MOTION-CONTROL SYSTEM OF BENCH-TOP CT SCANNER

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

By

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2008
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ABSTRACT
Patel, Tarpit. M.S. Egr., Department of Biomedical, Industrial and Human Factors Engineering, Wright State University, 2008. Motion-Control System of Bench-Top CT Scanner

Computed Tomography (CT) imaging has found applications in many areas such as diagnostic visualization, quantitative estimation, and therapeutic verification. In this wide range of applications, a CT scanner that can provide the data collection schemes of both second- and third-generation data-collection geometries will be an asset for laboratory research. In this thesis project, we developed a mechanical design and constructed a dual-generation CT scanner that provides flexibility in accommodating a wide range of object sizes with minimum scan time. Using 3-D graphical design software, models of the current second-generation CT scanner and possible solutions for modification were simulated. Based on material availability, cost, and benefits of each design, an appropriate modification scheme was selected to upgrade the current second-generation CT scanner to a third-generation CT scanner.

The modified CT scanner requires integration of both hardware and software components for its motion-control system. An open-loop motion-control system, which incorporates stepper motors, drivers, and a motion controller, is used to provide both the translate-rotate and rotate-only data collection movements. The software was
developed in National Instrument’s LabVIEW graphical language and is designed to control the movements of both motors and to generate the necessary timing pulses for the detectors. The LabVIEW program provides a flexible, user-friendly interface to the motion-control system and synchronizes all motor movements with the timing pulses to ensure data collection at the desired scanner positions. For both scanner movements, a set of mechanical limit switches monitors the mechanical end positions, and all movements are suspended upon activation of any limit switch. Metal proximity sensors are used for each movement to establish a home position.

The modified CT scanner, with the new hardware and software integrated, provides a full rotation in 3.6 seconds. It retains the flexibility to be operated as a second-generation translate-rotate or a third-generation rotate-only CT scanner.
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ACKNOWLEDGEMENT

The gratitude should first turn to my thesis director, Dr. Thomas N. Hangartner, for providing me with the opportunity to assist him in his research laboratory. I gratefully acknowledge his invaluable guidance, patience, support, and cooperation during the completion of this thesis.

I would like to thank Dr. Julie A. Skipper for her support and encouragement through the completion of my Master’s program. I wish to express my sincere appreciation to Mr. David F. Short, with whom I have had fruitful and insightful discussions.

I would also like to thank Ms. Sangeetha Alladi for her time, suggestions, and valuable input to my writing. I wish to thank Mr. Bhushan Kable for his help in teaching me SolidWorks, and Mr. John Lawless for his untiring efforts to modify the scanner. A special thank you also to Mr. Larry Sunden for helping me understand the electrical aspects of the scanner. I am grateful to Mr. Jeff Trunick for providing invaluable aid in the scanner wiring.

In addition, I wish to thank all my colleagues of the BioMedical Imaging Laboratory for their help and suggestions.

Finally, I express my deep appreciation to my family for their never ending support and encouragement, without which it would have been impossible to do my thesis.
1. INTRODUCTION

The primary objective of the current project is to establish a mechanical design for a dual-generation CT scanner that incorporates the data collection principles of both second- and third-generation CT scanners.

A second-generation CT gantry was selected and was modified to include features of the third-generation scanner geometry. 3D-graphical design software was used to simulate models of both the current CT gantry and suggested modifications. This allowed for visualization of the different modification schemes and facilitated to choose the optimum modification scheme.

The next step was to examine the changes to the motion-control system required to add the extended rotate motion. This task involved selecting suitable motion-control components and assessing them in terms of torque, speed, accuracy, resolution, and reliability.

Compatibility of the different components is the key in determining the success of the implementation. Performance studies in terms of speed, repeatability, and position accuracy were used to test the efficiency of the collective motion-control system in the modified CT scanner.
2. BACKGROUND

Imaging has become the most important non-invasive diagnostic tool in both the technological and clinical areas. The discovery of x-rays gave birth to medical imaging in the 19th century. Since then, non-invasive imaging techniques were developed in various modalities such as x-ray imaging, ultrasound imaging, magnetic resonance imaging, and computed tomography imaging. Computed Tomography (CT) imaging is one of the most frequently used diagnostic imaging modalities.

2.1 Computed Tomography (CT) Scanner

A CT scanner is a device that provides cross-sectional images of slices through the object using ionizing radiation. The major components of a CT scanner are an x-ray source and detector, which are rotated about the object being imaged. The first CT scanner was built by the British engineer Godfrey Hounsfield at EMI Laboratories in 1971.(1) Allan Cormack shared the 1979 Nobel Prize with Hounsfield for his mathematical contributions in the development of CT. (2) CT is used for a wide range of applications including diagnostic visualization, quantitative estimation, and therapeutic verification. CT scans can be performed with non-radioactive contrast agents to enhance the visibility of regions of interest when imaging blood vessels and organs such as the kidney. (3) Quantitative CT (QCT) scans are helpful in providing quantitative measurements of bone mineral content that evaluates the extent of bone breakdown in osteoporosis.
Since its advent, tremendous research and development has been made in CT in terms of speed and resolution to provide excellent image quality for diagnostic confidence at the lowest possible x-ray dose.\(^{(4)}\)

### 2.1.1 Principle of CT Scanner

The basic principle of CT is to represent an object using its density map, generated by visualizing the object from different angles. Each view is called a projection. Projection data are estimated by passing a collimated x-ray beam through the object. Since the object is composed of tissues of different densities, the resultant difference between the incident and attenuated x-ray beam is measured by detectors. The logarithms of the ratios of the unattenuated to the attenuated x-ray intensities are called projection data, which are used to reconstruct a cross-sectional image through mathematical algorithms. The following gives a more detailed description of the mathematical development of image reconstruction in CT.

Mathematically, *projections* can be defined as a set of integrated values of a relevant imaged parameter of the object. Let’s assume \( f(x,y) \) to be the imaging parameter of an object (Fig 2.1). In x-ray computed tomography, \( f(x,y) \) represents the linear attenuation coefficients.

The projection value \( p(t,\varphi) \) is the line integral of \( f(x,y) \) along a straight line \( s(t,\varphi) \)

\[
p(t,j) = \int_{s(t,j)} f(x,y) \, ds \quad \text{(i)}
\]

where \( \varphi \) is the view angle and \( t \) is the distance from the origin.
Collecting the projection value for different values of $t$ at a constant value of $\varphi$ gives one set of line integrals. By repeating this process for multiple values of $\varphi$ ranging from $0^\circ$ to $180^\circ$, one complete set of projections is obtained, which is required for reconstruction of an image.

During the reconstruction process, these projections are projected back onto the image plane under the same angle as collected. In order to avoid artifacts, the projections are filtered before back projection. Therefore, this image reconstruction algorithm is called the filtered back projection algorithm.
2.1.2 Source-Detector System and Data Acquisition Geometries

CT scanners have ordinarily been classified into five generations based on their data acquisition geometry. The first clinical CT scanner had one gamma-ray source and two photon detectors in adjacent planes that were forming pencil-beams.\(^1\) In such a first-generation CT scanner, the source-detector assembly moves across the object in a straight line, collecting projection data along the way. After the first translation, the assembly rotates by a certain angle and translates again to collect more projections (Fig. 2.2a). This process is repeated until data are collected over 180°. This method of scanning is referred to as \textit{rectilinear pencil beam scanning} and involves parallel beam reconstruction. The typical measurement time of a first generation scanner was 5 minutes for a single slice. Despite the fact that two slices were measured simultaneously with the first EMI head scanner, there was a need to shorten the measurement time.\(^5\) This need led to the development of scanners with a shorter scanning time to acquire a slice.

The \textit{second-generation CT scanners} are able to shorten the measurement time using a single source and an array of about 5-20 detectors, generating a number of pencil beams at the same time (Fig. 2.2b). Because of the divergence of the x-ray beams, one scan across the object results in as many projections as there are detectors, scanning an object with fewer linear movements. This scanner generation is also based on the translate-rotate principle like the first-generation scanners. The scanning time was reduced to 10 to 90 seconds.\(^6\)
Figure 2.2: Different generations of CT scanners
(a) first-generation, (b) second-generation, (c) third-generation, and (d) fourth-generation CT scanner geometry.

The concept of the fan-beam geometry lead to a new generation of CT scanners, the *third generation*, where the detector array is large enough to accept an x-ray fan that covers the whole cross-section to be measured. The source-detector assembly rotates 360° around the object (Fig. 2.2c). Translation is eliminated to significantly reduce the scanning time to 0.5 to 10 seconds. Faster scanning not only allowed to scan more anatomy in less time but also reduced motion artifacts. In the early stages, limitations on the length of the cables forced the gantry to rotate both clockwise and counterclockwise to acquire projections. After slip-ring technology was introduced, the third-
generation scanners extended their use as spiral CT scanners. The third-generation CT technology is currently one of the most popular scanner types.

Fourth- and fifth-generation CT scanners challenged the third-generation CT scanner in terms of geometric design with stationary detectors in the fourth (Fig. 2.2d) and stationary detectors and sources in the fifth generation. However, the cost increases with the increase in the number of detectors and sources made these systems less popular.

2.2 Motion-Control System

A motion-control system is a system that is composed of a motion system and a control system, which are used to generate and control motions of a machine based on speed, distance, and direction. Motion-system components typically consist of a motor and a driver. Control-system components combine the user interface and translate high-level motion commands to low-level driver input. The user interacts with the controller to describe the motion path using a high-level program (e.g., LabVIEW, MATLAB, or C). In addition, motion control systems also contain position feedback sensors, home sensors and limit switches.

A motion-control system can be classified as a closed-loop or an open-loop motion control system. A closed-loop motion-control system (Fig. 2.3) has one or more feedback sensors attached to the motor. The feedback sensors continuously compare the motion system output-response with the input commands. Based on the deviation
measured by the feedback sensors, the motion controller makes the necessary adjustments. The mechanism for generation of feedback forms the basis for different sub-classifications of the closed-loop motion control system. *Velocity control-loop systems* use a tachometer as a feedback sensor to detect changes in the speed of the motor. *Position control-loop systems* use a position encoder to measure the motor position.

![Figure 2.3: Block diagram of a basic closed-loop motion-control system.](image)

![Figure 2.4: Block diagram of a basic open-loop motion-control system.](image)
On the other hand, an open-loop motion-control system (Fig. 2.4) does not have any speed or position feedback information. The motion controller independently decides the necessary current or voltages to achieve the desired speed, position, or distance. As there are no feedback sensors, the open-loop motion-control system totally depends on the controller commands, and, thus, there are more chances to accumulate position or speed errors. However, open-loop motion control systems are often specified for applications where the motion is simple, the load remains constant, and low positioning speed is acceptable.

2.2.1 Motion System
A motion system is the hardware part used to generate a defined physical action. The driver supplies the necessary amount of current or voltage to the motor to produce the mechanical shaft movement.

