ROTATION ENCODING OF C-ARM FLUOROSCOPES WITH ACCELEROMETER

by

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Abstract

Accurate, practical, and affordable pose tracking on manually operated C-arm fluoroscopes is a major technical challenge. Conventional tracking methods, such as optical cameras and radiographic fiducials, are hampered by significant shortcomings. Optical cameras are delicate, costly, and have a complex system setup that is easily susceptible to camera obstruction in cluttered operating room. Radiographic fiducials occupy a significant portion of the fluoroscopic imaging space. Using fiducials also requires segmentation that limits clinical use. In this thesis, an alternative form of tracking is proposed to encode the rotational joints of manually operated C-arms using a tilt sensing accelerometer for tracking the C-arm rotational pose. The technique is evaluated by affixing an accelerometer to a full-scale C-arm where a webcam is used as a substitute for X-ray imaging. Ground truth C-arm rotational poses were obtained from the webcam by tracking a checkerboard plate. From these rotational poses, a series of angle and structural correction equations were formulated that can properly relate the accelerometer angle readings to the C-arm rotational pose in real-time and compensate for systematic structural C-arm deformations, such as sagging and bending. Real-time rotational pose tracking of the primary and secondary joint rotations of the C-arm showed an accuracy of 0.5 degrees in the entire range of interest.
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Chapter 1

Introduction

Many devices are used that aid in capturing and manipulating medical images. One such device is the fluoroscopic C-arm, which is ubiquitous in its applications throughout healthcare. This X-ray imaging device has essentially remained unchanged over the years and remains a versatile, compact, and mobile real-time imaging resource. Fluoroscopic C-arms can take on many different forms ranging from simplistic, manually operated designs to sophisticated, precision controlled machines. These characteristics make C-arms a desirable and well-established imaging resource that are becoming prevalent in computer-assisted interventions. Such inventions use the quick acquisition of X-ray images coupled with computational image processing techniques to provide new avenues for medical professionals to gather information. A common C-arm application is to provide multiple two-dimensional (2D) X-ray images of specific patient anatomy or medical implants that can be used to create a three-dimensional (3D) model of the patient. Using 3D reconstructions can provide new information previously unseen or unrecognizable in 2D images and can improve pre-operative planning and provide intra-operative assessment of surgical procedures.
1.1 Motivation

The motivation for our work is intra-operative implant reconstruction in fluoroscopy-augmented prostate cancer brachytherapy [8], shown in Figure 1. This procedure involves implanting radioactive seeds into a patient’s prostate in order to irradiate and destroy the cancerous tissue therein. Through the use of transrectal ultrasound (TRUS) imaging a pre-operative planning is performed to optimize the placement of the seeds within the prostate to eradicate the cancerous tissue, while avoiding damage to surrounding healthy anatomical structures. During the surgical procedure, the surgeon updates the pre-calculated plan and inserts needles with radioactive seeds into the patient’s prostate under TRUS imaging for visual guidance. However, it is difficult for the surgeon to efficiently determine how accurately the seeds were placed into the prostate. Even though the surgeon has ultrasound imagery available, the imaging quality of ultrasound is rather poor, which can contribute to inaccurate seed localization. The inserted radioactive seeds are highly reflective causing artifacts within the images that can resemble seeds creating difficulty for the surgeon to discern between real and false appearances of seeds [4]. Alternatively, acquiring X-ray images would allow for the seeds to be easily visualized, but only in 2D and with no tissue information making the prostate and relevant structures invisible. The solution is to use multiple 2D X-ray images to create a 3D reconstruction of the implanted seeds that is registered to TRUS in order to properly localize that seeds within the prostate and provide the surgeon with detailed information on how well the seeds were placed into the prostate [4].
The general procedure of prostate cancer brachytherapy augmented with fluoroscopy to help provide information for creating a 3D reconstruction of the implanted radioactive seeds.

In order to successfully reconstruct the seeds into a 3D representation, it is necessary to know the pose of the C-arm producing the 2D X-ray images. The C-arm pose represents the rotational (angle) and positional information of the X-ray source emitting an X-ray beam that travel through a target that imprints an image on the X-ray detector. Then acquiring multiple 2D X-ray images at known X-ray beam locations provides trajectory lines that can be traced back from the detector, through the target, to the source. With information on multiple projection lines, these lines will then intersect at a common point in 3D space. Tracing back the image points into 3D space is the basis of creating a 3D reconstruction of an object from the 2D image information.

A major component in creating a 3D reconstruction is finding the C-arm pose for each image. Currently, high-end fluoroscopic C-arms are sophisticated enough to provide joint rotation information through motorized joints and encoders that are pre-calibrated to provide the orientation of the C-arm accurately. These high-end systems incur a much higher purchase cost for hospitals and clinics as compared to the cost of a manually...
operated C-arm. Many of these facilities are unable to make such an investment. In contrast, the simpler, manually operated C-arms are more affordable and have been around much longer than their motor-driven counterparts. Manually operated C-arms represent the most common C-arm already found in medical facilities. In order for computer-assisted inventions to be effective with these types of C-arms, they are required to be retrofitted with a tracking method that can reliably calculate its current pose. Designing an accurate, practical, and affordable pose tracking method for manually operated unencoded fluoroscopic C-arms is a major technical challenge.

1.2 Proposed Technique

The work presented in this thesis proposes, develops, and evaluates an innovative C-arm rotational encoding technique by utilizing an accelerometer to encode the rotational joints of a fluoroscopic C-arm. This is possible by exploiting the accelerometer’s ability to sense gravity plus the inherent geometric properties that allow the accelerometer to be configured as a tilt sensor. By attaching the accelerometer to the C-arm and then performing a calibration process that models the rotating properties of the C-arm experienced by the accelerometer, the rotational joints of the C-arm can be encoded. However, the proposed technique can only provide the rotational (angle) portion of the full pose of the C-arm. Determining the remaining positional information of the C-arm pose requires knowledge of the forward kinematics, which models X-ray beam orientation through the joint parameters and structural dimensions of the C-arm. By applying the rotational values provided by accelerometer into the joint parameters of the
forward kinematics, the full C-arm pose can be recovered [3]. A diagram illustrating the proposed technique to rotational encoding of a fluoroscopic C-arm is shown in Figure 2.

**Figure 2: Rotation Encoding with an Accelerometer**

Using the accelerometer as a tilt sensor for rotation encoding of the C-arm. For our technique to be successful it was posited that it is possible to relate the accelerometer angle to the rotational pose of the C-arm.

### 1.3 Thesis Objectives

The main objective of this thesis is to develop a technique for tracking the rotational pose of the C-arm that is efficient, affordable, and practical for use in fluoroscopy-augmented prostate cancer brachytherapy. For the technique to be successful it is posited that a relationship can be determined by analyzing the differences between the tilt angle given by the accelerometer to the rotational pose of the C-arm. To validate this claim, two stages for experimentation were performed: the first stage evaluated the technique as a
proof-of-concept by tracking the rotational pose of a constructed C-arm analogue; and the second stage showed the actual viability of the proposed rotational encoding technique applied to a full-scale C-arm.

1.4 Thesis Contributions

A summary of the contributions of this thesis are as follows:

- Implementing an accelerometer to act as a tilt sensor.
- Development of the calibration process and formulating the tracking equations for relating an accelerometer to a fluoroscopic C-arm.
- Implementation of an optical webcam and checkerboard pattern to substitute for the X-ray imaging modality.
- Construction of a C-arm analogue for the first stage of experimentation for a proof-of-concept evaluation of the proposed technique.
- Evaluation of the proposed technique on a full-scale C-arm for the second stage of experimentation.

1.5 Thesis Outline

This thesis is divided into six chapters organized as follows:

**Chapter 2 Background:** provides brief descriptions on the current techniques of pose tracking and the initial posited theory of accelerometer positional tracking.

