Long Bone Panoramas from Fluoroscopic X-ray Images

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This paper presents a new method for creating a single panoramic image of a long bone from a few individual fluoroscopic X-ray images. The resulting panorama is the equivalent of a single X-ray image with a field of view several times wider than that of the individual images. The method uses readily available hardware, requires a simple image acquisition protocol and minimal user intervention, and works with most existing fluoroscopic units without modifications.

Keywords: computer-aided surgery, orthopaedic surgery, X-ray fluoroscopy, X-ray image processing, panorama.

1. INTRODUCTION

Current orthopedic practice heavily relies on fluoroscopic X-ray images to perform a variety of surgeries such as fracture reduction, total hip replacement, osteotomies, and pedicle screw insertion, to name a few. Surgeons use these images, acquired with a mobile C-arm unit during surgery, to determine the relative position and orientation of bones, implants, and surgical instruments. While inexpensive and readily available, X-ray fluoroscopy has several important limitations, including a narrow field of view, limited resolution and contrast, and geometric distortion. These limitations require the surgeon to mentally recreate the surgical situation from several uncorrelated images, make frequent use of the fluoroscope to obtain alternative images, and preclude precise measurements. The surgeon's reduced capability leads to positioning errors, cumulative radiation exposure to the surgeon, and suboptimal results in a non-negligible number of cases.

While some modern fluoroscopic units incorporate geometric distortion correction and contrast enhancement, none, to our knowledge, addresses the issue of the narrow field of view. In this paper, we describe a novel, simple, and inexpensive method for creating a single panoramic image from a few individual fluoroscopic X-ray images. The method, called image mosaicing, finds correlations between individual overlapping images and composes them to produce an undistorted panoramic view, which is the equivalent of a single X-ray image with a field of view several times wider than that of the individual images. The method uses standard, readily available, and inexpensive hardware: a video frame grabber, a computer, and a standard radiolucent X-ray ruler with graduations. It can be used with most existing fluoroscopic units without any modification, involves a simple imaging protocol, and requires minimal user intervention.

Undistorted fluoroscopic X-ray images with a wide field of view can be very useful in a variety of intraoperative situations. For example, in long bone surgery, they can be used for determining the mechanical axis of the bone, aligning bone fragments, measuring extremity length and anteversion, and assessing the position of long implants, such as hip implants and medullary nails. All these require the presence, in the same image, of relevant anatomical features, such as the condyles, the femur head and the femur neck. In other surgeries, such as pelvis and spine surgery, it can be used to obtain an overall view of the anatomical structures and to document for future reference the final outcome of the surgery. These images and measurements are difficult or impossible to obtain with existing methods and can help to improve diagnosis, shorten surgery time, and improve outcomes.

2. PREVIOUS WORK

The creation of image panoramas, also called image mosaicing, has a long history and is an active area of research in computer graphics and computer vision ([5,6,9] to name a few). Panoramic images are created by correcting individual images for distortion (when necessary), aligning them, and then compositing them. The most technically challenging step is image alignment. The main technical issues are the number of images and the amount of overlap between them, the geometric constraints on camera poses, the type of mapping between images, and the identification of commonalities in two images. Most existing methods assume many closely related images, usually obtained from a video movie, where consecutive images are nearly identical. Identifying commonalities in two consecutive images is difficult, as anatomical features are hard to find robustly and accurately.

Medical applications include generating panoramic views of nailfold capillary patterns from video sequences [1] and creating panoramas from ultrasound images [7]. Both methods assume that a sequence of many, largely overlapping images taken in a single plane, is available. These methods are not applicable to the current practice of fluoroscopy, where the undesirable continuous mode is seldom used. Instead, we are interested in producing the panorama from between 5 and 10 partially overlapping images. Note that distortion correction is essential, as distortion increases with the wider field of view. Correcting for geometric distortion in individual fluoroscopic images is well understood and has been addressed in previous research [2,3,8]. It will not be discussed here.

3. MATERIALS AND METHODS

We describe a method to obtain a single composite panoramic image from a small number (between 5 and 10) of partially overlapping fluoroscopic X-ray images. We adapt techniques from image processing and computer vision to match overlapping images, determine their relative position, and compose them by pairwise fusing them into a single panoramic view.

We begin by describing the equipment setup and image capture protocol. The equipment consists of the mobile X-ray fluoroscopic unit in the operating room, a standard PC computer with a video card and a monitor, a custom dewarp grid, and a standard radiolucent X-ray ruler with graduations commonly used in orthopedics. Images are directly downloaded from the fluoroscopic unit to the nearby PC computer via a digital port, or captured from the video output port with an analog to digital frame grabber. The images are stored and processed in the computer and the resulting panoramic view is displayed on the computer screen or on fluoroscope screen. The custom dewarp grid is used to correct the images for geometric distortion. The X-ray ruler is used to establish a common reference between the images.