2.2.1.1 Electric Motors
Electric motors, which transform electric energy into mechanical motion, are used to achieve the motion in the motion system. An electric motor works based on the principle of electromagnetism and the Lorentz force law. The Lorentz force law states: When an electric current ($I$) flows through a wire that is placed in an external magnetic field ($B$), the wire experiences a force ($F$) in the direction perpendicular to both the external magnetic field and the electric current (Fig. 2.5).
An electric motor has two main electric components: the stationary part called “stator” and the rotating magnet assembly called “rotor”. The external magnetic field is generated either by supplying current thorough the stator or with a permanent magnet. Due to interaction of the magnetic field produced by the stator and rotor, the rotor experiences an electromagnetic force and rotates about its axis. Based on the type of current used to produce the magnetic field, electric motors are classified as either alternating current (AC) motors or direct current (DC) motors.

### 2.2.1.1 AC Motors

AC motors, as the name implies, operate with an alternating current supply. The alternating current continuously flows through the stator of an AC motor and reverses its direction at regular intervals. This alternating current produces an alternating magnetic field in the stationary wire windings and applies electromagnetic forces to the rotor.
These electromagnetic forces cause the rotor to turn perpendicular to the magnetic field and the current flow (Fig. 2.6). Based on the speed of the rotor and the way of producing the magnetic field in the rotor, AC motors are divided into two classes: induction motors and synchronous motors.

Figure 2.6: Relationship between current flow and rotor direction. Alternating current energizes the electromagnetic stator windings causing the magnetic rotor to rotate about its axis. As the current stops the rotor will hold its position. When the direction of the current is changed (anti-clockwise direction), the rotor also changes the direction of rotation. In single-phase AC motors, an additional set of windings is used to set the initial direction as there is no normal direction of rotation (adapted from 7).

In induction motors the magnetic field in the rotor is produced by the principle of electromagnetic induction. Instead of supplying current to the rotor to establish an electromagnetic force, an electric current is induced in the rotor as in an electric transformer. In other words, the current carrying stator forms one set of electromagnets, which behave like the primary windings of a transformer. These primary windings induce an opposing current in the rotor windings, which produces a secondary magnetic
field. Both magnetic fields are separated by an air gap, and interactions between them produce electromagnetic forces which cause the rotor to rotate.

In the induction motor, a voltage must be induced from the stator to the rotor, which is possible when the magnetic field is changing. In the rotor the changing magnetic field, which occurs as a result of the rotating magnetic field of the stator, is delayed. Thus, for a voltage to be induced into the rotor, the rotor must rotate more slowly than the speed of the rotating magnetic field. If the rotor is turning at same speed as the rotating magnetic field, there is no induced voltage in the rotor. The rotor would not have a magnetic field to interact with the stator’s rotating magnetic field. This difference in the speed is referred to as slip. Because of this difference in speed, induction motors are sometimes called asynchronous AC motors. The constant-speed property of induction motors makes them most useful in applications requiring constant speed.

To avoid the above described difference in speed, the rotor of the motor must be energized from another source to produce the magnetic field. In a synchronous motor, the rotor has permanent magnets, which produce the electromagnetic field. The magnetized rotor locks on to the rotating magnetic field generated by the stator to cause the rotor to rotate at the same speed as that of the rotating magnetic field. Thus, the synchronous motor runs at constant speed, which is proportional to the frequency of the supplied electric current.
AC motors use electric current directly from the building power grid, which reduces the expenses of any rectifier circuits and provides rotary power with high efficiency. Also, AC motors are simple in design with a series of windings or a permanent magnet as stator and a simple rotating shaft. In most cases, AC motors do not use brushes, which reduce maintenance costs. On the other side, AC motors are limited concerning speed control. The speed of AC motors is dependent on the frequency of the AC supply. Although AC motors can be equipped with adjustable frequency or voltage controllers to change the speed, these controllers are complicated and expensive. The number of windings defines the base speed of AC motors. This speed gets reduced as load increases. For applications with a speed less than 1/3 of the base speed, AC motors overheat and cause damage to the stationary windings. Despite these limitations, AC motors are still in use where speed control is not necessary. A DC motor should be considered in the applications where accurate positioning and speed control is required.

### 2.2.1.1.2 DC Motors

DC motors operate with direct current supply. The magnetic fields are generated either by supplying direct current to electromagnetic windings or with permanent magnets. The rotor rotates on its axis as a result of electromagnetic interactions with the stator. During motor operation, the magnetic fields repeal and attract each other, and the rotor continues to rotate. Based on the construction, DC motors are split into three types: brushed DC motors, brushless DC motors, and stepper motors.
Brushed DC motors

The brushed DC (BDC) motor is a type of DC motor that is mechanically commutated to switch the current so that it does not require an external switch from the controller. The stator is made up of either electromagnetic windings or of a permanent magnet, sometimes called field windings or field pole. The rotor is composed of windings, called armature, that are connected to a commutator-brush assembly. The armature is an electric component of the DC motor that is linked to the rotating shaft. The commutator-brush assembly supplies current to the armature. The commutator is made of copper and surrounds the armature in two or more segments (Fig. 2.7). The brushes are made of carbon and slide over the commutator. As the motor turns, the brushes slide on different segments of the commutator. These segments of the commutator are connected to different windings of the armature causing current in each winding to switch direction at the proper time for the individual winding. The commutator also aids in reversing the direction of the motor by changing the polarity of the voltage. This change in the voltage causes a change in the magnetic field around the armature, resulting in the forces on the armature to be reversed. The brushed DC motors are divided into two types based on the way the stationary magnetic field is produced in the stator: the wound-field DC motors and the permanent-magnet DC motors.

The wound-field DC motors use electromagnetic windings for the stationary magnetic field. The direct current is applied to the stator and the armature to generate magnetic fields, which interact with each other to produce electromagnetic forces. Faraday’s law states: If an electric conductor is moved through a magnetic field, an electric current will
flow in the conductor converting mechanical energy of the moving wire into electric energy of the current that flows in the wire. In the wound-field DC motors, the armature coil is rotated in the external magnetic field generating an opposite-polarity voltage (to the line voltage) on the commutator segments called the counter-electromotive force (CEMF) voltage. This CEMF voltage is generated when the motor is running, and it is directly proportional to the stationary magnetic field flux and the speed of the motor. The CEMF voltage cancels out some of the line voltage to the armature and reduces the armature current as well. Thus, the speed of wound-field motors is directly proportional to the current supply to the armature and inversely proportional to the magnetic flux. There are three basic types of wound field motors: series-wound, shunt-wound, and compound-wound motors.
The *series-wound DC motor* has the stator windings in series with the armature windings (Fig. 2.8a). When the motor is not running, there is no CEMF voltage, and the full line voltage is available to the armature, providing a large armature current. Because of the series connection, the same current creates a large stationary magnetic field. The combination of a large magnetic field and armature current provides a large magnetic force at the start. The drawback of these motors is its characteristic to run away under no-load conditions. As the motor speed increases, the armature current also increases. So, theoretically the motor will continue to accelerate to infinite speeds, which is dangerous in applications where operation with no load is required.

![Diagram of series-wound DC motor](image)

**Figure 2.8:** Types of wound-field DC motors. (a) series-wound DC motor, (b) shunt-wound DC motor, and (c) compound-wound DC motor (adapted from ⁸).

In a shunt-wound DC motor, the winding is connected in parallel with the armature windings (Fig. 2.8b). Because of the parallel connection, current flowing through the stator winding is dependent only on the supply voltage, and the field flux is not affected by the CEMF voltage. Because the speed of the shunt-wound motors is independent of load, the shunt-wound motor tends to run at a relatively constant speed. The speed of the motor can be controlled easily by controlling the supply voltage. Inserting a
resistance in the armature or stator winding can also help decrease or increase the speed, respectively.

The compound-wound DC motor has both a shunt-wound and a series-wound stator winding (Fig. 2.8c). The main purpose of the series winding is to give a higher starting force. Once the motor is running, the CEMF voltage reduces the strength of the series winding, allowing the shunt windings to be the primary source of the field flux and provide speed regulation.

The only drawback of these connections is in reversing the direction. In wound-field motors, reversing the direction of the supply voltage reverses both armature and field windings, causing the motor to run in the same direction. To reverse the direction of rotation, the polarity of only the armature would have to be reversed.

*Permanent-magnet DC (PMDC) motors* use permanent magnets for the stator to generate the external magnetic field (Fig. 2.9). The armature of the PMDC is similar to that of the wound-field motors. The speed of the PMDC motor depends on the current applied to the armature windings as the magnetic flux of the stator remains constant.

![Diagram of PMDC motor connections](image)

*Figure 2.9: Permanent-magnet DC (PMDC) motor connections (adapted from ⁸).*
PMDC motors respond more quickly to change of speed than wound-field motors because the stator field is constant. The only disadvantage of PMDC motors is that the stator loses magnetism over time.

Brushless DC motor

Although brushed DC motors are highly efficient, they have the disadvantage that the brush-commutator system wears out, causes dust, is noisy, and requires maintenance. The brushless DC (BLDC) motor operates without brushes by taking advantage of electronic switching. The BLDC motor differs from brushed DC motors in several ways. The BLDC motor uses permanent magnets for the rotor, and the stator has poly-phase windings. It uses electronic sensors to detect the rotor position. These electronic sensors are mainly Hall-effect devices, located within the stator windings and wired to switching circuits (Fig. 2.10). Based on the sensor information, the switching circuits energize different windings to make the rotor rotate. The BLDC motors require complicated designs in terms of controlling speed. They cannot be reversed by just reversing the polarity of the power supply; the order of energizing the windings must be

![Figure 2.10: Three-phase brushless DC motor connections. H1, H2, and H3 are the Hall-effect sensors that detect the rotor position and energize the windings.](image-url)
reversed to obtain the reverse direction. This makes the driver electronics of BLDC motors more complex and expensive.

Stepper Motor

A **stepper motor** is a type of DC motor that converts electric pulses into unique shaft movements. This means that the stepper motor will move in fixed angular increments each time an electric pulse is applied to the motor. This fixed angular increment is determined by the number of rotor and stator poles. The stepper motor has a permanent magnet rotor and a stator with poly-phase windings. The stepper motor follows the same principle as the brushless DC motor. The rotation of the shaft can be achieved by energizing the stator windings one after the other around the circle. As the rotor turns by a fixed increment with each pulse, the controller knows the exact position of the stepper motor, which eliminates the use of Hall-effect sensors and allows the control system to be operated in open loop. The forward and reverse direction can be achieved based on the pattern of pulses applied to the windings. There are three types of stepper motors: permanent-magnet, variable-reluctance, and hybrid stepper motors.

The **permanent-magnet (PM) stepper motor** uses a permanent magnet as a rotor. The stator poles consist of electromagnetic windings. The energized stator poles produce a magnetic field, which repeals and attracts the magnetic rotor. This rotor does not have teeth but is circumferentially magnetized and turns until its poles are aligned with the stator poles (Fig. 2.11a). One of the advantages of the PM stepper motor is that the rotor tends to align with a stator pole even when no power is applied because the rotor
will be attracted to the closest magnetic pole. This property is desirable in many applications where the motor needs to hold its last position even when all power is removed. The only limitation with the PM stepper motor is that it is difficult to manufacture multi-pole magnetized rotors.