**Chapter 3 Rotation Encoding with Accelerometer:** describes the accelerometer, configuration of the accelerometer into a tilt sensor, and introduces the calibration process to formulate the relationship between the accelerometer and the C-arm.
Chapter 4 First Stage – C-arm Analogue: describes the experimental setup and provides the results for a series of experiments using a constructed C-arm analogue.

Chapter 5 Second Stage – Full-Scale C-arm: describes the experimental setup and provides the results for a series of experiments using a full-scale fluoroscopic C-arm.

Chapter 6 Conclusion: provides a summary of the author’s contributions, a description of the proposed intellectual property and patenting, and describes ongoing work to further develop the technique to rotational encode a fluoroscopic C-arm with the accelerometer.
Pose-tracking techniques for unencoded fluoroscopic C-arms have been in existence for many years. Existing techniques can be broken down into two general methodologies: external tracker-based (Section 2.1) or image-based (Section 2.2) techniques. Both are able to recover the full six degrees-of-freedom (6DOF) representing the three corresponding rotation directions (α, β, γ) and three translation directions (x, y, z) of the C-arm pose with high accuracy and precision. While either method is applicable when performing 3D reconstructions in a clinical setting, both techniques have shortcomings that prevent them from being a practical solution for prostate cancer brachytherapy.

During prostate cancer brachytherapy, X-ray images are captured using the C-arm in a step-and-shoot mode of operation where the C-arm is moved to a position, stopped to capture an image, and moved to another position to repeat the same sequence. Using these images, a 3D reconstruction of the seed implants is created relative to the prostate gland and other surrounding structures observed in TRUS imaging. Based on the localization of implanted seeds visualized in the 3D prostate reconstruction, the surgeon can re-optimize placement of the remaining seeds for improved radiation dose coverage of the prostate. For a successful implant reconstruction, the rotational pose needs to be recovered with an ideal error of less than 1° [8,11,16], which would provide greater than
98% seed localization with less than 2 mm in positional error. Various constraints imposed by potential collisions with the patient, operating table, and standard brachytherapy instrumentation limit the usable range of the C-arm to approximately a 30° cone in the canonical vertical position, shown in Figure 3. Even though this work primarily focuses in prostate cancer brachytherapy, other potential computer-assisted applications are not excluded from benefits of the proposed technique.

![Figure 3: Constraints imposed by clinical procedure](image)

C-arm rotation angle constraint in fluoroscopy-augmented prostate cancer brachytherapy caused by potential collisions with patient in lithotomy position, operating table, and medical instrumentations.

### 2.1 External Tracking

In external tracking, a marker called a dynamic reference body (DRB) is attached to the C-arm. This DRB can be detected by external equipment, such as optical cameras or electromagnetic sensors, which can estimate their position(s) in 3D coordinate space.
With this information, the problem becomes a matter of relating the coordinate frame of the C-arm detector (image) plane to the coordinate frame of the DRB and the external tracking system. In short, the two coordinate frames must be calibrated to one another. Once the tracking system is calibrated, full pose tracking can be achieved with potentially high accuracy and precision [13]. A diagram of optical and electromagnetic pose tracking is shown in Figures 4 and 5, respectively.

![Figure 4: Optical Tracking](image)

Optical tracking of the C-arm involves use a camera system to track the DRBs that are calibrated to the C-arm image space in order to recover the pose.
Electromagnetic tracking works in the same way as Optical Tracking where instead using a camera to track the DRBs, a magnetic field is generated with the sensor positions determined relative to the field.

Both tracking systems can track the C-arm pose accurately with an added benefit of being able to negate inherent problems with a C-arm such as transient oscillations and structural deformations experienced through normal operation. The transient oscillations arise from the inherent designs of the C-arm, where the heavy detector and source on the ends of the C-structure have excess inertia imposed by positioning movements that the wheel locks cannot prevent from occurring. Structural deformations arise from the heavy X-ray source and detector that are positioned at the ends of the C-structure, which are pulled down by the force of gravity. This causes the C-structure to bend and deform.

It is worth noting that each methodology comes with special considerations. For example, optical tracking provides better accuracy over electromagnetic, but requires that the DRBs are in the line-of-sight of the camera system. During a clinical procedure the
operating room can contain many medical instruments that could potentially clutter and limit the usable workspace. This can cause problems for the optical system since this line-of-sight can be easily obstructed by an instrument, thus causing the tracking of the C-arm pose to fail. Electromagnetic tracking is beneficial in that it does not require a DRB-to-camera line-of-sight since a magnetic field is generated that propagates outward. Instead, the DRBs are electromagnetic sensors that can detect their position relative to the magnetic field, so their requirement is that the DRBs are within the range of the field. Similar to optical tracking, the workspace within the operating room can cause problems for electromagnetic tracking with the presence of metallic objects that will distort the magnetic field. Within an operating room, the majority of the medical instruments, and more notably the C-arm itself, have metallic components that will distort the magnetic field inducing tracking errors.

An additional shortcoming to using either system is that they require an involved calibration process to properly relate the C-arm image space to the DRBs and tracking space. This calibration process needs to be performed each time the markers are placed including if one or more DRBs are accidentally shifted or moved making placements of the DRBs a delicate and crucial component to the calibration process. In all, external tracking tends to lead to a complex, labor-intensive, and ultimately costly setup for most care facilities. Moreover, in the specific case of prostate cancer brachytherapy, external tracking is not a practical solution for finding the C-arm pose because of these aforementioned shortcomings.
2.2 Image-Based Tracking

The other common method for C-arm pose tracking is an image-based methodology. The principal component behind this tracking technique is to use a radio-opaque object of known geometry (commonly referred as a fiducial) that is placed inside the imaging field [4,10,17]. Using this fiducial, it is possible to recover and track the complete 6 DOF pose of the C-arm, given that fiducial has sufficient specificity. A beneficial aspect of image-based tracking is that each fluoroscopic image acts as an independent, standalone tracker to provide accurate pose information [10]. This negates the need for a complex calibration process as well as cumbersome system setup. A diagram of image-based tracking is shown in Figure 6.

Figure 6: Image-based Tracking

Image-based tracking involves using a fiducial of known geometry, placed into the imaging field of the fluoroscopic C-arm. By acquiring X-ray images of the fiducial and segmenting the structure it is possible to determine the orientation that reproduces the 2D X-ray image, thus providing information that relates to the C-arm pose. The fiducial shown here is the FTRAC developed by Jain et al [9].
While image-based tracking is inexpensive and accurate, using a fiducial has shortcomings that prevent it from being a practical solution to C-arm pose tracking for prostate cancer brachytherapy. By placing a fiducial within the X-ray imaging field the valuable imaging space is greatly reduced. This space reduction forces the positioning of the desired target, for instance radioactive seeds, to be shifted from the ideal center of the detector plane to the edges where detector imaging experiences inherently increased distortion. This shift, in turn, could lead to inaccurate pose recovery and induce additional errors in the 3D reconstruction of the target object. Another major aspect that complicates the image-based tracking method is the need for fiducial segmentation. Segmentation is an important step, since the image points of the fiducial structure are extracted in order to compare to the 3D geometry of the fiducial to find the orientation that creates the 2D image. This means that for image-based tracking, the fiducial within the image holds the information of the pose. If the segmentation is inaccurate, the tracked C-arm pose will have increased error that could potentially cause failure. Commonly, the fiducial is manually segmented, but doing so is a tedious task and difficult to efficiently perform during an operation by a surgeon or support staff. While automatic segmentation algorithms attempt to alleviate the issue, they are not yet robust enough to repeatedly produce accurate and reliable results. In general, this segmentation problem has been a common point of failure in clinical procedures [8,11].

2.3 Initial Accelerometer Theory

Our initial theory postulated the use of accelerometers as a positional tracker, by performing a double integration of the acceleration measurements to retrieve positional
information. Attempting to use accelerometers as positional trackers is not a new concept as previous literature have successfully used accelerometers for robotic navigation applications [1,12,14]. By adopting the strategies from robotic navigation systems, we thought it would be possible to calibrate the positional measurements recovered from the accelerometer to the actual C-arm pose. A diagram illustrating the theory of accelerometer positional tracking is shown in Figure 7.

