A STEERABLE SYSTEM FOR POSITIONING C-ARM FLUOROSCOPY MACHINES

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INTRODUCTION

The most common way to acquire intraoperative images during many kinds of surgery is by using a C-arm fluoroscopy machine. This device consists of a relatively large (~1m diameter) C-shaped structure carrying an x-ray emitter at one end and an image intensifier or flat plate sensor at the other end mounted to a mobile (wheeled) base through a four degree of freedom kinematic structure to allow adjustment of the C relative to the patient (see Figure 1). The curve in the C allows the machine to be positioned around the patient so that x-rays can pass from the emitter to the sensor through the anatomical structures of interest to the patient.

Figure 1. Typical C-arm fluoroscopy machine

This machine is normally operated by a radiology technologist under the direction of the surgeon. The emitter is essentially a point source of x-rays, so the x-ray occupy a cone-shaped volume between the emitter and sensor. The diameter of the cone at the point where the anatomical structures of interest generally lie is therefore normally on the order of 10-15 cm. Since the structures of interest are internal to the patient and the patient is covered with surgical drapes, it is relatively challenging to centre the x-ray beam's axis at the position and orientation desired by the surgeon, so the positioning process is typically iterative, involving an ongoing conversation between the surgeon and the technologist as the technologist repeatedly releases and repositions the C-arm, takes a test x-ray shot, and discusses with the surgeon how to reposition the machine to optimize the view. Frequently, the machine is moved away from the surgical site to allow the surgeon to perform part of the surgical task and then brought back into position to assess progress or confirm the results of the surgical intervention. Such repositionings are often themselves iterative as there is no simple way to accurately reacquire the initial position.

Experienced technologists and surgeons who have worked with each other for a significant period of time can often perform these positioning tasks quite effectively, but much of the time, these interactions at the least interrupt the flow of the procedure and distract the surgeon and at worst are a significant source of frustration and delay in the procedure and expose both the patient and the surgical team to more x-ray radiation than necessary (Suhm 2003).

It is therefore desirable to find some means of steering the C-arm machine to the desired position more reliably and quickly in order to decrease surgical time, radiation exposure and frustration. Two previous groups have developed motorized C-arms (Suhm 2004, Bindera 2006), and commercial equivalents are now available (eg, the Ziehm Vario), but the original research devices have not yet been demonstrated to significantly improve the operative workflow, in part because the control and interaction process remains somewhat cumbersome, and the commercial devices have proven most useful in providing an off-centre isocentre, but have not yet demonstrated improved initial positioning. A commercial navigation system has been integrated with a C-arm and has been shown to decrease radiation exposure in repositioning maneuvers, but has not decreased repositioning time (Matthews 2007).

In response to these limitations of existing research devices, we have therefore proposed a simpler 'smart steering' system called Navi-C which aims to accomplish the goals listed above. In this paper, we present the design of this machine, along with initial performance results in a lab setting.

NAVI-C SYSTEM DESIGN

The initial design concept was developed at UBC in the context of a senior engineering physics design project supervised by Dr. Hodgson. The concept is to use steered wheels on the C-arm to allow the technologist to push the cart directly to the desired position using accurate position measurement and computer control to steer the cart. We purposely do not drive the wheels in order to keep the technologist in control as much as possible in order to enhance safety and allow natural handling of unexpected situations.

The system consists of the components illustrated in Figure 2: an optical tracking system for measuring the locations of key objects of interest, an optically-tracked pointing tool for the surgeon to use to indicate the desired view positions and orientation, a steering subassembly placed underneath the C-arm base to replace the function of the standard wheels and casters, and a display and control unit mounted next to the C-arm control panel to allow the technologist to control the Navi-C device.

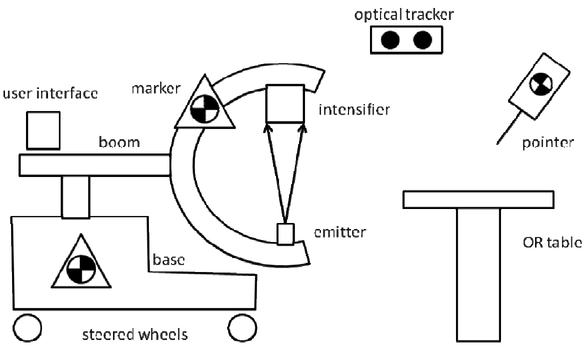

Figure 2. Components of Navi-C system.