The variable-reluctance (VR) stepper motor differs from the PM stepper motor in terms of rotor design. The VR stepper motor is constructed with a toothed rotor made up of magnetically soft iron. The motor works on the principle of minimizing the reluctance along the path through a magnetic circuit. In other words, when a piece of magnetic material is free to move in the magnetic field, it will align itself with the magnetic field to minimize the reluctance of the magnetic circuit. The stator is made up of electromagnetic windings. The VR motor usually comes in a poly-phase stator design with a toothed rotor (Fig. 2.11b). The rotor tooth is attracted to the closest energized winding pole, but the force is less than that of the PM stepper motor. As there is no magnetization in the rotor, the VR stepper motor does not hold its last position when there is no current flowing through the stator.
The *hybrid stepper motor* combines features of both the permanent magnet and variable-reluctance stepper motor. Hybrid motors have a magnetic multi-toothed disc rotor and a multi-toothed stator. The magnetic rotor provides a detent torque to hold its position even when the power is turned off. The variable reluctance property of the hybrid motor allows it to provide high torque even at higher speeds. Hybrid stepper motors have vibration problems at high speeds because of their variable reluctance design, but these vibrations are not as severe as in VR stepper motors.

### 2.2.1.2 Driver

A driver in the motion system is responsible for converting the control system’s output commands to the motor. The driver must match the motor type and provide continuous current and voltage to the motor. If the driver supplies more current than the motor allows, the motor is damaged. If the driver supplies too little current, the motor cannot produce enough torque for the application. The driver must be capable of driving its associated motor and is classified as AC-motor driver or DC-motor driver.

#### 2.2.1.2.1 AC-Motor Driver

The speed and direction of an AC motor can be controlled by adjusting the frequency of the supply current, changing the pole pair number, or controlling the current supplied to the motor. Though speed changes can be made by changing the voltage, they are very small and do not have much effect under heavy load conditions. The only efficient way to control the speed of an AC motor is to be able to change the frequency of the line.
voltage. This can be done with power conversion units that are able to convert the line voltages of 60 Hz into a range of voltages and frequencies. There are two main choices to control the speed of AC motor: variable-frequency (V/Hz) driver and vector driver.

Variable-Frequency Driver

The variable-frequency driver, also known as variable-hertz driver or inverter, changes the motor’s speed by controlling the frequency and voltage. There are two basic steps in the variable-frequency driver (Fig. 2.12). The first step is to convert the AC line power source to DC power. The standard 60-Hz AC line power is converted to DC with a silicon-controlled rectifier (SCR). The SCR also controls the magnitude of the DC voltage. The second step is to convert this DC power back into AC at the desired frequency. This is done with output switching devices, usually transistors, which are controlled by the control system. The controller sends an on and off sequence of pulses to turn the transistors on and off in such a way that results in a pseudo-sine wave.

Synchronous motors will run at the synchronous speed which is the ratio of the frequency to the number of poles. For a specific motor, the number of poles is fixed, so the speed can be controlled only by adjusting the frequency. In induction motors, the driver works because the impedance is directly proportional to the applied frequency. One thing to remember is that the torque capability is directly proportional to the
magnetic flux density in the motor’s air gap. This magnetic flux density is inversely proportional to the applied frequency, which is controlled by the driver.

Vector Driver

A vector driver is mainly used in AC induction motors. There are two different currents flowing in an AC induction motor. The first is the current that produces the magnetic field flux in the stator, and the second is the current that creates the torque in the rotor and causes the rotation. The vector sum of these two currents is the actual current of the motor. The vector driver controls these two currents separately. To adjust the slip, the vector driver uses current sensors and vector sensors. The current sensor on the motor identifies the flux-producing current and the torque-producing current. The position sensor gives information about the speed and current position of the motor. Using information coming from the sensors, the controller sends adjusting signals to the driver.

Variable frequency drivers are more complex in terms of converter and inverter design. But the simplicity and reliability of AC motors with their lower maintenance overrides the complexity of the drivers.

2.2.1.2.2 DC-Motor Driver

The driver of the DC motor converts the low-level signal from the controller into a signal strong enough to run the motor. In the cases of the brushless DC motor and the stepper motor, the driver circuit provides the sequence of energizing the phases of the motor,
which can be done by a controller. However, stepper motor drivers also come with micro-stepping, which varies the speed of energizing and de-energizing multiple windings at same time. Micro-stepping allows the motor to position the load more precisely.

The DC motors with brushes typically receive analog voltages from the controller, which are amplified by the driver. During amplification, the signal controls both the direction and the magnitude of the current in the motor windings. The classical way to do this is with a linear drive. In this method, a linear power amplifier is used to amplify the signal before it goes to the motor. The linear power amplifier uses a current amplifier, which amplifies the current but does not change the voltage. Also, the power transistors in a linear amplifier are continuously “on” even for a lower output torque, which causes thermal load to the driver circuit. A more efficient technique than the linear amplifier is the pulse-width modulation (PWM). A PWM driver works based on the principle that the motor can be regulated by pulsing the power at a certain frequency. Power is supplied to the motor as a square wave with constant amplitude but with varying pulse width. The duty cycle of the PWM sets the speed of the motor. The power transistors in a PWM system are efficient for switching as they supply required current in the “on” condition and stop current flow in the “off” condition causing only a small amount of power dissipation in the transistor.
2.2.2 Control System

A control system is the combination of hardware and software used to generate the necessary information for the motion system. The motion controller contains a microprocessor, which accepts high level commands from the user interface and converts them into corresponding low level input signal for the driver. The motion controller is programmed to perform all required mathematical computations to accomplish the planned motion path such as velocity, distance, direction, acceleration, and deceleration. The motion controller calculates the desired pulses based on the move trajectory parameters given by the user via the user interface. Based on the desired target position, maximum target velocity, and acceleration/deceleration values, the motion controller determines the different segments of the trapezoidal move profile (Fig. 2.13). With the system at rest, the motion controller issues command pulses to start the motion. The motion begins with a prescribed acceleration from the stopped position and ramps up until the speed reaches the prescribed velocity. The motion continues at constant velocity until the controller determines that it is time to begin the deceleration, slow down the motion and stop the motor at the target position.

![Figure 2.13: Trapezoidal profile of motion path (adapted from [11]).](image)

---

25
The motion controller monitors the limits and emergency stops to ensure safe operation. In a closed-loop control system, the motion controller also reads the signal coming from the feedback sensor, compares it with the desired output, and adjusts the motion to minimize errors. In multi-axis motion applications, the motion controller synchronizes the movement of several motions.
3. SCANNING GEOMETRY

Rapid development of CT scanners has provided reasonable scan times with minimal motion artifacts. On the other hand, development from a single pencil beam to a fan beam necessitated more detectors. Increasing the fan size increases the amount of collected scatter, which requires improved detector collimation or software scatter corrections. \(^{(12)}\) \(^{(13)}\) Second-generation CT scanners have the flexibility to accommodate a wide range of different object sizes, whereas object sizes in third-generation CT scanners are limited by the geometry of the source-detector system and their distance from the source. \(^{(13)}\)

The BioMedical Imaging Laboratory (BMIL) at Wright State University currently has an inoperative second-generation CT scanner other than the functioning OsteoQuant®. The first goal of this project is to upgrade this inoperative current CT scanner to take advantage of the improved scan times of third-generation CT scanners. However, in research, it is desirable to have flexibility with the object sizes that can be provided by second-generation CT scanners. The current CT scanner can be rotated through 180°. It is possible to modify the design of the current CT scanner to achieve rotation through 360°.

This chapter describes the simulation of the model of the current CT scanner and suggests design modifications. Based on material and labor costs, an appropriate
solution is selected to upgrade the current CT scanner. SolidWorks, a 3D mechanical design program, was selected to simulate the model of the CT scanner because of its motion simulation capability.

3.1 Design and Motion-Control System of Current CT Scanner

It is important to study the current CT scanner before suggesting any design modifications to achieve the desired application requirements. The current CT scanner (Fig. 3.1) is a second-generation system with an isotope source (S) and an array of 16 detectors (D), which together generate a 16-beam fan. The source-detector assembly is

![Figure 3.1: SolidWorks model of the current CT scanner. The source (S) – detector (D) assembly is mounted on the translate plate (T). The translate motor (M_T) moves the translate plate with a lead-screw assembly (L). The rotate motor (M_R) is connected to the small gear (G_S) using a right angle gear-box (G_A) and shaft (R_S). The large gear (G_L) is driven by the small gear and is connected to the rotate plate (R). The rotate plate is connected to the base (B) through a semicircular assembly (A_S).]
mounted on the translate plate (T), which scans a total length of 188 mm in linear motion. The rotation of the scanner gantry is achieved through an additional rotate plate (R), which rotates the source-detector assembly over 180°. The translate and rotate plates are connected using a pair of high-precision linear ball-bearings. These linear ball-bearings slide in a double V groove on the rotate plate.

The rotate plate has a hollow circle of 220 mm and a large gear (G_L) attached to its back side. The hollow circle of the rotate plate is connected to the double-sided ball bearing assembly and has an open diameter of 200 mm. The ball-bearing assembly is connected to the base (B) of the scanner through a semicircular shaped assembly (A_S), which supports the rotate plate. The large gear (G_L) (204 teeth) is coupled to the small gear (G_S) (17 teeth) with angled teeth to avoid backlash. This small gear is connected to the shaft (R_S) of the right-angle gear box (G_A). The gear box has a gear ratio of 1:15. This gear box is connected to the motor (M_R) that rotates the rotate plate. The translate plate is directly connected to the lead-screw assembly (L) (pitch of 2 mm, zero backlash). The translate motor (M_T) is placed on the rear side of the lead-screw assembly and is connected to the lead-screw with a toothed belt gear (gear ratio 1:1).

Motion-control system
Both translate and rotate motions of the current CT scanner are created by stepper motors. These motors are capable of dividing a single revolution into 200 individual steps. Each stepper motor is connected to an individual driver, which uses a micro-stepping technique. The motion system of the current CT scanner is controlled by a
motion controller that decides the acceleration, deceleration, and velocity of the scanner. Pre-wired metal proximity sensors are used to establish a home position for the linear and rotate motion. A set of mechanical limit switches for each motor movement is used to ensure safe operation.

Limitation of current CT scanner

Based on the design, the only limitation of the current CT scanner is its inability to rotate beyond an angle of 180°. This is because the lateral side of the base blocks the rotation path of the translate motor.

3.2 Design Modification of Current CT Scanner

This section discusses the various design options that can be considered to overcome the limitation of the current CT scanner. Each design is described in detail along with its advantages and disadvantages.

3.2.1 Modification Option 1: Extension of Semicircular Assembly and Gear-Box Shaft

The first design option is based on the extension of the semicircular assembly and the gear-box shaft. The semicircular assembly of the current CT scanner has a depth of 23 mm. It is possible to increase this depth by an amount that is greater than the width of the translate motor. This increase in depth will provide enough space for the translate motor to pass through the gap between the rotating plate and the base (Fig. 3.2). The shaft of the gear box also needs to be extended beyond the width of the motor. This
extension in gear-box shaft (EGₜ) is required to maintain connection between the small gear and right angle gear box.