Shortly before surgery, the fluoroscope is placed in the orientation which will be used in acquiring the images for the panorama. The dewarp grid is placed on the fluoroscope's image intensifier and an image of it is acquired and transferred into the computer, which computes an image distortion correction map. The patient is then brought into the room and surgery begins. When the panoramic view is required, the X-ray ruler is placed next to the patient, roughly parallel and at same height of the long bone to be imaged. A sequence of overlapping images is then taken by translating the fluoroscope parallel to the bone. Subsequent images should overlap by between 20% and 60% of their area. As the images are acquired, they are downloaded to the computer, which computes and displays the resulting undistorted panoramic image. This protocol minimizes the patient's radiation exposure and eliminates the exposure to the surgeon. We assume a pin-hole camera model for the fluoroscope, as this has been shown to be a very good approximation of the X-ray imaging process.

The algorithm creates a single rectangular panoramic view from the individual images in three steps: distortion correction, alignment, and compositing. Distortion correction is performed by applying to each image the distortion map, which is computed from the previously acquired grid image and the geometric model of the grid. Alignment is performed on pairs of subsequent images by finding correspondences in their overlapping regions and computing a rigid transformation between them. Compositing is performed by placing the images in their computed position and computing pixel values at locations where images overlap.

For distortion correction, we compute the distortion map using local bilinear interpolation, as described in [8]. For image compositing, we generate the panoramic image as follows. First, we compute the bounds of the panoramic image from the individual image sizes and their transformations. Then, we compute each pixel value in the new image by backward mapping the pixel location to the individual undistorted images and compositing the pixel values at those locations. Composited pixel values can be average, median, maximum, or minimum of the individual pixel values.

Image alignment, also called image registration, is the most technically challenging step. It consists of estimating the transformation parameters which map points in one image to their location in a second image. The type of transformation and its parameters being estimated varies according to the transformation model used, from the simplest model, planar rigid transformation (three parameters), to similarity, affine or projective transformation (eight parameters). Once the type of transformation has been established, the alignment process consists of establishing and reducing the dissimilarity between the images [4]. The disparity between two images can be established based on geometric features or on pixel intensity values. Feature-based alignment requires feature segmentation but works with less overlap between images [9]. Intensity-based matching does not require segmentation but only works for nearly identical images. Neither feature-based nor intensity-based alignment are directly applicable to our problem. Accurate segmentation of anatomical features is difficult and not sufficiently robust in all situations. In addition, some anatomical structures, such as long bones, do not have sufficient distinct features. The required significant overlap between images precludes the use of intensity-based methods as several dozens of images are required.

We propose a feature-based alignment method based on a radiolucent orthopedic ruler with graduations and rigid planar camera pose geometry. The ruler is placed next to the anatomy of interest and must appear in all images. We extract from the image the ruler graduations and use them to pairwise align the images. Since the images are acquired by translating the fluoroscope parallel to the ruler, camera poses are assumed to lie on a plane with negligible rotation around the optical axis. The planar transformation relating the images consists of three parameters, two translations and a rotation. The parameters are computed by first finding the rotation and translation perpendicular to the ruler's main axis and then estimating the translation parallel to its main axis.

The ruler's angle and the distance from the origin are computed using a Hough transform. The difference in angle and translation between pairs of images are the first two alignment parameters. Next, we compute the translation parallel to the ruler's main axis from the histogram of the ruler's image. We isolate the ruler from the image and compute its histogram. Since there is only one object, the histograms has two peaks, corresponding to the background (high gray level values), and to the ruler (low gray level values). The threshold that segments out the ruler is the minimum value between the two peaks in the histogram. The ruler graduations can then be directly identified in the binary threshold image. The visible graduations define the possible relative image translations along the axis parallel to the ruler. Since there are at most a few dozen such graduations, the search space for the translation is both discrete and small. We use a linear similarity measure, normalized cross correlation, computed for all possible translations and choose the best fit for the parallel translation. Since the bone and the ruler are at approximately the same height, aligning the ruler segments will also align the bone.

Once all pairwise alignment transformations are computed, we choose a reference frame (for example, the first image) and align all images to it. After alignment to the reference frame the resulting panoramic image shows partial overlaps between successive images. The pixel values at the overlaps are computed by either averaging, choosing the minimum, maximum or median value of the original image pixels.