The current prototype was designed in collaboration with the British Columbia Institute of Technology's Health Applied Research and Development group using standard design controls to facilitate future certification through the US Food and Drug Administration process (Navi-C would likely be regarded as a Class 2 device).

Tracking System: In its current incarnation, the system uses an optical tracking system manufactured by Claron Technologies (Toronto, Ontario), which is based on a camera system from Point Grey Technologies (Vancouver, BC). This is a dual-camera stereo vision system which performs real-time tracking and segmentation of passive markers with characteristic shapes (high-contrast circles and rectangles divided into black and white sections). The software automatically identifies these shapes and estimates the crossing points to sub-pixel resolution with an update rate of approximately 10-15 Hz. The accuracy of the system is claimed to be submillimetric over a workspace which is approximately a cube with 2 m edges. Markers are created by printing these patterns on selected materials (we use a washable vinyl) and applying them to the objects we wish to track: the surgical pointer (described below), the C-arm bow, and the machine base.

The major challenge in selecting a tracking system is finding an appropriate trade-off between cost and performance. We had originally considered using tracking systems commonly used for computer-assisted surgical systems (eg, the Northern Digital Polaris system (Waterloo, ON)), but such systems are quite expensive (~$15k) and are designed for smaller workspaces (approximately 1 m^3) and higher accuracy applications (accuracies are on the order of 0.3 mm). Our Navi-C application does not require such tight accuracies – end-to-end positioning accuracy only needs to be on the order of 1-2 cm – so we can theoretically accept a less accurate system in return for significant cost savings. The Claron system costs approximately half of the NDI system, and its accuracy is acceptable, but it has some limitations in the overall workspace size and further cost reductions would be desirable, so this system is not necessarily ideal for a final product. Nonetheless, it has adequate capabilities to be used to assess the Navi-C concept at the prototype stage if appropriate consideration is given to its limitations when evaluating the assessment results.

Surgical Pointer: The primary purpose of the surgical pointer is to allow the surgeon to directly point out the desired position and orientation of the x-ray beam axis, so this tool was designed to have a clearly visible axis which the surgeon would naturally interpret as the intended direction of the x-ray beam. The pointer element has a tip which allows the user to indicate specific points; this feature is currently used in a precalibration process to identify the locations of key C-arm machine points in the local coordinate frames defined by the attached markers, but is otherwise not used in the current application. The tool also has an array of markers attached which allow its 3D position and orientation to be fully resolved; through a process of calibration, the position and orientation of the pointer can be determined in the local frame of reference defined by the locations of the printed markers.

One challenge with the current system for our application is that the minimum size of the markers increases in proportion to the distance from the camera. At the typical distances we would need to use for this application, the markers need to be relatively large – on the order of 4-5 cm in diameter. Unfortunately, this makes the pointer appear to be somewhat large and clumsy. For a final product, we would like to invest further effort in making this pointer tool smaller, but, as with the tracking system itself, it is acceptable for the purpose of evaluating the Navi-C prototype.

Steering Subsystem: The steering subsystem is the heart of the Navi-C concept. A standard C-arm is equipped with two fixed rear wheels (which can be swung through 90° to allow lateral movement of the machine) and a front caster. We replace the function of these wheels with a cart which fits underneath the C-arm and lifts the machine off its regular wheels. This cart has three independently steerable wheels which are located adjacent to the original wheels and which are equipped with computer-controlled steering motors and encoders to measure the wheels' heading angles.

After the surgeon uses the pointer to indicate the desired views (typically at least two views are acquired to ensure that the surgical intervention can be properly assessed in 3D space), the system software computes the optimal approach angle for the C-arm base. The C-arm itself is an eight degree of freedom device, so it has two redundant degrees of freedom. The eight degrees of freedom and their implementations are defined as follows: two translations and one rotation in the plane of the floor are allowed by the wheels and caster, one vertical movement is provided by a lifting column installed on the C-arm base, redundant fore/aft (extension) motion and yaw (side-to-side) motions are provided in the boom, and two rotations (pitch and roll) are implemented in the bow of the C itself.

The positioning computation solves the inverse kinematics problem for the redundant C-arm architecture in several steps.

- First, we assume that the boom's extension and yaw motions are locked in their current positions (normally the boom is initially fully retracted and set in the neutral position in yaw). This removes the two redundant degrees of freedom from our calculations.
- Second, we compute the desired final position of the base as described in the following section.
- Third, we compute splines which connect the current position and orientation of the C-arm to the desired final position.
- Finally, we compute the current desired wheel steering angles based on these splines.

  These third and fourth steps are repeated on a continuing basis as new position information is received from the tracking system.