Figure 3.2: SolidWorks model of the CT scanner with modifications based on the first scheme. Extended semicircular shaped assembly (EAₜ) and extended gear-box shaft (EGₜ) protrudes the current CT scanner allowing the motor to pass through the gap. Reference line (RL) shows that both plates and the translate motor clear the base of the scanner. To avoid deformation of the shaft and balance the scanner weight, additional support for the shaft (SGₜ) and extra base plate (SB) is added to the design.

Extension of the semicircular assembly provides flexibility in positioning arms, legs, phantoms, or animals. Protrusion of rotate and translate plates also provides space for the cable guide to wind and unwind cables on the provided support. On the other hand, this extension of the semicircular assembly requires an extension of the rotation drive shaft. In order to allow proper contact of the gear teeth, extra support for the extended drive shaft is needed. A plate can be added at the bottom of the semicircular assembly with a bearing or bushing to allow free rotation of the extended shaft. The costs for this modification are listed in Table 3.1.
Table 3.1: Quotation for the modifications from the instrument shop based on the first scheme.

<table>
<thead>
<tr>
<th>Project Material</th>
<th>Cost (in USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semicircular assembly extension (11.5 O.D. x 7.5 I.D. x 4.75)</td>
<td>508.00</td>
</tr>
<tr>
<td>Shaft extension</td>
<td>20.00</td>
</tr>
<tr>
<td>Support (0.75 x 9.0 x 11)</td>
<td>62.00</td>
</tr>
<tr>
<td>Base plate (0.5 x 14.5 x 17.50)</td>
<td>207.00</td>
</tr>
<tr>
<td>Bearing</td>
<td>25.00</td>
</tr>
<tr>
<td>Grinding of semicircular assembly</td>
<td>56.00</td>
</tr>
<tr>
<td>Estimated labor</td>
<td>520.00</td>
</tr>
</tbody>
</table>
| Total                                                  | 1398.00       

3.2.2 Modification Option 2: Placing the Translate Motor on the Front Side

The second design option places the translate motor on top of the lead-screw assembly (Fig. 3.3). The translate motor is placed in such a way as not to obstruct the x-ray power supply to be mounted on the translate plate. The lead-screw assembly needs to be lengthened for this purpose.

Extension of the lead-screw assembly and placing the motor on top will increase the width and height of the overall geometry. The extended lead-screw assembly (EL) and the translate motor will be obstructed by the surface of the base during rotation. To avoid this obstruction, the base needs to be extended so that it allows the extended lead-screw assembly and translate motor to clear the bottom of the base while rotating.

The second modification allows the scanner to rotate beyond an angle of 180° without any protrusion. This design avoids the problem with the rotational gear contact but needs the base to be remodeled, adding weight to the overall scanner. It also requires a new lead-screw assembly, as extension of the current lead-screw assembly is difficult.
This addition increases the implementation cost. Extra support plates and holders will be required to provide flexibility in positioning arms, legs, phantoms, or animals. The costs for this modification are listed in Table 3.2.

![Figure 3.3: SolidWorks model of the CT scanner with modifications based on the second scheme. The translate motor on top of the extended lead-screw assembly (EL) allows to rotate over 360°. The base is extended (EB) to compensate for the extra height and width of the scanner.](image)

<table>
<thead>
<tr>
<th>Project Material</th>
<th>Cost (in USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-screw assembly</td>
<td>350.00</td>
</tr>
<tr>
<td>Base</td>
<td>620.00</td>
</tr>
<tr>
<td>Support plates</td>
<td>20.00</td>
</tr>
<tr>
<td>Estimated labor</td>
<td>1241.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2231.00</strong></td>
</tr>
</tbody>
</table>

3.2.3 Modification Option 3: Placing the Translate Motor on the Lateral Side

The third scheme places the translate motor on the lateral side of the lead-screw assembly in such a way that the motor shaft faces the lead-screw shaft (Fig. 3.4). This
design scheme requires the semicircular assembly and the gear-box shaft to be extended, but the increase in depth is less than in the first scheme. Due to the smaller extension of the gear-box shaft, additional shaft support may not be necessary.

Figure 3.4: SolidWorks model of the CT scanner with modifications based on the third scheme. The translate motor on the lateral side requires a small extension of the semicircular assembly (EA₅), and shaft (EG₅), and also necessitates the base to be extended (EB) to clear the motor.

Placing the translate motor on the lateral side of the lead-screw assembly will increase the width of the scanner. During rotation, the motor will hit the bottom of the base plate. The base needs to be extended in height to ensure that the motor clears the bottom plate. This extension of the base will add more material and cost to the overall modification. The drawback of this modification scheme is that it does not provide enough space between the base and the rotating plate to accommodate a cable carrier. The costs for the modification are listed in Table 3.3.
Table 3.3: Quotation for the modifications based on third scheme.

<table>
<thead>
<tr>
<th>Project Material</th>
<th>Cost (in USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semicircular assembly extension (11.5 O.D. x 7.5 I.D. x 3.5)</td>
<td>412.00</td>
</tr>
<tr>
<td>Base</td>
<td>620.00</td>
</tr>
<tr>
<td>Support plate</td>
<td>10.00</td>
</tr>
<tr>
<td>Shaft extension</td>
<td>20.00</td>
</tr>
<tr>
<td>Grinding of semicircular assembly</td>
<td>100.00</td>
</tr>
<tr>
<td>Estimated labor</td>
<td>833.00</td>
</tr>
<tr>
<td>Total</td>
<td>1995.00</td>
</tr>
</tbody>
</table>

3.2.4 Modified CT Scanner

Considering the advantages and disadvantages of each design, the optimum choice in terms of material and cost appears to be the first design, which is selected to achieve the goals of the current project.

The source-detector assembly of the modified CT scanner can be rotated through 360° and can also be translated in the horizontal direction. For safety reasons, both motor movements are limited using mechanical limit switches. This protection is important because malfunction of any hardware or software parts can cause plates to move at high speed into the dead-end of the scanner and possibly damage the scanner. The movement in the horizontal direction is limited using two mechanical limit switches. For the rotation, an additional angle $\alpha$ beyond 360° is provided to allow acceleration and deceleration on top of the 360° of rotation (Fig. 3.5). For the rotation, two mechanical limit switches are used to limit the movement of the rotate plate. The arc between these two limit switches defines the additional angle beyond 360°. A position encoder will be
used to keep track of the position of the scanner and to activate the appropriate limit
switches and the home-position sensor.

3.3 Conclusion

The modified CT scanner can fulfill the requirements of a second- and third-generation
scanner. Because of the desire for a higher photon flux and unavailability of an isotope
source, an x-ray tube will be used in the modified CT scanner, which also improves the
geometric resolution because of the smaller focal spot size. The x-ray tube will be
mounted on the scanner with its power supply and cooling fans. To allow enough space
for the power supply to clear the base plate, the base height must be extended. The use
of an x-ray tube and its power supply makes the scanner heavier, requiring strong
motors with adequate torque to accomplish the scanner movements.
4. MOTION-CONTROL SYSTEM

The motion-control system of a CT scanner typically consists of one or more motion controllers, motor drivers, and electric motors. These components work together to provide reliable and accurate translate and rotate motions. The goal of this chapter is to explain the basis for selection of the electric motors, the drivers and the motion controller that are most suitable for the demanding requirements of the modified CT scanner.

4.1 Motion System Selection Guide

Selection of motion components is a critical step in the design of the motion-control system. The electric motor is the main motion-producing component of the motion-control system. The selection of drivers to run the motors is directly linked to the decision of using either an AC or DC motor. AC motors have the advantage of being easy to design, less expensive and are associated with the least amount of maintenance due to the absence of a brush-commutator assembly. AC motors are most commonly used in industrial applications. The disadvantage of using AC motors is the minimal ability to regulate speed, which is dictated by the frequency of the supply voltage. However, AC motors can be equipped with variable frequency or voltage drivers, but these reduce the torque and increase the cost of the overall system. An additional limitation of AC motors is the inaccuracy in positioning, which makes them
less desirable for use in applications that require high-precision control. This is a consequence of the stator and rotor design and the method used to produce the rotating magnetic field.

Advantages of DC motors are their greater ability to regulate speed and their inexpensive and simple driver mechanism. As described in Chapter 2, DC motors are classified into different kinds such as BDC motors, BLDC motors, and stepper motors. In precise positioning applications, BDC and BLDC motors need to have a feedback loop and are called DC servo motors. The use of feedback sensors allows precise positioning but increases the cost and complexity of the system.

The main advantages associated with wound-field DC motors are their ability to regulate their speed in response to varying loads and a higher starting torque. However, the motor operation results in excessive heat in the rotor windings. The only outlet for the heat generated is the air gap between the rotor and stator windings. In order to ensure heat dissipation, adequate space must be provided, and this results in an overall increase in motor size. The current in the rotor of the BDC motor is applied by a segmented commutator consisting of two or more brushes sliding on a ring of segments. When these brushes wear out, the resulting dust particles affect the cleanliness of the surrounding components. This necessitates frequent replacement of the brushes, increasing the maintenance cost of the system.
On the other hand, BLDC motors use permanent magnets as rotors, and this improves the thermal efficiency compared to BDC motors. However, BLDC motors use Hall-effect sensors to decide which winding is to be energized, and this in turn increases the cost of the system. Both BDC and BLDC motors are very quiet at high speeds and do not produce resonance or vibration during their operation. The closed-loop control of DC servomotors makes them ideal in applications where the load is continuously changing.

Stepper motors are wound in such a way that each rotation of the shaft correspond to a certain number of discrete steps. By keeping the track of number of the input pulses to the stepper motor, position information can be obtained. This eliminates the need for feedback sensors and allows the use of the motor in an open-loop control system. Stepper motors provide higher force at low speeds compared to other types of DC motors. The lower inertia of stepper motors allows them to accelerate or decelerate quickly in response to control system commands. Stepper motors do not use a brush-commutator assembly, and this reduces their maintenance cost. Unlike other DC motors, the stepper motors cannot be damaged by excessive mechanical loads. Stepper motors may show large vibrations at certain step frequencies, but micro-stepping can reduce the vibrations.

The ideal motor choices for use in a motion-control system are stepper motors, BDC servomotors, and BLDC servomotors. These motors are often the best option because they provide precise positioning control with easy speed regulation. The modified-CT scanner represents a constant-load application and does not require rapid acceleration,
deceleration, or high speed operation. Based on the application requirements, stepper motors are a cost-effective, reliable, and safe choice. In addition to that, ease in set up and long operating life makes stepper motors a strong choice for the motion system of the modified CT scanner.

4.1.1 Stepper-Motor System

A stepper-motor system is a motion system that is composed of a controller, a driver (sometimes called amplifier), and a stepper motor. While the control system of other DC motors provide continuous input voltages that produce continuous rotary motion, stepper-motor systems receive step and direction pulses that rotate the motor shaft in discrete steps. The stepper motor driver converts input pulses into necessary current to make the stepper motor shaft rotate. The stepper motor then converts this digital information into a proportional mechanical movement.