4. EXPERIMENTAL RESULTS

We have implemented the algorithm and acquired a few sets of individual fluoroscopic images of dry long bones (humerus and femur) with an X-ray ruler with 5mm graduations next to them following the protocol described above. The overlap between consecutive images was about 50%, and there were 5 to 8 images in each set. We created single panoramic images from the undistorted images with the program in a few tens of seconds. We showed the results to an orthopedic surgeon for evaluation. A qualitative evaluation showed very satisfactory results: the bone structures and the ruler showed continuous boundaries, with very small "jumps" (one or two pixels) at locations where images where composited. The images were deemed accurate and with clinical value. Figure 1 is an example of our method.

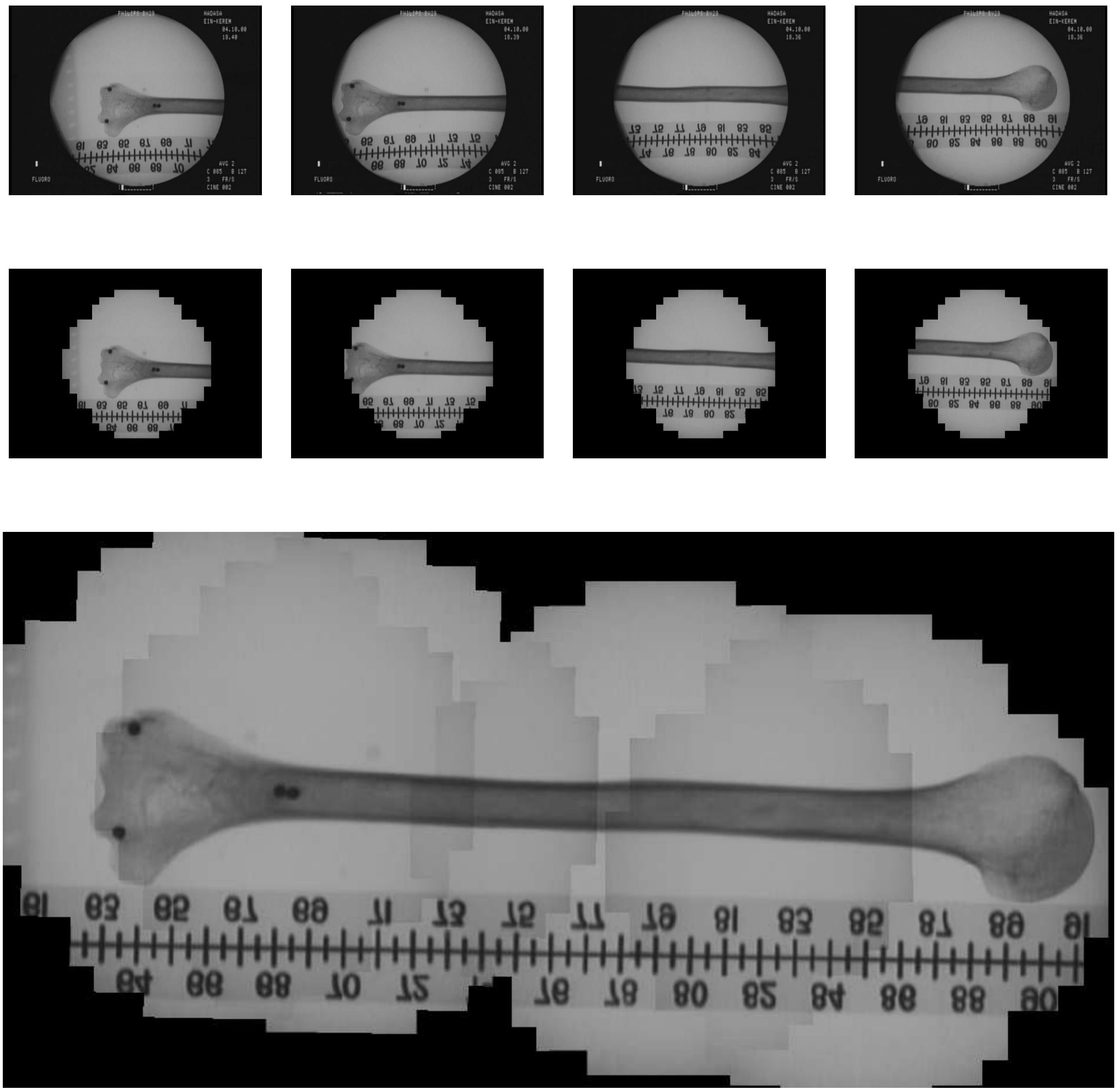

Figure 1. Panorama of a dry humerus. Top row shows the original images, the middle row shows the images after distortion correction, and bottom row shows the resulting panorama.

Our next step is to quantify the quality of our results. We plan to conduct accuracy measures to determine the error of the compositing process by comparing it with direct measurements on the dry bones or on a CT scan. We are also planning to evaluate the clinical usefulness of the panoramic view on actual patient cases.

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