![Accelerometer Positional Tracking](image)

**Figure 7: Accelerometer Positional Tracking**

Accelerometer positional tracking double integrates acceleration data to retrieve positional movement of the C-arm. Then the accelerometer is calibrated to properly track the C-arm pose.

However, applying those methodologies to find the pose, or slight variations thereof, proved to be problematic. The initial challenge was in dealing with the poor quality of the acceleration signal. An accelerometer has inherent issues that complicate the ability to simply record acceleration data and perform double integration [15,18]. During normal operation, the acceleration signal contains a significant amount of ever-present
noise inherent to the accelerometer technology that stems from mechanical, thermo, and electronic (transistors) properties [15]. Another source, in particular the three-axis accelerometer used for our experimentation, occurs from cross-talk sensitivity between each axis sensor. Complicating matters further is the noise is still present even when the accelerometer is in a stationary steady-state. When attempting to integrate this signal, any present noise-error is carried forward and magnified through the integration process causing a substantial amount of drift. The results for an initial test showed the accelerometer errors were quadrupled after double integrating rendering the positional information unusable. These inherent accelerometer problems are illustrated in Figure 8.

![Figure 8: Problematic issues with accelerometers](image)

The acceleration signal from the accelerometer has a significant amount of noise that makes it difficult to properly filter and double integrate. During continued use the position information of the accelerometer drifts too much to be reliable and useful over time.
A major issue halting progression of accelerometer-based positional tracking involves the rotational characteristics of the C-arm structure, illustrated in Figure 9. As the C-arm rotates about a joint, the attached accelerometer will move in tandem. This rotational movement exerts two forces on the accelerometer: motion acceleration and gravitational acceleration. The problem is that the accelerometer cannot differentiate between the two forces and outputs a combined acceleration signal. For this reason, positional tracking fails to progress any further. Without the true motion from the accelerometer, any positional information retrieved from double integration is invalid. A potential solution is to find the gravitational forces acting on the accelerometer in order to remove them from the total reading to yield the required true motion acceleration. This requires the addition of a gyroscope to provide orientation information relating to the static gravitational forces, which increases the complexity and potential costs of the tracking.
Our goal of creating an efficient, accurate, and practical alternative to C-arm pose tracking would not be met through pursuing such a method. However, through attempting positional tracking, the strength of an accelerometer is in its ability to accurately measure gravitational acceleration in a stationary position. In Chapter 3, we introduce the work presented in this thesis that exploits the accelerometer’s strength, creating a new form of tracking with direct benefits for computer-assisted applications.
Chapter 3

Rotation Encoding with Accelerometer

3.1 Accelerometer

The key to the proposed technique presented in this thesis is an accelerometer. These devices are small, low cost, and have low power requirements, allowing them to be self-contained sensing systems. While they can be custom manufactured for a desired application, many general purpose packages are widely available ranging from 1, 2, and 3 DOF sensors. Through researching recent publications on uses of accelerometers, they generally are used within inertial measurement units for determining orientation (roll, pitch, and yaw), which conveniently provides the ability to find the C-arm pose. The principle behind the proposed approach begins with each axis of the accelerometer measuring the influence of gravity. In a stable-state with no motion force, each axis will measure a component of the overall gravity force of 1g, shown in Equation 1 and illustrated in Figure 10. Knowing this property, calculating the desired angles is a matter of reformulating the general equation to find the appropriate ratios that produce the desired angle [2]. Equation 2 gives an example, where the orientation of the accelerometer constraint the type of angles that can be retrieved $\alpha$ and $\beta$ are the angles along $x$-axis and $y$-axis, while the $z$-axis acts as the reference axis or gravity axis. The three accelerometer values, $A_x$, $A_y$, and $A_z$ that form Equation 2, can be rearranged depending on the chosen orientation of the accelerometer mounted on the C-arm. Figure
illustrates how the tilt angle of the $x$ axis is derived using simple trigonometry and constrains inherent to the accelerometer.

\[
\sqrt{\frac{A_x^2}{A_y^2 + A_z^2}} + \sqrt{\frac{A_y^2}{A_x^2 + A_z^2}} + \sqrt{\frac{A_z^2}{A_x^2 + A_y^2}} = 1g
\]  

(1)

\[
\alpha = \tan^{-1}\left(\frac{A_x}{\sqrt{A_y^2 + A_z^2}}\right) \quad \beta = \tan^{-1}\left(\frac{A_y}{\sqrt{A_x^2 + A_z^2}}\right)
\]  

(2)

![Figure 10: Accelerometer geometric constraints](image)

The acceleration experienced on each axes on the accelerometer are constrained by the force of gravity, which equals 1g and represents the gravity axis. When the accelerometer is stationary both the $x$ and $y$ axis will be zero making the gravity axis $z$. This is the normal operating orientation of the accelerometer, but it is possible to re-orientate the accelerometer maintaining same functionality of a tilt sensor.
Figure 11: Determine accelerometer tilt angle

The tilt angle is computed for the accelerometer $x$ axis ($\alpha$ in Equation 2) as the inverse tan of the acceleration value in $x$ over the square root of the squared sums of the acceleration values in $y$ and $z$.

In the previous chapter, section 2.3, it was mentioned that the accelerometer has inherent issues such as drift and noise in the acceleration signal. The benefit of using the accelerometer as a tilt sensor alleviates the effects of these issues making them easily accounted for. The drift in the accelerometer is quite minimal with the largest occurrence right after start up, so a 10-15 minute warm-up time is required before using the accelerometer to acquire minimally-drifting, steady-state measurements. Signal noise is handled by a MATLAB program that calculates the accelerometer angles using Equation 2. Prior to calculation, the program filters the acceleration readings from the accelerometer using a robust local regression smoothing operator to reduce the influence of noise, creating a consistent acceleration signal. After filtering, the mean value is taken for a set of 50 sample readings from each axis of the accelerometer, which is then used to compute the angle to be displayed on-screen.
For our experimentation, we used a Sparkfun™ Electronics WiTilt v3 packaged device. This is an all-in-one general purpose device that contains a class 1 Bluetooth® communication link, microcontroller, and accelerometer all housed in one small package. The convenient integration of this accelerometer package allows easy attachment to the detector or source without interfering with normal use of the C-arm, plus the Bluetooth wireless communication does not clutter the operating room with additional cabling. The accelerometer sensor contained within the WiTilt is a Freescale MMA7260Q triple-axis capacitive micromachined accelerometer. The technology of the accelerometer has numerous features such as high sensitivity to provide accurate gravitational readings for tilt angle calculation, low power consumption, and small electronic footprint for flexible configuration. Additional higher-level information on the accelerometer’s features and design technology can be found in the datasheet for the device located at the following link: [http://www.sparkfun.com/datasheets/Accelerometers/MMA7260Q-Rev1.pdf]

3.2 Calibration

The proposed rotational encoding technique has a novel calibration process that models the relationship between that accelerometer tilt angle and C-arm rotational pose. This calibration method was developed using a simplistic approach by incorporating general mathematical modeling principles while maintaining practicality for use in the medical environment. A workflow diagram for the calibration process is shown in Figure 12.
Figure 12: Calibration workflow

This is the core of the C-arm rotation encoding technique where a model is formulated to track the rotational pose of the C-arm with an accelerometer.

The diagram in Figure 12 provides a general overview of the calibration process, but the actual process has several important steps in order to perform a successful calibration. The following provides an in depth description of the steps involved in the calibration process:

1.a) **Mount the accelerometer on the C-arm**
For convenience the axes of the accelerometer are aligned with the rotational axes of the C-arm. This can be an approximation, since the calibration process handles the initial offset between the accelerometer and C-arm.