4.1.1.1 Stepper Motor

A stepper motor is an electro-mechanical device that converts change in current flow into precise defined increments of rotor positions. As discussed in Chapter 2, a stepper motor has teeth or poles of a magnetically permeable material that form the stator and the rotor. When excited, the stator and the rotor produce a magnetic flux that passes through the small air gap between them (Fig. 4.1). Both the stator and the rotor experience equal and opposite forces, which attempt to pull them together to minimize the air gap between them. There are two main force components, the normal force \( n \) and tangent force \( t \). The normal force attempts to close the air gap and the tangent
force attempts to move the teeth sideways with respect to each other. The product of the tangent force and the radius of the rotor provide the rotational force on the shaft, called torque. This torque specifies the motor’s strength. The torque that maintains the position of the rotor at rest with the windings energized is called holding (or static) torque. In contrast, PM and hybrid motors have a restoring torque to hold their rotor even when the windings are not energized. This is called the detent (or residue) torque.

Based on the method of construction, stepper motors are available with a variety of stator and rotor combinations. Each phase of the stator is essentially a set of windings, which have two or more field coils connected in series. Based on the number of phases, stepper motors are classified into two-, three-, four-, and five-phase stepper motors. Two-phase stepper motors are commonly used in most applications because they provide larger torque compared to other stepper motors. Supplying current to a particular phase of the stator will attract the rotor to align itself to that corresponding pole and will hold this position until de-energized. The sequence of current flow is changed by a pulse. The rotation angle is directly proportional to the number of pulses.
applied, and the speed of the motor is proportional to the frequency of these pulses. The number of rotor teeth (or poles) together with the number of phases determine the size of each step, the step angle (Eq. ii). PM motors are available with step angle sizes from 3.6° to 90°, which corresponds to 100 to 4 steps per revolution respectively. VR and Hybrid stepper motors are available with step angle sizes ranging from 0.72° to 15°, which corresponds to 500 to 24 steps per revolution.

\[
\Theta_{ST} = \frac{360\degree}{N_p \cdot N_r}
\]

where: \( \Theta_{ST} \) = Step angle
\( N_p \) = Number of phases
\( N_r \) = Number of rotor teeth (or poles)

Torque-Speed Curve

The torque is a function of motor speed, system load, and inertia. The torque-speed characteristic curve (Fig. 4.2) shows that an energized motor will hold its position with the highest amount of torque, the holding torque. As the speed increases, the torque decreases. The frequency values less than the maximum starting frequency define the

![Torque-speed characteristic curve](image)

Figure 4.2: Torque-speed characteristic curve (adapted from 16).
The step rate at which the motor can start, stop, or reverse without missing any steps. The pull-in torque curve shows the maximum value of torque that can be produced by the motor at a corresponding speed.

The start/stop operation is called single-step mode, where each step is independent from every other step. The pull-out torque curve shows the maximum value of torque that a motor can generate without losing steps when it is running at maximum speed. In the slew range, the stepper motor cannot stop or reverse instantaneously.

The torque-speed characteristic curve describes how much torque a motor can deliver at an assigned speed. The torque delivered by a motor depends upon the type of driver and current supplied by it. The torque-speed curve is specific to a given combination of a motor and a driver. The same motor can have different torque-speed curves when used with different drivers.

The current CT scanner before modification was using a stepper-motor system to execute the motions. The stepper motor used in the system was a 2-phase PM stepper motor with a step angle of 1.8° (SIGMAX™ 802 series, stepper motor, model number: 802D3437B038, Sigma Instruments, Braintree, Mass). It was able to produce a maximum torque of 550 oz-in at a speed of 200 steps per second with a rating current of 5 Amp/phase (Fig. 4.3).

After modification of the scanner, the increase in weight adds to the torque requirements. During the selection of stepper motors for the modified CT scanner, the
minimum required torque was estimated to be 700 oz-in at a speed of 200 steps per second.

Figure 4.3: Pull-out torque curves of 802D3437B038 stepper motor. (17)

Though many types of stepper motors will be able to fulfill the torque requirements, the particular stepper motors considered are based on additional requirements such as physical size, weight, and available step size. Hybrid stepper motors combine features of both PM and VR stepper motors and could be selected over other types because they provide higher torque at the same ratings.

Hybrid stepper motors with a step size of 1.8° are very common and widely available at low cost. They are available in different case sizes (17 (1.7” dia.), 23 (2.3” dia.), 34 (3.4” dia.), and 42 (4.2” dia.)). The size of the motor defines the rotor diameter and allows
more windings to be wound in the stator design. As the number of windings is directly proportional to the torque, larger sized motors provide greater torque. Stacking of two or more multi-poled rotors in series increases the torque for a specific size. Of the available case sizes, size 34 and 42 are capable of producing the torque that meets the requirements of the modified CT scanner. Hybrid stepper motors of size 34 will be given preference as stacking the rotors in the motor provides the necessary torque. They will also occupy less mounting space and have less weight than size 42 motors.

4.1.1.2 Stepper-Motor Driver

The stepper-motor driver in the stepper-motor system is responsible for converting the control system’s output commands into the necessary current to produce enough torque and to energize the appropriate motor windings. There are several types of drivers available which differ in current rating and construction technology. Not all drivers are suitable to run all motors.

As discussed earlier, the torque in any stepper motor is developed by displacement of the magnetic flux of the stator and the rotor. Thus, the torque output is directly proportional to the intensity of the generated magnetic flux. The magnetic flux (H) and, consequently, the torque is generated by energizing the windings and is proportional to the current (Eq. iii).

\[
H = \frac{N \times I}{L} \quad \text{(iii)}
\]

where:
- \(N\) = Number of winding turns
- \(I\) = Current supplied to the windings
- \(L\) = Magnetic flux path length
This relationship also shows that the torque is directly proportional to the number of winding turns. The windings of the stepper motor are made of copper and have two physical properties, resistance and inductance, which limit the performance of the motor. A winding can be modeled as a resistive-inductive circuit (Fig. 4.4).

![Resistive-inductive winding model](image)

Figure 4.4: Resistive-inductive winding model. (18)

The resistance of the winding dissipates power (Eq. iv) and heats up the motor. In the selection of the motor, it is advantageous to choose a motor with lower winding resistance to achieve better performance in terms of thermal characteristics.

\[ P = R \times I^2 \]  
\[ \text{where: } P = \text{Power Loss} \]  
\[ R = \text{Winding Resistance} \]  
\[ I = \text{Current supplied to the windings} \]  

The inductance of the windings opposes the change in current (Eq. v). The time constant \( \tau \) is the time it takes a motor winding to raise the current to 63% of its maximum value.

\[ \tau = \frac{L}{R} \]  
\[ \text{where: } R = \text{Winding Resistance} \]  
\[ L = \text{Winding Inductance} \]
In a motor with a higher winding inductance, it takes a longer time to build up the rated current than in a motor with a lower winding inductance (Fig. 4.5). At low speed, the current has enough time to reach the maximum value of the rated motor current; therefore, inductance does not play a big role in low-speed applications. However, in high-speed applications, the current is supplied to a new set of windings before it reaches its maximum value of the rated motor current, which reduces the overall motor torque. To overcome the inductance problem at high speeds, it is necessary to either increase the current or decrease the time constant with minimum power dissipation.

There are two possible solutions to this problem. The first is the constant-voltage driver, which increases the supply voltage and adds a resistor in series to the inductive circuit. This forces the current to build up faster through the windings and, thus, decreases the time constant. The second solution is the constant-current driver, which continuously regulates the voltage to achieve a continuous high current flow.

Figure 4.5: Relationship between current and inductance (adapted from 19).
Constant-Voltage Driver

A resistance-limited driver, also known as a L/R driver, supplies a high voltage to force current through the windings. This design limits the amount of current by supplying an external resistor (also called a dropping resistor or ballast resistor) in series (Fig. 4.6). The amount of resistance is calculated based on the motor current and voltage rating. The addition of an external resistor shortens the time constant $\tau$ allowing the current to reach its maximum value in less time.

The drawback of the L/R driver is its inefficiency due to the amount of heat generated by the external resistors. As a solution to the power waste, a bilevel driver can be used.
This bilevel driver supplies an initial high voltage to enable the current to reach its maximum level ($I_{\text{MAX}}$) in a short time. When the appropriate current level is reached, the driver turns off the high-voltage supply and switches on the low-voltage supply to maintain the rated current (Fig. 4.7). The only drawback with this driver is that it requires two voltage supplies.

![Figure 4.7: Winding model of bilevel drive with current vs. time (adapted from 18, 20).](image)

**Figure 4.7: Winding model of bilevel drive with current vs. time (adapted from 18, 20).**

**Constant-Current Driver**

A pulse width modulation (PWM) driver, also known as a chopper driver, provides an optimal solution to produce a large torque at high speeds. The PWM driver supplies a voltage higher than the rated motor voltage to the windings. This high voltage allows the current to rise in less time, and when the current reaches a specific level $I_{\text{MAX}}$, the voltage is cut off. After a short time, the voltage is reapplied, and as the current rises to its specific level, the voltage is cut off again. Modulating this “on” time and “off” time, an average voltage and current is applied to the windings (Fig. 4.8).

![Diagram](image)

**Constant-voltage drivers are used in applications where low and moderate speed is required. At high speed, constant-voltage drivers lose their efficiency and do not**
produce enough torque because of the higher inductance value. On the other hand, chopper drivers provide high torque at low and high speeds with optimal efficiency. Because of its reliability, high efficiency and capability of producing maximum torque at both low and high speeds, the chopper driver represents a suitable selection for our application.

![Figure 4.8: PWM drive current and supply voltage vs. time (adapted from 18).](image)

Commercially available drivers require either a DC or AC supply. Drivers with a DC supply are generally cheaper but necessitate purchasing an additional voltage supply. AC-powered drivers include the DC supply voltage and will be given priority during selection of the motion-system components. Often, step and direction pulses from the control system provide erroneous pulses due to the noisy electrical environment. To prevent this, opto-isolation connections should be considered during stepper-motor driver selection.
4.1.2 Excitation Methods and Characteristics

The stator design of a stepper motor is comprised of two or more windings in which current is passed to form a magnetic field. Flow of the current through its windings generates a magnetic field in the stator of a stepper motor. Changing the current flow from one winding to the other produces a necessary change in the magnetic field direction. The method used to implement this change in the direction of current flow allows classification of the stepper-motor system into unipolar and bipolar configurations.

Figure 4.9: Unipolar and bipolar configuration. (21)

Unipolar Configuration

In the unipolar (or bifilar) configuration, as its name implies, a single (or half) pole of the winding is excited at a time causing the rotor to turn by a certain degree (Fig. 4.9a, b). The windings of the stepper motor are center tapped and connected to the supply voltage. Other terminals of the windings are grounded to have the current flowing in one
direction only. At any given instant, the current is flowing through only half the coil of each winding depending on which half is grounded. Change of flux direction can be achieved by moving the current from one half to the other half of the windings. This results in a reversal of the magnetic poles.

A 2-phase stepper motor in the unipolar configuration has 6-lead wires coming out of the motor with two individual center-tap wires. Sometimes, these two center-tap wires are internally connected to make the stepper motor a 5-lead wire motor. These stepper motors are referred to as four-phase if they have four field coils that can be energized independently. The current in the unipolar configuration always travels in one-direction through the coil.

Bipolar Configuration

In bipolar (or unifilar) configurations, change in flux direction can be achieved by reversing the current through the entire coil by switching the supply voltage (Fig. 4.9c). A 2-phase stepper motor in bipolar configuration has 4- or 8-lead wires coming out of the motor. 8-lead wire bipolar configurations are available either in series or parallel connections (Fig. 4.9e, f).

