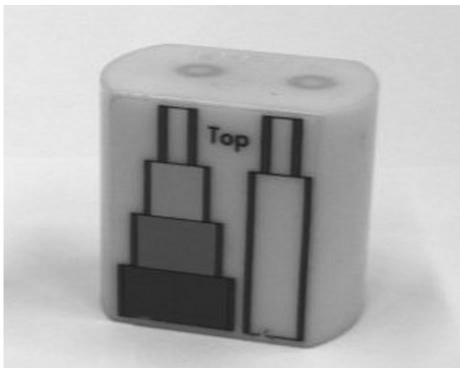


Figure 2. Reconstruction phantom

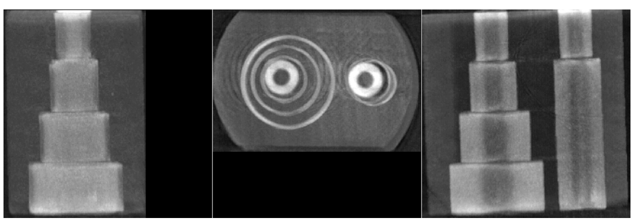
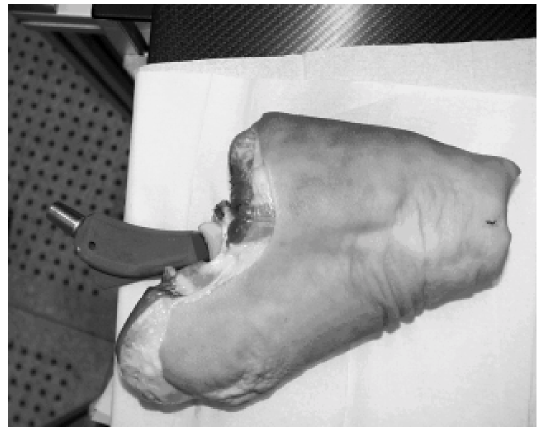
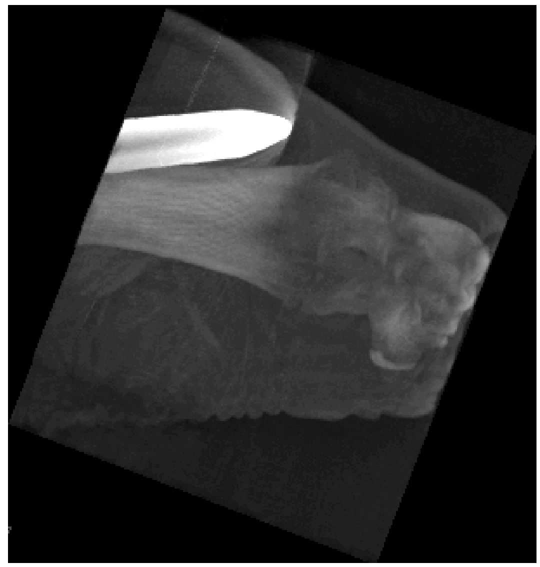


Figure 3. 3D reconstruction using optical camera and optical markers for estimation of the C-arm motion

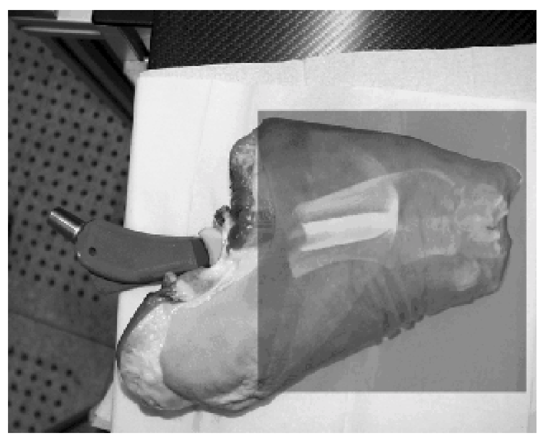
Figure 4 shows the principle idea of overlaying the optical image and the result of 3D reconstruction. The top image shows the original CCD image, the center image the reconstructed volume (visualized as a MIP). The bottom image shows the result of overlay. The coordinate system of the reconstructed volume is the same in which the pose of the optical camera has been estimated. The projection is therefore straight forward using the projection matrix estimated for the pose of the CCD camera.