1.b) **Place C-arm tracking fiducial into imaging space**
Using the image-base tracking technique to provide rotational pose information is a simple and effective method. During experimentation the actual poses can be provided using a fiducial such as the FTRAC developed by Jain et al [9].
2. Acquire test images while logging the initial accelerometer angles
   The angles of the test images should have a wide range to cover the
   rotational motion of the C-arm in order to properly model the offset
   between accelerometer and C-arm.

3. Compute reference rotational poses using the fiducial

4.a) Compute the differences for both primary and secondary C-arm
    rotational angles
    By analyzing the differences between the initial accelerometer angles
    and C-arm rotational poses, a relationship can be formulated to correct
    for the differences in the two and therefore properly encode the
    rotational movement of the C-arm. This creates what we call Angle
    Correction Equations that will be discussed in-depth below.

4.b) Acquire new set of test images while logging the corrected
    accelerometer angle provided by the Angle Correction Equations

4.c) Compute reference rotational poses using the fiducial

4.d) Compute the differences for both primary and secondary C-arm
    rotational angles
    By analyzing the differences of the new set of image captured using
    the corrected angle output additional offsets caused by structural
    deformations in the C-arm can be accounted for. This creates the
    Structural Compensation Equations.

5. Confirm the accuracy of calibration on subset of independent
    angle measurements left out from the calibration computations
    This ensures an unbiased testing for validating the calibration of the
    accelerometer to the C-arm. If the accuracy is not satisfactory level
    repeat (6) to improve the accelerometer encoding model.

The basis of the calibration process for our technique is to formulate a series of
equations that model the effects of the C-arm acting on the accelerometer. Within the
model are two sets of equations. The first set is the Angle Correction Equations (ACEs)
that handle the initial misalignment between the C-arm and accelerometer. The second
set is the Structural Compensation Equations (SCEs), which were not fully developed until the second stage of experimentation, that handle the additional differences encountered by the accelerometer due to the structural deformations of the C-arm. Both the ACEs and SCEs are formulated by applying best fit models to the errors between the accelerometer angle readings and ground truth C-arm rotational pose. The ACEs take the initial accelerometer angle value as an input and corrects the output to match the rotational pose of the C-arm. This is different from the SCEs as the input comes from the ACEs and adds a compensating value to counter the offset experienced by the accelerometer at different rotational positions of the C-arm. Our methodology of modeling the motion properties of the C-arm has similarities to the paper published by Gorges et al. [5]. In their paper, they treat the C-arm as a pinhole camera and model the effects of the motions of the C-arm through the camera’s intrinsic/extrinsic parameters.

Once the ACEs and SCEs are created, the accelerometer is calibrated to the C-arm and the fiducial, specifically the FTRAC fiducial used during calibration, is no longer needed within the imaging field. This frees up valuable imaging space, thus improving the quality of the X-ray images as the target can be placed at the ideal center of the C-arm detector, which is an area generally assumed to be free of distortions. The calibration continues to be valid for subsequent uses given that the accelerometer remains affixed to the same location on the C-arm.

3.3 Image Acquisition Gaiting

A beneficial aspect of using an accelerometer is it’s the ability to monitor structural oscillations after the C-arm has been repositioned and therefore helps to reduce additional
imaging and pose error. These structural oscillations, as previously mentioned, arise from the inherent designs of the C-arm, where the heavy detector and source on the ends of the C-structure have excess inertia imposed by positioning movements that the wheel locks are unable to prevent from occurring. If image acquisition occurs during this period of time, the images may be blurred which would affect the quality and calculation of the pose estimates. The accelerometer has the ability to sense these rapid changes and presented them as spikes in the acceleration signal. By continuously monitoring for the spikes to subside (thus reading a steady-state) a “go-ahead” indicator can be flagged to inform the operator when images can be captured to avoid adding errors to the image. An illustration, in Figure 13, shows the benefit of using an accelerometer to gait image acquisition.

Figure 13: Residual motion gaiting with accelerometer

The accelerometer helps to gait the imaging process by informing the operator when it is safe to acquire an X-ray image without inducing errors from residual motions.
To evaluate the proposed rotation encoding technique, two stages of experimentation were performed and will be discussed in the following chapters. The first stage involved testing on a constructed metal C-arm analogue as a proof-of-concept experiment that was recently published in a journal [6]. The purpose of the analogue was to mimic the mechanical functionality of a C-arm, but the analogue did not possess X-ray imaging capabilities. Therefore, to substitute for X-ray imaging, an optical webcam was attached to one the end of the C-arm. Optical imaging is analogous to X-ray imaging, since both modalities produce 2D images, so determining the image pose is comparable to the use of a checkerboard pattern as a fiducial. The advantage of using a webcam is the removal of the harmful effects that come with ionizing radiation from X-rays. The second stage was a full-scale C-arm experiment that retained the use of the webcam for experimentation. This stage evaluates the true capability of the proposed technique in the ability to accurately model the motions of an actual C-arm [7].
Chapter 4

First Stage: C-arm Analogue

4.1 Experimental Setup

Our proposed technique to rotational encoding a C-arm with an accelerometer is a novel approach to solve practical pose tracking. This warranted a different type of experimentation to determine if the technique was a viable method. To reduce the laboratory turnaround time, avoid radiation exposure, due to limited access to an actual C-arm, a radiation-free, downscaled model of a C-arm was constructed. This C-arm analogue was built to mimic the mechanical rotations of a full-size clinical C-arm. Using the analogue was not enough, so it was coupled with a webcam to provide optical imaging in place of X-ray imaging. Accompanying the webcam was a checkerboard pattern that acted as a fiducial to be used in calculating the rotational pose of the webcam images. For visual and practical purposes the checkerboard was visually aligned to the webcam $x$ and $y$ axes, which in turn required the webcam to be align with the rotational axes of the C-arm analogue. The alignment and subsequent adjustments were based on visually examining the checkerboard pattern being centered in the webcam frame throughout each axis of rotation for the C-arm. Figure 14, shows images of the checkerboard from the perspective of the webcam and the checkerboard is aligned to the webcam frame. The experimental setup of the C-arm analogue is shown in Figure 15.
Figure 14: Checkerboard alignment to webcam C-arm Analogue

The checkerboard is aligned to webcam, which is aligned to the rotational axes of the C-arm analogue.

Figure 15: Stage 1 Experimental Setup – C-arm Analogue

C-arm Analogue experimental setup with a Microsoft LifeCam VX-3000 webcam, checkerboard, and attached Sparkfun™ Electronics WiTilt v3 accelerometer. The scale from the source to detector distance of the C-arm analogue to a true C-arm is approximately 1:2.
The workflow for rotational encoding with an accelerometer, described in Chapter 3, was applied to the constructed C-arm analogue. Mounting the accelerometer and placement of the checkerboard fiducial was performed first, followed by image acquisition using a “step-and-shoot” mode recording the raw, initial angle readings from the accelerometer. The set of test images were acquired at angles of approximately \([0^\circ, \pm 4^\circ, \pm 8^\circ, \pm 12^\circ, \pm 16^\circ, \pm 20^\circ]\) for the primary angle (PA) and secondary angle (SA), independently. This test set was chosen to provide an evenly-spaced, wide range of angles for experimentation. Moreover, this test set included angles that surpassed the constraints of clinical application motivating this work for validation of additional angles that may be useful in other clinical applications.

Once the test images were acquired, the rotational pose of the images needed to be determined for comparison. This was performed by determining the transformation matrix or extrinsic parameter of the webcam that contains information on the acquisition angle of the webcam. With the webcam mounted to the C-arm this provides a direct relationship to the C-arm rotational pose. In order to calculate the webcam’s extrinsic parameter required the use of a known object within the test image, which was provided by a checkerboard pattern. Then a freely available MATLAB camera calibration toolbox calculates the extrinsic parameter \(M\), which can be decomposed into a rotation matrix \(R\):
With the rotation matrix $\mathbf{R}$ extracted from the extrinsic camera parameter the resulting primary and secondary angles are computed using Equation 3.