To compute the final position of the base, we proceed as follows:

1. We begin by affixing markers to both the C and the base of the machine and performing a calibration process in order to determine the fixed transforms relating key components of both the C-arm bow and the machine base to the local reference frames defined by the attached marker arrays. On the C-arm bow, we use the surgical pointer to digitize the x-ray axis and the plane of the C. On the base, we use the pointer to digitize the locations of the steered wheels. This calibration can be performed prior to the procedure.
2. Intraoperatively, the most common case (as indicated earlier) is that the surgeon will indicate two viewing axes. These two axes nominally intersect one another, though due to the fact that each one is acquired independently without being constrained to satisfy this intersection condition, the two indicated axes will in practice always be offset from one another (typically by a few millimeters). We therefore compute the mutual perpendicular to the two indicated lines and take the midpoint of this mutual perpendicular as the target point. We then define the target plane for the C-arm as the plane passing through this point with its normal aligned with the mutual perpendicular of the two indicated view axes.
3. We next compute the intersection of a horizontal plane through the target point with the C-arm target plane. The resulting horizontal target line indicates the desired final approach position of the C-arm machine; the vertical plane through the centre of the boom will be steered so as to come into alignment with this final target line.
4. Using the rigid body transform between the marker arrays attached to the C and the base, we map the final target line into the base's frame of reference. This defines the necessary position and orientation of the base.

Given the desired final position of the base and the measured current position, we use the spline interpolation method described above to compute the current desired heading angles for each wheel and implement a PID (proportional-integral-derivative) controller to drive the wheels to this orientation.

User Display and Interface Unit: The user interface unit consists of a touchscreen display unit mounted alongside the standard C-arm controls at the end of the boom and several screens:

1. A pair of calibration screens which allows the user to identify the key points on the C-arm and the base, as well as the operating table.
2. A steering screen, which presents a plan view of the operating room setting consisting of an image of the operating table, a dashed outline showing the final target position of the C-arm, and a solid outline showing the current position of the C-arm. The screen updates in real time as new position information becomes available and it indicates when the C-arm base is in the correct position by changing the colour of a targeting indicator from green ('go') to red ('stop').
3. A rotational alignment screen which provides guidance to the operator in positioning the C in height, roll and pitch.

Since the positions of the base and the C are monitored separately, the user can activate the redundant degrees of freedom (boom extension and yaw) and the system can immediately compensate by computing a new target position for the base. This allows the technologist to easily compensate for unmodelled limitations on the machine's motion such as an undesirable location of the operating table pedestal or an acute approach angle.

SYSTEM EVALUATION

The key performance metrics for this system are (1) the accuracy with which the system can be placed on the specified target, and (2) the time needed to put the system in place. To date, we have addressed the first metric in a lab setting.

To measure positioning accuracy, we created a paper target and fixed it to a model of an operating table (emulated by a standard worktable). Using the pointer tool, we positioned the tip on this target from two orientations roughly 90° apart. We mounted a fixed structure to the cart containing the steering system which included a pointer whose position relative to the cart was determined using a calibration procedure and whose tip was taken to model the midpoint of the x-ray beam axis. The steering algorithm was used to move the cart from a starting position approximately 1.5 m from the final position in order to place this calibrated tip as close to the original target point as possible using only the user display to guide the movement of the C-arm. Once the C-arm was at rest, we placed a dot on the paper target immediately underneath the pointer tip. We repeated this process 26 times (in 3 sets of 7-10 repetitions) from a variety of starting positions and measured the (x,y) coordinate pairs of each stopping position relative to the initial target.

The distance of the mean rest position from the origin (a measure of accuracy) averaged 10 mm and the root mean square distance from the mean rest position (a measure of repeatability) ranged from 3-6 mm. This experiment showed that the targeting process was reasonably accurate and repeatable.

DISCUSSION AND FUTURE WORK

In summary, we have demonstrated a functioning prototype of a 'smart steering' system for positioning C-arm fluoroscopy machines and shown that it is capable of positioning the x-ray beam axis on the desired target with good repeatability. Since the diameter of the x-ray cone at the point where anatomical structures are usually placed is usually on the order of 10-15 cm, an accuracy of ±10-20 mm should have little impact on the utility of the resulting fluoroscopic image.

Before moving to commercial development, we must run the Navi-C prototype through a further series of tests aimed at verifying that the anticipated improvements in operating room workflow efficiency can be achieved first in a simulated surgical setting and subsequently in live clinical trials. We plan to begin these tests shortly.

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