optical image



3D reconstruction



overlayed image

Figure 4. CAMC would enable the superimposition of the reconstructed volume on top of optical images

2 Real-time overlay of X-ray and optical images

2.1 Introduction

C-arm X-ray systems are used in many surgical procedures as an interventional 2D imaging system. Often the clinician performs the procedure by looking at the screen where the X-ray images are presented. In these cases the X-ray images are presented on a monitor and in a different space than the patient space.

We propose a method and apparatus that enables the clinician to visualize the X-ray images combined and in the same space as the patient. This is done by blending the X-ray image with the video images taken from the patient with no need for 3D reconstruction. Using double mirror technology, we provide our optical imaging system with the same projection geometry as for the X-ray system. In this way the clinician can observe the X-ray and optical images and merge them to have the advantages of both systems. This can play an important role in many interventional procedures. This can not only provide better visualization, but it can also reduce the necessary X-ray fluoroscopy exposure for both clinician and patient during the intervention.

2.2 Principle and mechanical design

For a number of applications it would be advantageous to merge the current 2D X-ray and optical image without the need of a pre-computed 3D reconstruction. This requires that both images are taken from the same viewpoint, which is physically impossible. We therefore propose to use two mirrors to bend the principal axis of the CCD camera in such a way that both principal axes are aligned. This is visualized in Figure 5.

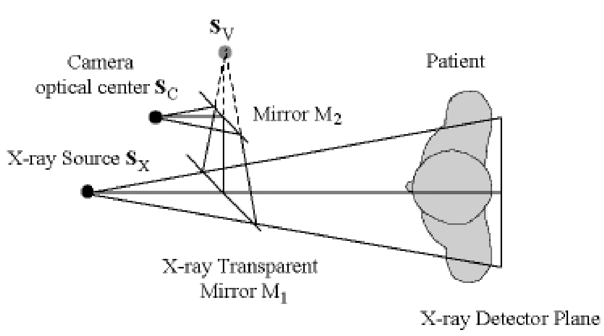


Figure 5. Conceptual design of the system

S_x is the focal point of the X-ray source. Ideally, we would need a camera with its optical center precisely at S_x, in order to have a viewing identical to the X-ray source. However, this is physically not possible. Mirror M_1 reflects the incoming light towards S_x to a new optical center S_v. The second mirror M_2 reflects the incoming light to S_v to a new optical center S_c, where the optical center of the video camera should be. If the video camera had the same viewing angle and imaging parameters as the X-ray system, then the camera would see exactly what the X-ray source sees.

2.3 Calibration procedure

In order for the Camera-Augmented X-ray C-arm system to work as specified in the previous section, we need :

1. Precise alignment of the principal axes of both X-ray and optical imaging systems. This can be achieved by proper positioning of the two mirrors M_1 and M_2, and the optical camera.

2. 2D-2D image co-registration (in-plane rotation and translation, and scaling) that corrects for the difference in intrinsic parameters for the two imaging systems

We satisfy both of the above calibration requirements through a single calibration procedure. The basic idea is to fix the two parallel mirrors and move the camera until a single planar transformation can fully register the X-ray and optical views for all 3D objects seen by both systems. This is only possible when the optical centers are aligned, in which case the planar transformation corrects for the difference in intrinsic

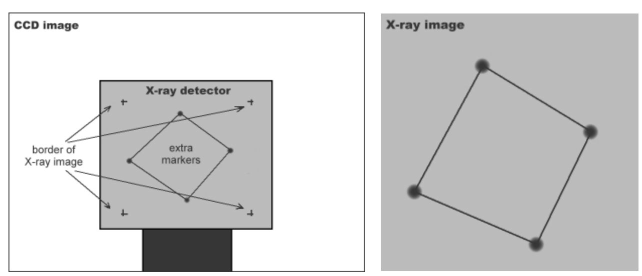


Figure 6. Calibration: X-ray image (right) is transformed such that it fits into the borders of the X-ray image as seen by the CCD camera. The mirrors have then be positioned such that the principal axes are aligned and the extra markers are co-registered.