Primary Angle:

$$PA = \sin^{-1}\left(\frac{r_{32}}{\sqrt{r_{11}^2 + r_{21}^2}}\right) \cdot \frac{180}{\pi}$$

Secondary Angle:

$$SA = \sin^{-1}(-r_{31}) \cdot \frac{180}{\pi}$$

The error was then calculated and displayed in Table 1, with the differences obtained by subtracting the initial accelerometer angle reading from the C-arm analogue rotational pose.

**Table 1: Stage 1 Experimentation – Initial Results**

The error between the initial accelerometer angle and actual webcam pose angles.

<table>
<thead>
<tr>
<th>Initial Accelerometer Readings</th>
<th>Primary Angle (PA)</th>
<th>Difference</th>
<th>Secondary Angle (SA)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-arm analogue</td>
<td></td>
<td>C-arm analogue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotational poses</td>
<td></td>
<td>Rotational poses</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>22.33</td>
<td>2.33</td>
<td>18.73</td>
<td>-1.27</td>
</tr>
<tr>
<td>16</td>
<td>18.22</td>
<td>2.22</td>
<td>14.78</td>
<td>-1.22</td>
</tr>
<tr>
<td>12</td>
<td>14.03</td>
<td>2.03</td>
<td>10.89</td>
<td>-1.11</td>
</tr>
<tr>
<td>8</td>
<td>9.85</td>
<td>1.85</td>
<td>6.69</td>
<td>-1.31</td>
</tr>
<tr>
<td>4</td>
<td>5.88</td>
<td>1.88</td>
<td>2.59</td>
<td>-1.41</td>
</tr>
<tr>
<td>0</td>
<td>1.73</td>
<td>1.73</td>
<td>-1.39</td>
<td>-1.39</td>
</tr>
<tr>
<td>-4</td>
<td>-2.36</td>
<td>1.64</td>
<td>-5.61</td>
<td>-1.61</td>
</tr>
<tr>
<td>-8</td>
<td>-6.63</td>
<td>1.37</td>
<td>-9.35</td>
<td>-1.35</td>
</tr>
<tr>
<td>-12</td>
<td>-10.49</td>
<td>1.51</td>
<td>-13.46</td>
<td>-1.46</td>
</tr>
<tr>
<td>-16</td>
<td>-14.56</td>
<td>1.44</td>
<td>-17.33</td>
<td>-1.33</td>
</tr>
<tr>
<td>-20</td>
<td>-18.91</td>
<td>1.09</td>
<td>-21.73</td>
<td>-1.73</td>
</tr>
</tbody>
</table>

From Table 1, one can observe a significant offset error existing between the accelerometer and the actual C-arm pose angles. To interpret these errors, Figure 16
provides a graphical view of the error. This representation suggests that a linear trend could possibly be formulated and applied to correct for the observed error. By applying best-fit lines to the data, the equations necessary to relate the accelerometer angle to the rotational joints of C-arm analogue were created that effectively encoded the rotations of the C-arm. The resulting ACEs are shown in Equation 4 and Equation 5.

Let \( x \) represent the initial \( PA \) accelerometer reading then the new

\[
PA^* = 1.027 \cdot x + 1.730
\]  

(4)

Let \( z \) represent the initial \( SA \) accelerometer reading then the new

\[
SA^* = 1.009 \cdot z + 1.380
\]  

(5)

Figure 16: Stage 1 Experimentation – Graphical view of error and ACE formulation

Graphical visualization of the initial error between accelerometer and C-arm rotational pose. Best fit lines were applied to highlight and quantify the trend in the error, so that the offset can be corrected for.

Upon closer examination of the data in Figure 16, it was discovered that using the simple linear best fit method to create the ACEs may not be the only option. The data
seem to show non-linearity, so as an alternative polynomial-fit lines were applied to model the data as closely as possible, shown in Figure 17, which created the corresponding ACEs (Equations 6 and 7).

Let \( x \) represent the initial PA accelerometer reading then the new

\[
PA^* = 2E^{-05} \cdot x^3 + 9E^{-05} \cdot x^2 + 1.022 \cdot x + 1.730
\]  

(6)

Let \( z \) represent the initial SA accelerometer reading then the new

\[
SA^* = -6E^{-06} \cdot z^4 + 6E^{-06} \cdot z^3 + 0.002 \cdot z^2 + 1.008 \cdot z + 1.480
\]  

(7)

Figure 17: Stage 1 Experimentation – Polynomial ACE formulation
Polynomial fit method applied to the data to create a new set of Angle Correction Equations.

4.2 Results
With the calibration process complete for the C-arm analogue, several tests were conducted to evaluate the robustness of the formulated ACEs when tracking rotational pose. The first test used a new set of angles \([ 0^\circ, \pm 2^\circ, \pm 6^\circ, \pm 10^\circ, \pm 14^\circ, \pm 18^\circ ]\) for
evaluation of the accuracy of the linear ACEs. Using different angles for this test helped
remove bias for evaluating the capability of the formulated ACEs to interpolate the in-
between angles unused during the calibration process. Furthermore, this would also help
to indicate if the rotational motions of the C-arm analogue were being properly accounted
for. Table 2 shows the results of the first test along with the mean (µ) and standard
deviation (σ) of the error.

Table 2: Stage 1 Experimentation – Test #1 Results
The error between the corrected accelerometer angles and C-arm analogue rotational poses

<table>
<thead>
<tr>
<th>ACE Accelerometer Readings</th>
<th>Primary Angle (PA)</th>
<th>Secondary Angle (SA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-arm analogue Rotational poses</td>
<td>Error Difference</td>
</tr>
<tr>
<td>18</td>
<td>18.68</td>
<td>0.68</td>
</tr>
<tr>
<td>14</td>
<td>14.67</td>
<td>0.67</td>
</tr>
<tr>
<td>10</td>
<td>10.66</td>
<td>0.66</td>
</tr>
<tr>
<td>6</td>
<td>6.66</td>
<td>0.66</td>
</tr>
<tr>
<td>2</td>
<td>2.83</td>
<td>0.83</td>
</tr>
<tr>
<td>0</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>-2</td>
<td>-1.06</td>
<td>0.94</td>
</tr>
<tr>
<td>-6</td>
<td>-5.25</td>
<td>0.75</td>
</tr>
<tr>
<td>-10</td>
<td>-9.36</td>
<td>0.64</td>
</tr>
<tr>
<td>-14</td>
<td>-13.41</td>
<td>0.59</td>
</tr>
<tr>
<td>-18</td>
<td>-17.38</td>
<td>0.62</td>
</tr>
</tbody>
</table>

µ = 0.70  σ = 0.11
µ = 0.19  σ = 0.10

A second test examined the ability of the linear ACEs to track diagonal angles where
both the PA and SA were rotated together to determine if the ACEs were able to maintain
correct tracking of the pose. For this test, the angle set reverted back to the original [ ±4°,
±8°, ±12°, ±16°, ±20° ], but as pairs of PA and SA rotations. Table 3 shows the mean
and standard deviation of the error differences for tracking PA and SA in each respective
quadrant (for example, the reading [+4,-4] means positive four degrees in PA and negative four degrees in SA).

**Table 3: Stage 1 Experimentation – Test #2 Results**
The means (µ) and standard deviations (σ) for the diagonal angle test, which is separated into four quadrants.