Unipolar configurations need one or two current switches in the driver design, whereas bipolar configurations need four or more current switches to change the direction of the current in the windings (Fig. 4.10). This makes the drive circuit of bipolar configurations more complex than that of the unipolar configurations. Unipolar configurations use only
half of the windings at any given time, reducing the winding inductance. Because only half of the winding is used, unipolar configurations do not give enough torque at low speeds, but they provide higher torque at higher speeds.

The bipolar-series configuration (Fig. 4.9e) uses the full coil and provides a 40% higher low-speed torque than the unipolar configuration. However, the torque at high speed is decreased because of higher inductance. Bipolar-parallel configurations (Fig 4.9f) use the full coil, hence give good low speed torque. Parallel connection of the windings keeps the inductance at a lower value compared to the bipolar-series configuration. This helps to provide good high speed torque. (Fig. 4.11) Sometimes stepper motors with 5- or 6-lead wires are connected in a bipolar configuration, ignoring the center-tap lead wire.
Based on the driver design, stepper motors can be operated in full-step, half-step or micro-step configurations.

**Full-Step Configuration**

In the full-step configuration, the motor repeatedly moves through its basic step angle to complete one revolution (i.e., a 90° step motor will need 4 steps to complete one revolution). Based on the number of windings excited, full-step configurations can be achieved via either a wave-drive or a two-phase drive sequence (Fig. 4.12a, b). In a wave-drive sequence only one winding is energized at a time, whereas in a two-phase drive sequence two windings are energized at a time. Two-phase drive sequences provide higher torque than wave-drive sequences but require twice the power.

**Half-Step Configuration**

Half-step configurations can be achieved by alternating wave-drive and two-phase drive sequences (Fig. 4.12c). This results in steps that are half the basic step angle to complete one revolution (i.e., a 90° stepper motor will now need 8 steps to complete one
revolution). Although half-step configurations provide less torque than two-phase drive configurations, they increase the angular resolution.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Phase</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A ) ( B ) ( A^- ) ( B^- )</td>
<td>( A ) ( B ) ( A^- ) ( B^- )</td>
<td>( A ) ( B ) ( A^- ) ( B^- )</td>
</tr>
<tr>
<td>1 1 0 0 0</td>
<td>1 1 1 0 0</td>
<td>1 1 0 0 0</td>
</tr>
<tr>
<td>2 0 1 0 0</td>
<td>2 0 1 1 0</td>
<td>2 1 1 0 0</td>
</tr>
<tr>
<td>3 0 0 1 0</td>
<td>3 0 0 1 1</td>
<td>3 0 1 0 0</td>
</tr>
<tr>
<td>4 0 0 0 1</td>
<td>4 1 0 0 1</td>
<td>4 0 1 1 0</td>
</tr>
</tbody>
</table>

(a) Wave Drive-Sequence (Full Step)  
(b) Two-Phase Drive-Sequence (Full Step)  
(c) Half-Step Drive-Sequence

Figure 4.12: Full-step and half-step configuration for two-phase stepper motor (adapted from \( ^{21} \)).

**Micro-Step Configuration**

In micro-step configurations, the driver controls the direction and amplitude of the current in the motor windings, dividing a single step into fractional steps between two poles. This principle works by energizing two adjacent field windings at the same time with different voltage levels (Fig. 4.13). Micro-step configurations improve speed and smoothness. They minimize the resonance and are used in applications that require accurate positioning. Micro-step configurations can divide the basic step by a factor of up to 256, allowing over 50,000 micro-steps per revolution. Based on the application of the current CT scanner, a minimum of 2000 micro-steps per revolution was selected, which allows 360,000 source positions during a single rotation of the rotate plate.
Rated Current and Peak Current

The current can be specified in two different ways, rated current and peak current. The rated current is the minimum current required to operate the motor, and the peak current is the maximum current that the driver can provide. In micro-step configurations with bipolar-parallel connections, it is important to select a driver that is capable of providing a peak current that is 1.4 times higher than the rated current in order to account for the increase in the number of coils. In the stepper-motor driver, the current is usually controlled by a potentiometer. It is also important to select a driver that is capable of automatically reducing the motor current after a certain time of inactivity to ensure thermally safe operation. Currently, stepper-motor drivers are available with fault protection against erroneous wiring, over-voltage protection, and over-temperature protection.
4.1.3 Stepper-Motor System Selection

More than one product may meet the requirements of the stepper-motor system. In this case, factors such as performance, cost, and availability may determine the selection.

Based on the criteria discussed above and availability, Table 4.1 and Table 4.2 contain a list of stepper motors and drivers that can be considered for the selection. All stepper motors in Table 4.1 are 2-phase hybrid stepper motors with a step angle of 1.8˚ and have size 34 configurations that fulfill the minimum torque requirement with the bipolar-parallel configuration.

Table 4.1: Stepper motor selection.

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Holding Torque (oz-in)</th>
<th>Rated Current (A/Φ)</th>
<th>Resistance (Ω/Φ)</th>
<th>Inductance (mH/ Φ)</th>
<th>Weight (Kg)</th>
<th>Cost (USD)</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 20 3451</td>
<td>1416</td>
<td>8.96</td>
<td>0.25</td>
<td>2.50</td>
<td>9.90</td>
<td>400.00</td>
<td>Penn Engineering Motion</td>
</tr>
<tr>
<td>ST 342 C</td>
<td>1200</td>
<td>6.30</td>
<td>0.50</td>
<td>4.00</td>
<td>8.40</td>
<td>440.00</td>
<td>API Motion</td>
</tr>
<tr>
<td>34N214 LW8</td>
<td>1195</td>
<td>10.00</td>
<td>---</td>
<td>1.80</td>
<td>8.40</td>
<td>360.00</td>
<td>Anaheim Automation</td>
</tr>
<tr>
<td>8717L 08P</td>
<td>1288</td>
<td>7.70</td>
<td>0.30</td>
<td>2.7</td>
<td>8.44</td>
<td>300.00</td>
<td>Lin Engineering</td>
</tr>
<tr>
<td>K32HRF M</td>
<td>1535</td>
<td>10.00</td>
<td>0.18</td>
<td>1.40</td>
<td>8.40</td>
<td>550.00</td>
<td>Pacific Scientific</td>
</tr>
<tr>
<td>AMH-1303-3</td>
<td>1303</td>
<td>9.00</td>
<td>0.25</td>
<td>2.5</td>
<td>8.27</td>
<td>450.00</td>
<td>Advanced Micro Systems</td>
</tr>
</tbody>
</table>

Table 4.2 shows a list of stepper-motor drivers capable of micro-stepping to achieve the desired resolution and having features like current reduction, optical isolation, and fault protection.
### Table 4.2: Stepper-motor driver selection.

<table>
<thead>
<tr>
<th>Driver Model Number</th>
<th>Peak Current (A/Φ)</th>
<th>Resolution (Steps/Rev)</th>
<th>Power Supply</th>
<th>Cost (USD)</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>6410/6415</td>
<td>0.626 – 5.0</td>
<td>200 – 50000</td>
<td>Required</td>
<td>349.00</td>
<td>Pacific Scientific</td>
</tr>
<tr>
<td>R710</td>
<td>1.0 – 7.0</td>
<td>2000</td>
<td>Required</td>
<td>189.00</td>
<td>Lin Engineering</td>
</tr>
<tr>
<td>PDO 5580</td>
<td>0.5 – 5.0</td>
<td>200 – 50800</td>
<td>Line powered</td>
<td>750.00</td>
<td>Applied Motion Products</td>
</tr>
<tr>
<td>ST10-S</td>
<td>0.5 – 10.00</td>
<td>200 – 50800</td>
<td>Required</td>
<td>395.00</td>
<td>Applied Motion Products</td>
</tr>
<tr>
<td>CDR-8MPS</td>
<td>8.0</td>
<td>400 – 51200</td>
<td>Required</td>
<td>995.00</td>
<td>Advanced Micro Systems</td>
</tr>
<tr>
<td>DM8010</td>
<td>2.0 – 10.00</td>
<td>200 – 50800</td>
<td>Required</td>
<td>345.00</td>
<td>Microkinetics</td>
</tr>
<tr>
<td>MLP08641</td>
<td>1.5 – 8.00</td>
<td>200 - 12800</td>
<td>Line powered</td>
<td>495.00</td>
<td>Anaheim Automation</td>
</tr>
</tbody>
</table>

Giving preference to low cost, stepper motors 8717L08P and 34N214 LW8 make the short list. Based on the same criteria, the stepper-motor drivers DM8010, 6410, and MLP08641 are under preferred consideration. The driver R710 was eliminated from the selection process because of its fixed resolution.

Stepper motor 34N214 LW8 was selected because of a higher rated current than motor 8717L08P. Driver MLP08641 was selected for the application because it is a line-powered driver and can provide variable current and variable resolution. An additional advantage is that both selected products are made by the same manufacturer (Anaheim Automation), which guarantees a match between motor and driver and allowed us to obtain accurate torque curves for the combined system.


4.2 Control System Selection Guide

A motion controller acts as the brain of the motion-control system. The motion controller is responsible for creating trajectories for the motion path and for supplying step and direction signals to the motion system. The selection of the control components is a critical part of the motion-control system design. This is because motion components can often be changed midway through the design process but the motion controller involves software, and changing software means much more than just a part replacement.

4.2.1 Motion Controller

There are basically three types of motion controllers available that can be used for the control system: standalone controllers, PC-based controllers and programmable logic controllers (PLCs).

Standalone controllers can operate independently of computers. These motion controllers are basically programmable microprocessors or digital controllers that store motion programs on their non-volatile memory. Standalone controllers are usually dedicated to a particular application and require electronic switches or a keypad to initiate the program. Standalone controllers are very good at controlling motion but make the control system difficult to modify or expand. Standalone controllers are able to coordinate up to 16 axes.

PC-based controllers are available as cards that plug into PCs. These controllers can also coordinate up to 16 axes and allow the user to modify or expand the system. PC-
based controllers do not need any electronic switches or keypads to initiate the motion. The only drawback with this type of controller is that it requires complex and time-consuming programming.

PLCs are considered to be the simplest way to control motion. PLCs contain a microprocessor that has been preprogrammed to drive output terminals based on the signal from the input terminals. PLCs differ from PC-based controls in their way of programming. PC-based controllers require the user to do high-level programming; while the PLC program is usually developed using specific software that is provided by the manufacturer. The user needs to set motion-path parameters and motion constrains. PLCs can also coordinate up to 16 axes but are costlier than other available controllers.

4.2.2 Motion Controller Selection
A controller for our motion-control system should be capable of coordinating four axes. In the modified CT scanner, translation and rotation motions represent individual controller axes. The third axis should be able to generate necessary timing pulses for the detector to coordinate data readout with motor movement. The fourth axis could be considered for the future implementation of scanner positioning to provide flexibility and comfort to the patient. Velocity and travel distance of each motion of the modified CT scanner are determined based on the detector specifications and the desired scanning protocols. To maintain flexibility and user friendliness, a PC-based controller represents a cost-effective solution for this application.
LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a graphical program development application that interfaces a computer and instruments. The advantage of using LabVIEW is that it allows working in block-diagram form and is well suited for motion-control applications.