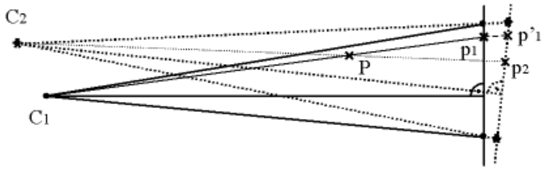


Figure 7. Calibration procedure used for matching X-ray image with the video camera image – simplified 2D case without mirrors.

parameters of the two imaging systems. In order to do this, we propose a simple and practical solution.

We use the corner points of the X-ray image, which are visible in the video camera image in order to compute the planar transformation between X-ray and video image, see Figure 6. Figure 7 shows the principle of our calibration procedure. C_1 represents the X-ray system, and C_2 the video camera that is to be positioned in order to co-register both images . For simplification reasons the two mirrors are left out and the camera geometries of X-ray system and video camera are unified. The 2 pairs of points at the borders (circles) – representing the borders of the X-ray image – are used to determine the planar transformation between the two images.

The planar transformation $\boldsymbol{H}$ maps the positions of each of the corner points on X-ray image to their corresponding points on the optical one. This planar transformation (homography) warps the X-ray image onto the image of the video camera. Regardless of the orientations of the two principal axes this transformation is valid for all points lying on the X-ray detector and can be estimated from 4 or more coplanar points. Alternatively, markers that are attached to the X-ray detector and are visible to both imaging systems can be used as calibration points.

We then take a point $\boldsymbol{P}$, which is visible on both X-ray and optical images and does not lie on the detector plane. This point is seen at position $\boldsymbol{p}_1$ on C_1 and $\boldsymbol{p}_2$ on C_2 imaging systems. The planar transformation $\boldsymbol{H}$ maps $\boldsymbol{p}_1$ from the X-ray image to a point $\boldsymbol{p}_1'$ on the optical image. If the two principal axes are aligned the two points $\boldsymbol{p}_1'$ and $\boldsymbol{p}_2$ will coincide. The calibration procedure is as simple as moving the video camera until these two points are superimposed.

These are the five consecutive steps of our calibration procedure :

1. Position four or more markers on the X-ray detector plane and one or more extra markers, which do not lie on the detector plane, the further from the image plane the better. The markers can only be used if seen by both imaging system. Corners of X-ray the image, which are visible on the video camera, can be also used instead as four in-plane markers.

2. Take one X-ray image.

3. Compute the image plane transformation based on the in-plane corresponding point pairs. Warp the X-ray image and blend it with the current video camera image (preferably in real-time). Note that all in-plane markers should be seen as perfectly superimposed.

4. Modify the camera position until the out-of-plane marker(s) are also superimposed. Note that the X-ray and camera optical axis are now aligned.

5. Fix the video camera. Record the final estimated planar transformation. This transformation will be used to correct for the difference in intrinsic parameters between the two imaging system. The system is now fully calibrated, and can provide real-time overlay of X-ray and optical images.

The clinicians can use a knob to control the blending coefficient, for example from 0 (only X-ray image) to 1 (only optical image). They can move the knob to find the correct blending coefficient, which satisfies the needs of a particular application. If necessary they can freeze the X-ray. The system will continue to blend the video images with this fixed X-ray image. If the region of interest is immobilized, the clinician can continue working under the guidance of this augmented video, and for example plan an intervention or orient a tool relative to a deep-seated anatomical structure. In this way the X-ray exposure for both patient and clinician is reduced. This may also result in higher accuracy for some interventional procedures by providing a direct link between patient's body and its X-ray view.