<table>
<thead>
<tr>
<th>Angle Difference Error</th>
<th>+PA</th>
<th>-PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>-SA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA</td>
<td>µ = 0.01</td>
<td>σ = 0.13</td>
</tr>
<tr>
<td>SA</td>
<td>µ = 0.26</td>
<td>σ = 0.31</td>
</tr>
<tr>
<td>+SA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA</td>
<td>µ = 0.41</td>
<td>σ = 0.17</td>
</tr>
<tr>
<td>SA</td>
<td>µ = 0.04</td>
<td>σ = 0.17</td>
</tr>
</tbody>
</table>

The remaining test used the polynomial ACEs as the method for tracking the rotational pose of the C-arm. For testing, the same angles set was used as in the previous diagonal angle test of [±4°, ±8°, ±12°, ±16°, ±20°] for PA and SA taken independently. Table 4 shows the results with the error differences obtained by subtracting the ACE accelerometer readings from the C-arm analogue rotational poses.
### Table 4: Stage 1 Experimentation – Test #3 Results

The polynomial ACEs for tracking the C-arm analogue rotational pose.

<table>
<thead>
<tr>
<th>ACE Accelerometer Readings</th>
<th>Primary Angle (PA)</th>
<th>Secondary Angle (SA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-arm analogue Rotational poses</td>
<td>Differences</td>
</tr>
<tr>
<td>20</td>
<td>20.53</td>
<td>0.53</td>
</tr>
<tr>
<td>16</td>
<td>16.39</td>
<td>0.39</td>
</tr>
<tr>
<td>12</td>
<td>12.34</td>
<td>0.34</td>
</tr>
<tr>
<td>8</td>
<td>8.12</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>4.06</td>
<td>0.06</td>
</tr>
<tr>
<td>0</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>-4</td>
<td>-4.13</td>
<td>-0.13</td>
</tr>
<tr>
<td>-8</td>
<td>-8.11</td>
<td>-0.11</td>
</tr>
<tr>
<td>-12</td>
<td>-12.45</td>
<td>-0.45</td>
</tr>
<tr>
<td>-16</td>
<td>-16.58</td>
<td>-0.58</td>
</tr>
<tr>
<td>-20</td>
<td>-20.47</td>
<td>-0.47</td>
</tr>
</tbody>
</table>

\[ \mu = 0.02 \quad \sigma = 0.41 \]
\[ \mu = 0.83 \quad \sigma = 0.79 \]

### 4.3 Discussion

The results showed that accelerometer was successful in encoding the rotations of a C-arm analogue. According to Table 1 and Figure 16, it was possible to create an offset equation that properly related the accelerometer angles to the C-arm rotational joints. The results from Table 2 showed that by using the ACEs, the accelerometer could properly track the rotational pose with less than 1° of error. Also of note is Table 3, where the accelerometer simultaneously tracked the PA and SA with a high degree of reliability, but accuracy decreased when tracking the SA during negative PA rotations.

This error can be attributed to the imprecision of the metal C-arm analogue, since it was rather crudely hand-constructed for the sole objective of mimicking the mechanical functionality of a C-arm. When the distribution of pose-calibration images was observed,
this showed imprecision of the C-arm analogue construction, shown in Figure 18. The circled area highlights the most probable causes for the decreased accuracy, since the PA rotational path does not remain straight, slanting into the positive SA direction. This in turn affects proper tracking of SA since an unaccounted offset must be the cause for the deviation in tracking the C-arm analogue rotational pose.

**Figure 18: Stage 1 Experimentation – Analysis of C-arm Analogue motion**

The distribution of the pose of calibration images for the webcam C-arm metal analogue. The circled highlighted area shows a slanting path during negative PA rotation, which created an unaccounted for offset during diagonal rotations.

Using the alternative fit method to create the ACEs produced mixed results. Examining Table 4, the third order polynomial for PA correction helped to improve the accuracy of pose tracking with only slightly less precision. However, the fourth order polynomial for SA correction unsuccessfully tracked the pose all-together, which was modeled too closely to the data and lacks robustness for variations in the motion of the C-arm. This indicated that in one case a better relationship was found, while in the other,
the original yielded better results. This suggests that a refinement may be required in the ACE-creation step of the technique where a testing loop could be added to examine a few fitted models and determine the model that yields sufficiently high accuracy to be permanently used with the C-arm. Regardless, a simple linear fit method provided a satisfactory tracking accuracy. This stage of the experimentation showed that the rotational encoding of C-arm by using an accelerometer has potential to warrant further investigation on a full-scale C-arm.
Chapter 5

Second Stage: Full-Scale C-arm

5.1 Experimental Setup

Through the use of the C-arm analogue, it was demonstrated that our rotational encoding technique could successfully track the rotational pose. This experiment was used as the foundation to construct a fundamental evaluation on a full-scale C-arm. However, moving to a larger scale environment raised several issues that could cause unknown effects upon the accelerometer, and thus, the ability to rotationally encode the C-arm. The use of an optical camera for experimentation was retained from the previous experimentation and the alignment of the checkerboard pattern to the C-arm was performed with the same methodology discussed in Section 4.1. This allowed for experiments to be performed without exposure to radiation, but also provided an opportunity to improve our encoding technique before transitioning to a clinically functional C-arm. In addition, the testing facility was not sanctioned to allow for live X-rays to be fired during the period of experimentation, so the alternative was required. The experimental setup of the full-scale C-arm is shown in Figure 19.
Figure 19: Stage 2 Experimental Setup – Full-Scale C-arm

Full-Scale C-arm experimental setup retaining the use of the Microsoft LifeCam VX-3000 webcam and checkerboard. The Sparkfun™ Electronics WiTilt v3 accelerometer is affixed to the X-ray source end of the C-arm. The C-arm is operating in “Flip-Flop” mode where the detector and source are flipped providing an easier location to mount the webcam, but this mode of operation is reversed to the traditional use of the C-arm.

With the full-scale C-arm, the calibration workflow was repeated in the same manner as the C-arm analogue experiment. For calibration images, the test set of angles used were at [ 0°, ±5°, ±10°, ±15°, ±20°, ±25°, ±30° ] for combination pairs of PA and SA plus independent rotations. As in the previous analogue experiment, this test set was chosen to provide an evenly-spaced, wide range of angles for experimentation and included angles surpassing the constraints of the clinical application motivating this work as well. The collected data was analyzed to compute the error, shown in Figure 20. Several fit lines were then applied to Figure 19, with the second-order polynomial fit
lines chosen as the ACEs found in Equations 7 and 8. Other fit lines were applied to the data such as linear and higher polynomial orders, but either the lines did not model the error correctly or they lacked the robustness as found from the previous C-arm analogue experiment.

Let \( x \) represent the initial PA then the new angle

\[
PA^* = \begin{cases} 
-0.0003 \cdot x^2 + 1.037 \cdot x + 1.250 & x \geq 0 \\
0.0002 \cdot x^2 + 1.047 \cdot x + 1.250 & x < 0 
\end{cases}
\] (8)

Let \( z \) represent the initial SA then the new angle

\[
SA^* = \begin{cases} 
-0.0004 \cdot z^2 + 1.034 \cdot z + 3.270 & z \geq 0 \\
0.0007 \cdot z^2 + 1.051 \cdot z + 3.270 & z < 0 
\end{cases}
\] (9)

Figure 20: Stage 2 Experimentation – Formulating ACEs

The error between the initially placed accelerometer and the full-scale C-arm rotational poses. Notice that the trend in the data is non-linear which created the piece-wise polynomial ACEs.

An initial test was performed and showed that using the ACEs resulted in poor tracking of the rotational pose of the C-arm (results shown in Figure 21). On the full-
scale C-arm, an unaccounted offset was present that the ACEs were not correcting for
during diagonal and stationary axis rotations.

The ACEs did provide high accuracy in tracking the independent PA and SA
rotations. These offsets indicated that error was attributed to a significant amount of
structural deformation on the C-structure of the C-arm, illustrated in Figure 22.

Figure 21: Stage 2 Experimentation – Initial Results

[inside cells – actual C-arm pose angles: PA (shaded) | SA below || outside border – C-arm
pose positions using ACEs accelerometer readings]

42
Figure 22: Deformation of the C-arm

While exaggerated the C-structure of the C-arm bends slightly cause error to the C-arm rotational pose that the accelerometer could be account for.