At present, National Instruments is the only manufacturer that provides PC-based controllers that can be programmed using LabVIEW. The NI-7334 controller is a low-cost, PC-based stepper-motor controller that can coordinate four axes at a time. The advantage of using this controller is that it can be connected easily to driver MLP08641 using a screw-terminal connection device (NI UMI-7764). The controller with the connection device and cable costs 1,360.00 USD.

4.3 Conclusion

Motion-control system components were selected so that they fulfill all requirements of the modified CT scanner. Figure 4.14 shows the torque-speed curve for stepper motor 34N214 LW8 with driver MLP08641 in bipolar-parallel configuration. The selected motor provides a torque of 680 oz-in at a speed of 200 steps/revolution, which is close to the estimated torque requirement. The stepper motor is a double-stacked motor and develops a higher torque than other rated motors. The driver MLP08641 is line powered with opto-isolation inputs and can provide up to 8 A peak current to the stepper motor. This peak current can be controlled by a potentiometer. The resolution of the driver can
be controlled using four dual in-line package (DIP) switches, allowing up to 12,800 steps per revolution.

The selected motion controller can communicate with the drivers via the NI UMI-7764 device. This device also allows connection of the limit switches, home sensors, and emergency stop for each individual driver. The Motion and Control Toolbox of LabVIEW provides the software interface for the user to program the motion controller with the required motions and can coordinate different axes easily.

The next step is to equip the modified CT scanner with all motion-control system components, program the necessary motions, and study the performance limits of the motion system.

Figure 4.14: Torque-speed curve for 34N214 motor with MLP08641 driver. (22)
5. MODIFIED CT SCANNER AND MECHANICAL PERFORMANCE EVALUATION

The performance of a motion-control system is directly related to the maximum load it can move, without stalling, at a given speed. Manufacturers of various motion components measure this to some extent, but only under ideal conditions. However, it is important to establish the performance of all components for a specific application under actual load. The first section of this chapter looks at the layout of the motion-control system in the modified CT scanner. The second section evaluates the performance of the motion-control system components after implementing them on the modified CT scanner. A LabVIEW-based graphical user interface facilitates programming of the various functions of the motion-control system.

5.1 Layout of Modified CT Scanner

The following section describes the layout of the hardware and software components of the motion-control system in the modified CT scanner (Fig. 5.1).

5.1.1 Scanner Hardware

The motion-controller board NI PCI-7334 is installed in the computer, and a LabVIEW GUI is used to program the necessary motions. The universal motion interface-7764 (UMI) is connected to the motion controller with a 68-pin D-sub connector. This UMI allows interfacing up to four drivers to the motion controller and simplifies
the connection between the motion system and controller. Each axis of the UMI has a motion I/O terminal block to which drivers, limit switches, and home sensor are wired (Fig 5.2). An external power supply of +5 VDC is required to operate the UMI.

Figure 5.1: Block diagram of the modified CT scanner including the motion-control system, home sensors, limit switches, and position sensor.
Two axes of the UMI are connected to the drivers (MLP08641) with a current-sinking configuration (Fig 5.3). The drivers (MLP08641) are connected to the stepper motors in bipolar-parallel configuration to achieve greater high-speed torque (Fig. 5.4). Timing pulses for the detector are also sent from the UMI. These timing pulses are sent through transmitter/receiver chips (ISL8491) to reduce environmental noise. These transmitter and receiver chips are connected with a twisted pair cable to ensure safe and noise-free signal transmission.
For the translate motion, the inputs to the UMI from the home sensor and limit switches are electrically inverted (Fig. 5.5). The limit switches and home sensor for the translate motion are activated by a small metal piece, which glides on the lead-screw assembly. Limit switches and the home sensor are connected to the voltage supply (1 in Fig. 5.5) in the inactive stage. Upon activation of any limit switch or the home sensor, the associated switch connects to ground (2 in Fig. 5.5) changing the input to the UMI axis.

![Bipolar-parallel connection between the MLP08641 driver and the 34N214S stepper motor](image)

**Figure 5.4:** Bipolar-parallel connection between the MLP08641 driver and the 34N214S stepper motor (adapted from 24, 25).

![Limit switches (TLF and TLR) and home sensor (THS) connection diagram for the translate motion](image)

**Figure 5.5:** Limit switches (TLF and TLR) and home sensor (THS) connection diagram for the translate motion.
For the rotate motion, a logic circuit receives inputs from the limit switches and 3-bit position encoder and enables or disables the limit switches and supplies the output to one of the axes of the UMI (Fig. 5.6). The output from the position encoder is also sent to the UMI for readout by the computer, which reads the scanner position. Based on the information received from the encoder and the home sensor, the position of the gantry is set to either at 0° or 360°. In mechanical switches, switch bounce can cause unwanted signals. To avoid this, the signals from all limit switches and home sensors are pulled up at the input to the inverter 74LS04.

Figure 5.6: Limit switches (RLF and RLR) and home sensor (RHS) connection diagram for the rotate motion.

The large gear of the scanner has been fitted with a small metal bar to activate the rotation limit switches and home sensor (Fig. 5.7). The limit switch activation bar covers 70°, and the home sensor activation bar covers 14° of the total 360° of large gear. Two small pins are fitted on the large gear, 180° apart from each other. These two pins rotate
the position encoder shaft by an angle of 36˚ as they pass by the encoder. Each time
the encoder shaft rotates by the given interval, the digital output of the encoder
changes. The pattern of outputs provides positional information and helps determine if
the large gear’s position is beyond 360˚ or below 0˚. This in turn enables the activation
of the limit switches and the home sensor (Table 5.1).

Figure 5.7: Rear view of the rotation limit switches, home sensor and position encoder with pins and
activation metal bar at -60˚.

Table 5.1: Truth table for rotation limit switch and home sensor activation.

<table>
<thead>
<tr>
<th>Scanner Position (degrees)</th>
<th>3- Bit Position Encoder (B1 B2 B3)</th>
<th>RLF</th>
<th>RLR</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90˚</td>
<td>0 0 0</td>
<td>0</td>
<td>1</td>
<td>Activate reverse limit switch</td>
</tr>
<tr>
<td>-60˚</td>
<td>0 0 0</td>
<td>0</td>
<td>0</td>
<td>Home position sensor active below 360˚</td>
</tr>
<tr>
<td>-30˚</td>
<td>1 0 0</td>
<td>0</td>
<td>0</td>
<td>Encoder increment by one step</td>
</tr>
<tr>
<td>+90˚</td>
<td>1 0 0</td>
<td>1</td>
<td>0</td>
<td>Deactivate forward limit switch</td>
</tr>
<tr>
<td>+150˚</td>
<td>1 1 0</td>
<td>0</td>
<td>0</td>
<td>Encoder increment by one step</td>
</tr>
<tr>
<td>+270˚</td>
<td>1 1 0</td>
<td>0</td>
<td>1</td>
<td>Deactivate reverse limit switch</td>
</tr>
<tr>
<td>+300˚</td>
<td>1 1 0</td>
<td>0</td>
<td>0</td>
<td>Home position sensor active beyond 360˚</td>
</tr>
<tr>
<td>+330˚</td>
<td>0 1 0</td>
<td>0</td>
<td>0</td>
<td>Encoder increment by one step</td>
</tr>
<tr>
<td>+450˚</td>
<td>0 1 0</td>
<td>1</td>
<td>0</td>
<td>Activate forward limit switch</td>
</tr>
</tbody>
</table>
5.1.2 Scanner Software

LabVIEW was used to facilitate programming the motion-control system. The following section describes the sequence of basic steps for the control of both translate and rotate motions.

Upon power-up of the scanner, the first step in the data collection process is to reset positions of both the rotate and translate plates. This is achieved using the home sensors and ensures that the information regarding the angular position of the scanner is available at the beginning of the first scan. A reverse-forward-reverse approach was used to find the home position (Fig. 5.8). In this approach, the scanner initially rotates in the reverse direction (forward edge to reverse edge) to search for the home sensor with predefined initial search motion-path parameters (Table 5.2). Upon finding the forward edge of the home sensor, the scanner decelerates and moves in the opposite direction (reverse edge to forward edge) for predefined distance (14°)

![Diagram of reverse-forward-reverse approach for reset procedure](Image)

**Figure 5.8: Reverse-forward-reverse approach for reset procedure.** (26)
Table 5.2: Motion parameters of reset procedure for the various resolutions.

<table>
<thead>
<tr>
<th>Resolution (Steps/Revolution)</th>
<th>Motion-Path Parameters for Initial Search Direction</th>
<th>Motion-Path Parameters for Approach Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity ($V_1$) (steps/sec)</td>
<td>Acceleration/Deceleration ($AD_1$) (steps/sec^2)</td>
</tr>
<tr>
<td>12,800</td>
<td>30,000</td>
<td>30,000</td>
</tr>
<tr>
<td>6,400</td>
<td>15,000</td>
<td>15,000</td>
</tr>
<tr>
<td>3,200</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>2,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Figure 5.9: Motion flowchart for resetting the modified CT scanner.
rotation and 25 mm in translation) to uncover the home sensor with same motion-path parameters. In the next step, the scanner again rotates in the reverse direction with slower motion-path parameters (approach motion-path parameters) until it finds the forward edge of the home switch. Position registers for both translate and rotate movements are set to zero when the home sensors are activated. Figure 5.9 shows the motion flow chart for the reset routine of the modified CT scanner.

At this stage, the user is able to decide whether to use a second- or third-generation data collection geometry (Fig. 5.10).

In the translate-rotate data collection geometry, the user provides information about the number of data points per projection, the number of projections, scan size, and exposure time. Based on the provided information, the controller calculates start position, target position, acceleration, and deceleration for both translate and rotate motions. Before starting the scan, the user can initiate the preset routine. During this stage, the scanner moves the associated plates to the starting position, taking into account additional travel needed for acceleration and deceleration. Upon pressing the start button, the translate plate scans to acquire one projection. Timing pulses are sent to the detector in parallel with this scanning process. After every translation, the rotate plate rotates through a rotating angle $\beta$, defined by the number of projections specified. This process repeats until projections over $180 - \beta$ degrees are collected.
In the 3rd generation scanning process, the user provides information about the number of projections and exposure time. Before each scan, the rotate plate moves to the starting position, again taking into account additional travel needed for acceleration and deceleration. Upon starting the scan, the rotate plate performs a smooth rotation. At
specified increments based on number of projections, timing pulses are generated and sent to the detector. This process continues until the rotate plate has rotated through 360 + α degrees. The statuses of all limit switches are continuously monitored during both translate and rotate modes. Upon activation of any limit switch, all movements are immediately suspended.