2.4 Experimental results

In this experiment we use a set of different metallic objects placed on the table as visualized in Figure 8. The same figure also shows the relative positioning of CCD camera, the two mirrors and the X-ray tube. The objects are placed on the table such that they occlude each other. The occluded parts can then be "seen" in the combined optical and X-ray image, see Figure 9. Here, we only applied a weak calibration procedure by roughly aligning both principal axes and using a set

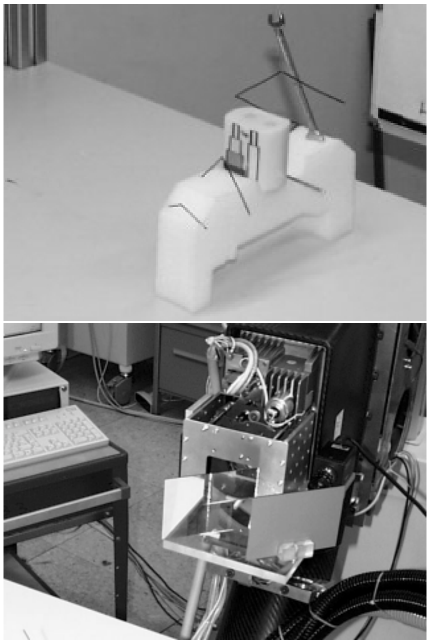


Figure 8. Experimental setup: Different objects positioned on the table (top), close-up view of the mirrors in front of the X-ray tube (bottom)

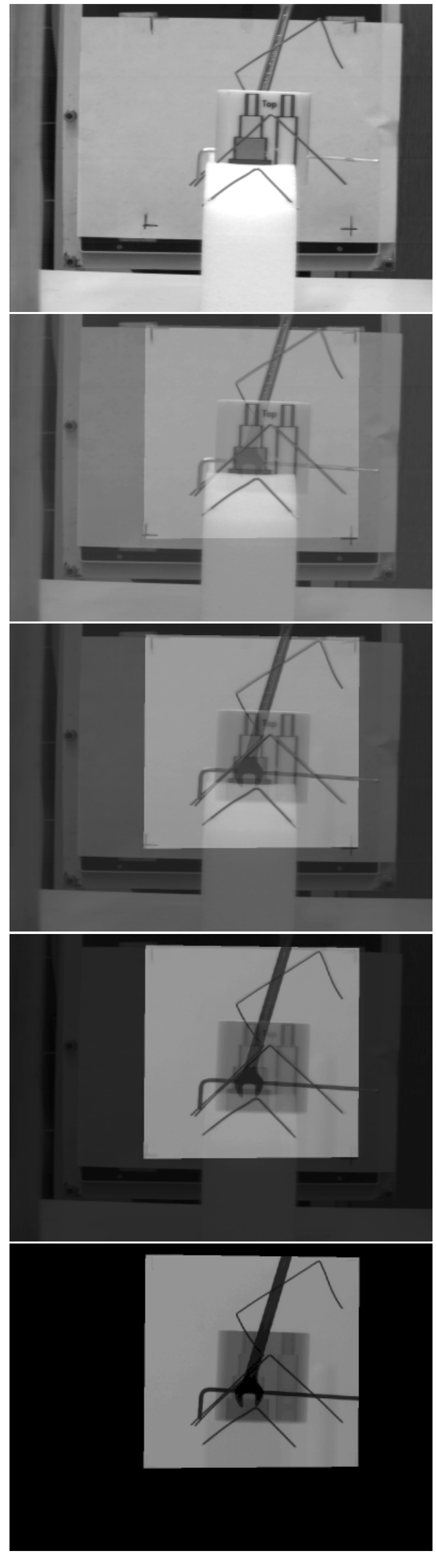


Figure 9. Experimental results: original video (top) and X-ray image (bottom), and result of overlay for 3 different opacities.

of points visible in both images (corners of wire structures) to estimate the planar (2D-2D) image transformation. The achieved accuracy of the correspondences between both images is satisfactory, but could be improved by using the more accurate calibration procedure described in previous section.