In order to understand the effects of the deformation experienced by the accelerometer, the rotational pose errors were plotted in Figures 24 and 25, for both the PA and SA rotations. Figure 23 provides a reference of how the structural deformations are labeled and separated into four quadrants.

Figure 23: Division of Structural Compensation Equations
Figure 24: Stage 2 Experimentation – C-arm structural deformation for Primary Angle
The visualization of the C-arm deformations with accompanying best fit lines for PA.

Figure 25: Stage 2 Experimentation – C-arm structural deformation for Secondary Angle
The visualization of the C-arm deformations with accompanying best fit lines for SA.
Figures 24 and 25 were plotted using the initial test errors acquired from the ACEs in Figure 21. The errors calculated for the stationary and diagonal angle rotations were zeroed by taking the error value at the zeroth angle and then subtracting this value from the remaining errors of the rotational path. Figure 26 illustrates an example of how the deformation graphs were created.

![Deformation Graphs](image)

**Figure 26: An example of how the deformation graphs were developed**

The deformation graphs lead to the creation of the subsequent deformation correction equations.

Figures 24 and 25 allowed for a way to visualize and interpret the amount of offset error that occurred during angle rotations, plus gave the ability to model the structural deformation acting on the accelerometer based on the rotational position of the C-arm. We posited that the deformation for the PA is caused by the rotation of the SA and vice-versa. This is evident from Figures 24 and 25, since both axes experience a greater deformation due to gravity as the C-arm deviates further from the vertical position.
Polynomial fit lines were applied on the data and the Structural Compensation Equations (SCEs) were created that were used to correct for this structural deformation during rotational movements. The SCEs for both the PA and SA are shown in Equation 10 and Equation 11.

Let \( w = PA^* \) and \( x = SA^* \) then the compensated angle

\[
PA^* = \begin{cases} 
  w + (0.0002 \cdot x^2 - 0.047 \cdot x) & \text{if } x \geq 0 \\
  w + (-0.0012 \cdot x^2 - 0.053 \cdot x) & \text{if } x < 0
\end{cases}
\]

\[
SA^* = \begin{cases} 
  x & \text{if } w \geq 0 \\
  x + (-0.0038 \cdot w^2 - 0.073 \cdot w) & \text{if } w < 0 \\
  x + (0.0075 \cdot w^2 - 0.093 \cdot w) & \text{if } w > \tau, x > \tau \\
  x + (-0.0030 \cdot w^2 + 0.019 \cdot w) & \text{if } w < -\tau, x > \tau \\
  x + (-0.0065 \cdot w^2 - 0.038 \cdot w) & \text{if } w > \tau, x < -\tau \\
  x + (-0.0113 \cdot w^2 - 0.135 \cdot w) & \text{if } w < -\tau, x < -\tau
\end{cases}
\]

The function of the SCEs was to provide a compensating value to the accompanying ACEs. From modeling of the structural deformation alone, it was not possible to create continuous equations. The solution to this problem was to create a series of piece-wise functions formulated to appropriately model the deformation error. However, an issue that stemmed from using the piece-wise functions is the potential conflict as to when the compensation needs to be applied. To avoid equation “competition”, the equations were split into four diagonal quadrants at 45° diagonals from a top-down perspective of C-arm.
(see Figure 23 for a visual representation) plus stationary rotations where PA and SA were operated independently. To control the activation of SCEs, a threshold value ($\tau$) was implemented and calculated through examining the deformation graphs of Figures 24 and 25 for when the offset began to increase rapidly. Then through another series of the tests, the values of $\tau$ were fine tuned to improve the tracking accuracy of the C-arm rotational pose.

A concern in applying the technique on a fully-functional X-ray imaging C-arm was determining the amount of images required to calibrate and construct the ACEs and SCEs. Since working with an optical webcam imposed no constraints on time or radiation exposure, acquiring a large, over-amount of images was of no concern. Conversely, the same cannot be said of X-ray imaging. For this stage of experimentation, 52 images were acquired for the calibration process while another 52 were taken for testing purposes, which assumed that the number of calibration/testing images were successful on first attempt. If multiple attempts are required to improve the modeling of the C-arm, this means that over time, the number of acquired images could potentially add up a significant amount. Therefore, to prepare for the eventual fully-functional C-arm experimentation, the number of calibration images required for ACEs and SCEs formulation were reduced to $[0^\circ, \pm10^\circ, \pm20^\circ]$ from the original data collected previously. The reduction of calibration images created a new series of equations that were evaluated to determine if proper rotational pose tracking could still be maintained. These ACEs are shown in Equations 12 and 13 and SCEs in Equations 14 and 15.
Let \( x \) represent the initial \( PA \) then the new angle
\[
PA^* = \begin{cases} 
1.028 \cdot x + 1.360 & x \geq 0 \\
1.056 \cdot x + 1.360 & x < 0
\end{cases}
\] (12)

Let \( z \) represent the initial \( SA \) then the new angle
\[
SA^* = \begin{cases} 
-0.0016 \cdot z^2 + 1.050 \cdot z + 3.290 & z \geq 0 \\
1.051 \cdot z + 3.290 & z < 0
\end{cases}
\] (13)

Let \( w = PA^* \) and \( x = SA^* \) then the compensated angle
\[
PA^\dagger = \begin{cases} 
w + (0.0004 \cdot x^2 - 0.045 \cdot x) & x \geq 0 \\
w + (-0.0031 \cdot x^2 - 0.104 \cdot x) & x < 0 \\
w + (-0.045 \cdot x) & w > \tau, x > \tau \\
w + (0.0013 \cdot x^2 - 0.038 \cdot x) & w < -\tau, x > \tau \\
w + (-0.0020 \cdot x^2 - 0.034 \cdot x) & w > \tau, x < -\tau \\
w + (-0.0034 \cdot x^2 - 0.112 \cdot x) & w < -\tau, x < -\tau
\end{cases}
\] (14)

\[
SA^\dagger = \begin{cases} 
x + (0.0024 \cdot w^2 - 0.045 \cdot w) & w \geq 0 \\
x + (-0.0044 \cdot w^2 - 0.067 \cdot w) & w < 0 \\
x + (0.0062 \cdot w^2 - 0.073 \cdot w) & w > \tau, x > \tau \\
x + (-0.0019 \cdot w^2 + 0.019 \cdot w) & w < -\tau, x > \tau \\
x + (0.0022 \cdot w^2 - 0.022 \cdot w) & w > \tau, x < -\tau \\
x + (-0.0094 \cdot w^2 - 0.099 \cdot w) & w < -\tau, x < -\tau
\end{cases}
\] (15)

5.2 Results

To evaluate the calibrated accelerometer and C-arm pairing, a series of tests were performed. The first test examined the capability of the piecewise ACEs with the newly
coupled SCEs to track the rotational pose of the C-arm at new set of angles: \([0^\circ, \pm 2^\circ, \pm 6^\circ, \pm 10^\circ, \pm 14^\circ, \pm 18^\circ, \pm 22^\circ, \pm 26^\circ]\) for both independent and combinational rotations. As in the previous C-arm analogue experiment, the new angle set avoided using the calibration angles to examine whether the ACEs and SCEs were able to properly interpolate the other angles. The results are shown in a chart in Figure 27.
Figure 27: Stage 2 Experimentation – Test #1 Results

The results from the first test that evaluates the tracking ability of the accelerometer with ACEs and SCEs.

- **inside cells** – actual C-arm pose angles: PA (shaded) | SA below

- **outside border** – C-arm pose positions using ACEs and SCEs accelerometer readings

Note: Due to the experimental setup the (±26°, ±26°) diagonal angle were unattainable.

Figure 27 shows that by using the ACEs and SCEs, the C-arm rotational pose can be tracked with an average error of $\mu = 0.11^\circ$ and standard deviation of $\sigma = 0.21^\circ$ for the PA, while an average error of $\mu = 0.08^\circ$ and standard deviation of $\sigma = 0.36^\circ$ were found for the SA.
A second test examined the ability of the calibrated accelerometer to appropriately track angles during a rotation sequence that would show if accurate tracking is maintained for varying combinations of PA and SA rotations. A diagram of the path of the acquired images is shown in Figure 28 and accompanying results in Figure 29.