Timing Pulses to the Detector
For each projection point (second-generation) or projection (third-generation), the third axis of the motion controller sends a timing pulse to the detectors through the UMI. To run any stepper motor, the motion controller sends step pulses to the stepper motor driver. The frequency of these step pulses can vary according to the motion parameters. The same principle is used for the third axis to generate timing pulses for the detector. The target position of the third axis is set to the required number of projection points or projections. To synchronize the timing pulses with other motor movements, motion parameters such as velocity, acceleration, and deceleration are stepped down based on the resolution and target position of the rotate or translate motor. Assume, for example, a total of 500 projections are required in one full rotation of the scanner. The rotate motor needs 360,000 steps to complete one full rotation of the rotate plate if the driver is set to a resolution of 2,000 steps/revolution. So, the target position of the rotate motor is 360,000 steps. The target position of the detector timing is set to 500 and must complete when the rotation motor finishes 360,000 steps. Consequently, the rotate motor axis and projection axis are related to each other by a factor of 720. Thus, the motion parameters for the projection timing axis are stepped down by a factor of 720 and are synchronized with the rotate motor.
5.2 Performance

5.2.1 Motion-Path Experiment

Experiments for motion-path parameters (the maximum rotation speed, acceleration, and deceleration) of the modified CT scanner were conducted for resolutions ranging from 2,000 to 12,800 steps/revolution. All experiments were conducted in the absence of limit switches. This allowed rotating the scanner through more than one revolution. The scanner was rotated over 1,080˚ to perform these experiments. An additional weight of 10 lbs. was added to the scanner to simulate the x-ray tube and power supply weights. The motor was supplied with 4 A of constant current through the driver. For each resolution setting, the maximum velocity was achieved with a constant acceleration and deceleration of 50,000 steps/sec^2 (Fig. 5.1). If the velocity was increased beyond its maximum value, the motor either stalled or missed steps.

![Graph showing relationship between resolution, velocity, and time](image-url)

Figure 5.11: Maximum velocity vs. resolution and minimum time for 360˚ rotation vs. resolution with a constant acceleration/deceleration of 50,000 steps/second^2.
The velocity curve in Figure 5.11 shows a linear rise in maximum velocity for resolutions 2,000 to 6,400 steps/revolution. Increasing the resolution to 12,800 steps/revolution shows a decrease in maximum velocity from the expected trend. This is because of a decrease in torque at higher step frequencies.

Using the values of the maximum achievable velocity as a constant, the maximum acceleration/deceleration for each resolution was tested (Fig 5.12). Considering maximum velocity and acceleration/deceleration values, the additional rotation path to account for acceleration/deceleration can be established (Table 5.2). The plot of distance vs. time can be obtained using the results of Table. 5.3 (Fig. 5.13). Results from Table 5.3 show that the minimum angle to cover acceleration and deceleration is between 11.4° to 37.2°, depending on the resolution.

Figure 5.12: Maximum acceleration vs. resolution and minimum time to reach maximum velocity vs. resolution with constant velocity.
Table 5.3: Motion parameter limits for the various resolutions

<table>
<thead>
<tr>
<th>Resolution (Steps/Revolution)</th>
<th>Number of Steps For 360°</th>
<th>Maximum Velocity (Steps/Second)</th>
<th>Total Time to Cover 360° (Seconds)</th>
<th>Time to Reach Maximum Velocity with Maximum Acceleration (Seconds)</th>
<th>Minimum Combined Acceleration and Deceleration Angle (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12,800</td>
<td>2,304,000</td>
<td>384,100</td>
<td>6.0</td>
<td>0.19</td>
<td>11.4</td>
</tr>
<tr>
<td>6,400</td>
<td>1,152,000</td>
<td>345,000</td>
<td>3.3</td>
<td>0.35</td>
<td>37.2</td>
</tr>
<tr>
<td>3,200</td>
<td>576,000</td>
<td>175,000</td>
<td>3.3</td>
<td>0.29</td>
<td>32.0</td>
</tr>
<tr>
<td>2,000</td>
<td>360,000</td>
<td>120,000</td>
<td>3.0</td>
<td>0.30</td>
<td>36.0</td>
</tr>
</tbody>
</table>

Figure 5.13: Degree vs. time with the maximum constant velocity and maximum acceleration and deceleration.

A resolution of 2,000 steps/revolution provides 360,000 different source positions and can deliver more torque with higher speed compared to other resolutions. This resolution was, thus, considered preferable for this application. Performance results show that the rotation through 396° can be achieved within 3.6 seconds when used with a resolution of 2,000 steps/revolution. Based on the requirements of the application, a
suitable combination of the velocity and acceleration can be used to achieve the translate and rotate motions.

### 5.2.2 Reproducibility Experiment

Experiments to test the positioning reproducibility of the modified CT scanner were conducted for resolutions ranging from 2,000 to 12,800 steps/revolution. During these experiments, inputs from the home sensors were directly connected to the UMI. This provided two active home regions for the rotation movement (at 0˚ and 360˚) due to rotational capability beyond 360˚. The scanner was initially reset using the described reverse-forward-reverse approach. After reset, the position register was set to zero, and the scanner was rotated over 380˚. Resetting the scanner after rotation over 380˚ will provide us the position of 360˚. During this second reset procedure, the position register was disabled, and the position after the second reset was recorded. This procedure was repeated 10 times. The recorded results were compared with the expected number of steps for 360˚, and absolute errors were calculated for different velocities for resolutions ranging from 2,000 to 12,800 steps/revolution. Figure 5.14 shows the plot of angular error vs. velocity for each resolution. Table 5.4 shows the minimum and maximum percentage angular error for each resolution.

A reproducibility experiment for the translate motion was also conducted for the resolution of 2,000 steps/revolution. During this experiment, the scanner was positioned at 90˚ and was translated with a constant speed of 20,000 steps/second. The scanner was initially reset using the reverse-forward-reverse approach, and the position register
Figure 5.14: Reproducibility results for different velocities at various resolutions.

Table 5.4: Angular error for the various resolutions.

<table>
<thead>
<tr>
<th>Resolution (Steps/Revolution)</th>
<th>Minimum Angular Error (Degrees)</th>
<th>Maximum Angular Error (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12,800</td>
<td>0.0019</td>
<td>0.0098</td>
</tr>
<tr>
<td>6,400</td>
<td>0.0074</td>
<td>0.0249</td>
</tr>
<tr>
<td>3,200</td>
<td>0.0034</td>
<td>0.0078</td>
</tr>
<tr>
<td>2,000</td>
<td>0.0052</td>
<td>0.0114</td>
</tr>
</tbody>
</table>

was set to zero. After reset, the scanner was translated backward and forward (-15 mm to +195 mm) ten times and was reset at the end without setting the position register to zero. The reset position was recorded and compared with the expected number of steps at the zero position. After repeating this whole experiment 10 times, the absolute difference between recorded and expected position was calculated to be 0.0944 mm. During these experiments, it was noticed that the deviations become larger as the
number of translations was increased. This is because running of the motor produces heat in the motor windings and decreases the motor torque.

To examine the effect of the error in positioning reproducibility on image quality, an independent analysis involving computer simulations of random errors in the rotation increment was performed. The analysis showed that even with a position error with a standard deviation of $\frac{1}{4}$th of a rotation increment (450 source positions over 360$^\circ$) the structures within the image could be discerned clearly. The background noise increased as the standard deviation of the error approached a value equal to the rotation increment. (27) The reproducibility experiment revealed an error of 0.0114$^\circ$ at 2,000 steps/revolution in rotational positioning, and this error is 70 times smaller than the rotation increment.

5.3 Conclusion

The selected motion-control system works within the performance parameters on the modified CT scanner. The modified CT scanner with the x-ray tube and power supply allows rotation over 360$^\circ$ and provides characteristic features from both second- and third-generation CT scanners. The LabVIEW GUI provides flexibility for the user in defining velocity, acceleration and deceleration. The complete motion-control system of the modified CT scanner allows a minimum rotation time over 360$^\circ$ of 3.6 seconds with a maximum angular error of 0.0114$^\circ$. Limit switches, home sensors, and timing pulses to the detector were tested for each motion, and they fulfilled all established requirements.
6. CONCLUSION

The aim of this project was to establish a mechanical design of a CT scanner that provides characteristic features of both second- and third-generation data collection schemes. Rotation of the gantry beyond 180˚ plus fan angle in the data collection scheme of the current second-generation CT scanner was blocked by the base of the scanner. 3D models of the modification schemes described in Chapter 3 have proven that the scanner can be rotated over 360˚ with different modifications. After conducting a detailed analysis of advantages, costs, and availability, we concluded to modify the scanner by extending the semicircular assembly and gear-box shaft (Fig. 3.2). After modification, the gantry can be rotated over 360˚ to accomplish the data collection scheme of a third-generation CT scanner.

Use of an x-ray tube in the modified CT scanner provided better precision and geometric resolution but added weight to the scanner. This needed to be taken into account when redesigning the motion-control system. Stepper motors and an open-loop motion-control system provided the necessary position accuracy and torque at relatively low and high speeds. The stepper-motor drivers are able to provide the required current with variable resolutions ranging from 2,000 steps/revolution to 12,800 steps/revolution, which provided from 360,000 to 2,304,000 source positions over a 360˚ rotation. The PC-based motion controller from National Instruments allows us to program a LabVIEW
based GUI to facilitate the user with flexibility in all motor movements. This flexibility also allowed generation of the necessary timing pulses for the detector.

For safety, both motor movements are limited using mechanical limit switches. During the translate motion, the translate plate is allowed to scan a maximum of 190 mm with acceleration and deceleration. To achieve rotation through 360° with constant velocity, acceleration and deceleration are provided beyond the range of 360°. An additional angle of up to 180° was incorporated between the two limit switches. This allows a maximum of 90° acceleration and 90° deceleration for a full 360° rotation at constant speed. With a simple approach, any rotation beyond 360° would activate both limit switches twice. An optical position encoder and associated logic circuitry was implemented to enable and disable the rotation limit switches appropriately.

Performance evaluation of the modified CT scanner with the selected motion-control system showed that the scanner could be rotated through 360° within 3.9 seconds.

The development of the dual-generation CT scanner provides a flexible CT platform by combining different data collection schemes, flexible geometric resolution, and variable scanning times. Addition of slip-ring technology would enhance the scanner by providing continuous rotation, thus enabling spiral scanning. At present, the source-detector system can be translated only in the horizontal direction. Addition of one more translation plate between the existing rotate and translate plates could provide an option for variable magnification. (13)
7. REFERENCES


(17) Copied from “Sigma Motion Control Products”

(19) Northwestern University: Stepper motor microstepping with PIC18C452. 
http://hades.mech.northwestern.edu/wiki/images/c/cc/00822a.pdf (accessed 
10/1/2008).

(20) Creative commons license: Drive circuit basics. http://www.solarbotics.net/library/ 

pgBipolarTutorial.htm (accessed 10/1/2008).

(22) Anaheim Automation: MLP08641 - Line powered microstep stepper motor driver. 

(23) University of Wisconsin: Universal user interface accessory - user guide. 
http://www.sal.wisc.edu/PFIS/docs/archive/public/Product%20Manuals/ni/motion 

(24) Anaheim Automation: MLP08641 - high performance microstepping driver-user 
guide. http://www.anaheimautomation.com/manuals/CAT0101%20-


(26) National Instruments Corporation: Motion control - FlexMotion™ software 
11/1/2008)

(27) Alladi, S: Ph.D. candidate, BioMedical Imaging Laboratory, Wright State 
University. Personnel communication.