The result of another experiment that is closer to an actual medical application is visualized in Figure 10. A part of a pigs leg is postioned on the table. The X-ray image (left) shows the bone structure. In the combined optical and X-ray image (right) the bone structure can be seen on top of the optical image of the leg.

3 Conclusion and Future Work

This is one of the first presentations of the Camera-Augmented Mobile C-arm (CAMC) and its many applications in advanced medical imaging. Two different augmented reality applications are described. The first one allows the user to reconstruct a 3D volume from its X-ray projections, and to render this 3D volume using the same viewing parameters as the optical camera attached to the C-arm.

This is possible because using CAMC the X-ray projection geometry and the 3D reconstruction are known in the same coordinate system as the optical camera. The second application consists of real-time co-registration of optical and fluoroscopic images. This is done by using a double mirror system and an appropriate calibration procedure.

Compared to the first application, this system has the advantage of running in real-time with no need for on-line calibration of camera geometry. This also results in a more precise registration between X-ray and optical images. However, the 3D-2D approach has all the advantages, which usually come with a 3D model. For example the surgeon can define a path in 3D and visualize it as a simulated X-ray image overlayed on patient's optical image. It is also easier to attach a camera to an existing C-arm rather than adding both camera and the pair of mirrors. However, without the mirrors the camera needs to use optical markers in the scene for pose determination, unless if the C-arm motion is reproducible, which is not the case in general. The best solution would be a combination of both systems, where the optical camera and the mirrors system are calibrated for real-time registration, and optical markers are used for dynamic calibration of both optical and X-ray geometry for 3D reconstruction. This is what we hope to realize in the near future.

Acknowledgement: Authors would like to thank Oliver Schuetz, Rainer Graumann, and Alok Gupta for their continuous support and encouragement. They would also like to thank Karl Wiesent and Wolfgang Seissler for providing the 3D reconstruction software.

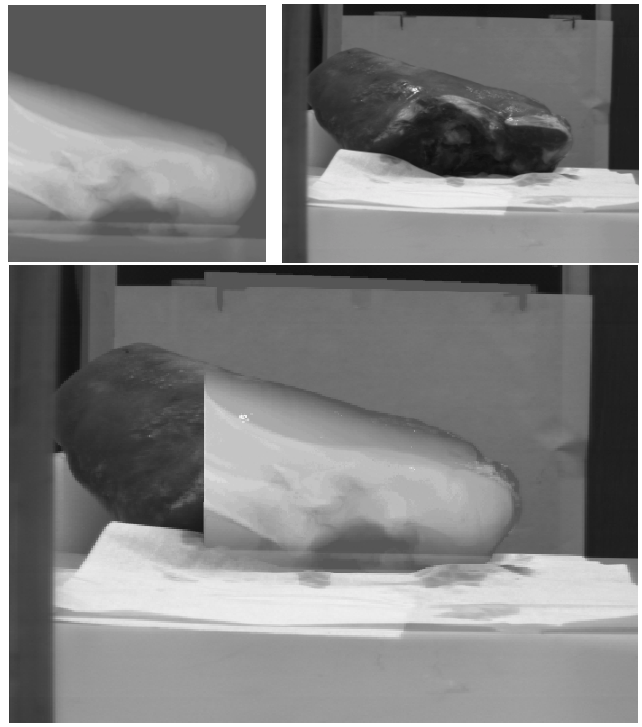


Figure 10. Experimental results: X-ray image (top left) and video image (top right) of a part of a pigs leg, overlayed optical and X-ray image of a part of a pigs leg (bottom).

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