![Figure 28: Stage 2 Experimentation – Test #2 Path of Acquired Images](image)

The path of C-arm, where the dots indicate the locations that the test images were acquired.

![Figure 29: Stage 2 Experimentation – Test #2 Results](image)

The results of the accelerometer tracking the C-arm rotation pose throughout the designated path of Figure 28.

The final test examined the ability of the accelerometer to track the rotational pose of the C-arm using only a limited number of calibration images for formulating the ACEs and SCEs. The same set of angles \([0^\circ, \pm 2^\circ, \pm 6^\circ, \pm 10^\circ, \pm 14^\circ, \pm 18^\circ, \pm 22^\circ]\) was used, like
in the first test, and images were taken for both independent and combinational rotations. The results are shown in Figure 30.

As shown in Figure 30, a reduction in the number of calibration images used to formulate the ACEs and SCEs still yielded robust results similar to Test #1 (Figure 27). The results of Test #3 show an average rotational pose tracking error of $\mu = 0.10^\circ$ and
standard deviation of \(\sigma = 0.27^\circ\) for the PA, while producing an average error of \(\mu = 0.18^\circ\) and standard deviation of \(\sigma = 0.64^\circ\) for the SA.

5.3 Discussion

The experimentation showed that proper C-arm rotation encoding was achieved by using an accelerometer as a tilt sensor, with adequately high accuracy and precision. The key to our tracking method’s success was in the development of the Structural Compensation Equations. These equations worked in tandem with the original Angle Correction Equations to compensate for inherent structural deformations of the C-arm. Within the complete range of relevant rotational poses for the motivating clinical application, prostate cancer brachytherapy, the results showed accuracy and precision of less than 0.5\(^\circ\), which is well within the “clinically acceptable” range of less than 1\(^\circ\) [8,11,16].

While the technique of using an accelerometer for tracking the rotational poses of a full-scale C-arm was successful, it was not completely without issue when ventured outside the clinical focus to encompass a larger range of operating angles. The results presented in Figures 27-30, showed that the tracking accuracy of the rotational pose starts to become unreliable at larger combined rotational poses. This effect could be attributed to the threshold values used to control when a given SCE compensates for the structural deformation of the C-structure. Even though it was clear that the values control the activation of these equations, it remained difficult to discern when or where they should start to be applied. For the clinical application, the SCEs were created by zeroing the offset created by the structural deformation, but it may be possible to start monitoring changes farther away from the origin. The reasoning behind this was that at the lower
angles about the vertical origin, the C-arm would experience less deformation caused by gravity and could still be within the capabilities of the ACEs to appropriately model the rotational motions. To improve upon this C-arm deformation modeling, a threshold *location* rather than a *singular conditional value* may prove to yield better results. This is an area for further development of the proposed technique that requires more investigation.

A significant outcome from this experimentation was the success in being able to track the rotational pose by formulating the ACEs and SCEs with a reduced number of calibration images. This result gave us confidence to continue to evaluate the rotation encoding technique on the next stage of work by applying the technique to a fully-functional C-arm using X-rays instead of an optical camera. Work on this stage has begun and initial test have yielded positive results.
Chapter 6

Conclusion

6.1 Summary of Contributions

In this work, we designed, implemented, and evaluated an alternative form of rotational pose tracking by encoding the rotational properties of a fluoroscopic C-arm through the use of an accelerometer. The rotational encoding technique implemented an accelerometer as a tilt sensor through exploiting the gravity sensing abilities of the accelerometer and inherent geometric properties. Through a calibration process, a series of equations (Angle Correction Equations and Structural Compensation Equations) are formulated to relate the accelerometer to the C-arm. Additionally, two stages of experimentation were performed to show that the concept was viable by applying the technique on a constructed C-arm analogue. The second full-scale C-arm experimentation provides strong support for the technique in being able to successfully track the rotation pose of an actual fluoroscopic C-arm.

6.2 Ongoing Experimentation

From the success and results of the of full-scale C-arm experiment provided enough confidence for work to continue on to the third stage of experimentation by applying the developed technique to a fully-functional C-arms, shown in Figure 31.
Figure 31: Fully-Functional C-arm Experimental Setup
The setup for our third stage of experimentation on a fully-functional C-arm. The setup on the left shows a manually operated C-arm, while on the right the C-arm used in our second stage of experimentation. The FTRAC provides actual pose information for comparison [9].

The results for the third stage are still rather preliminary, but accelerometer encoding results show promise in being able track the rotational pose of a the C-arm firing X-rays and not using a webcam as a substitute. A couple of insights have been gained using the manually operated C-arm, which were previously considered to be a failure point of the technique. One unexpected insight is that once the accelerometer and C-arm calibration have been completed, the accelerometer removed, and replaced in the same general area and orientation as previously attached (determined visually through structural landmarks on the C-arm) the calibration of the ACEs and SCEs remained valid and still provided accurate tracking of the rotational pose. Another interesting result came from having access to two different manual C-arms of the same make and model for applying the
tracking technique. The calibration results from the first C-arm were nearly inter-
changeable with the second, with only minor additional modeling required by
compounding the two sets of ACEs for tracking. This indicates that the construction of
C-arms of the same make and model may be relatively consistent. Thus, allowing for the
creation of a calibration model for one specific C-arm may be effectively ported to
another of the same type. Furthermore, this can open the potential for the manufactur-
ers of C-arms to pre-install and calibrate an accelerometer specifically to their device and
remove the need for the customer to seek a tracking implementation.

An unexpected issue arose, however, that is proving problematic is the change in the
structural deformation when using the normal operation orientation of the C-arm.
Previously, in the full-scale test the C-arm was operated in *flip-flop mode* (the source and
detector were flipped, compare Figures 19 and 31). For the experiment described in this
thesis, it was easier to mount the webcam to the C-arm in that mode, but this placed the
narrower source above the experimentation area. Now in the third stage, the C-arm is
used in the traditional mode with the detector on the top and source on the bottom. Due
to this change the structural deformation experienced by the accelerometer is different
requiring a new modeling method and work is being done resolve this issue to restore
tracking abilities to that were reported using the webcam.

To conclude, rotational encoding of a fluoroscopic C-arm with an accelerometer has the
potential to become a successful alternative for tracking the rotational pose in an
efficient, accurate, and practical manner for using in prostate cancer brachytherapy. Our
technique is not limited to this one clinical application and can be implemented in other areas that potentially could improve and provide better accessibility to computer-assisted inventions. With additional testing and development using real clinical conditions, we hope to be able to further refine our method to be suitable to a wide variety of C-arm fluoroscopes.

6.3 Future Work

The following suggestions for future work are made:

- For this work, the accelerometer was used to rotational encoding of the C-arm is considered a general purpose device containing a wireless Bluetooth communication link and is powered by a battery. However, these specifications of the accelerometer may not be clinically acceptable. Additional investigation is needed to examine different types, features, and properties of accelerometers to determine the suitable type for the clinically environment and experiments need to verify that the tracking accuracy of the device is maintained.

- Further development of a protocol for using an accelerometer to rotational encoding a C-arm is required to become a clinically viable solution. Some examples of the issues that need to be examined include determining the proper method of mounting the accelerometer to C-arm, longevity of accelerometer calibration, how to determine tracking failure, incorporating accelerometer angle output to the acquired X-ray images, and etc.
In this work, the accelerometer error and correction equations were modeled by applying polynomial fit lines to the error data. While this produced acceptable results, there is potential for improvement or simplification of the modeling process. Rather than formulating piece-wise polynomials to the data, fitting a continuous 2D spline could produce a better model of the structural deformation of the C-arm and improve the tracking ability of the accelerometer.
Bibliography


