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Short Communication

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Technical Considerations in Developing a Motion-Controlled Positioning System for Use in Radiation Experiments

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Abstract

In this work, we report the technical considerations involved in developing a motion controlled positioning set-up using a stepper motor system. This purpose of this set-up is to move a rectangular lead frame shield, which houses a radionuclide and detector for scanning underground object scatterer for Compton scattered tomographic imaging. A stepper motor, IP (Ingress Protection) rated, IP 65, US based National Electrical Manufacturing Association, NEMA 34, was selected to move about 60 kg lead frame housing a radionuclide source and detector. Findings show that, this programmable logic controller, PLC based stepping motor system being developed for this motion controlled positioning equipment will achieve precise 3-D scan of objects buried under the ground. Scattered photons from an object scatterer (whose image is desired) are received at the detector, D and the electron density distribution of the object is directly imaged by Compton scattering tomography, CST. The CST image reconstruction code to be used by this equipment has been developed and some phantom images obtained using this code is presented. By connecting the detector to a display computer, interfaced with the developed CST image reconstruction code, desired images of objects under the ground can be displayed on a computer screen.

Keywords: Stepper motor, Radionuclide, Detector, Compton scattering tomography, Imaging.

1. Introduction

Precision motion control and positioning systems find useful applications in various industrial settings which include mission control deployments in laser micro-machining, micro-assembly automation, optical inspection, semiconductor metrology, photonics components test and alignment applications, e.t.c. (Azonano, 2019). Devices or components of a machine that is responsible for moving and controlling mechanisms are known as actuators. They come in different types, such as, linear actuators, pneumatic actuators, electro-mechanical actuators, piezoelectric

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actuators, e.t.c., linear translation stages (which are built on the principle of linear actuators, but includes a work piece or platform for fixing an application load) come in varying forms including rotation stages, air-bearing rotation stages, goniometers or positioning goniometers (which are frequently used in X-ray diffraction and in crystallography to rotate samples). The motors used in these actuators are typically either DC servomotors or stepper motors (Wikipedia, 2019a). A motion-control positioning system can be achieved using a programmable logic controller, PLC or a computer to control a stepper motor system, and the development of this set-up for use in the precise control of the movement of a gamma-ray emitting radionuclide and detector set-up is the objective of this work. A stepper motor system is usually made up of three basic components; namely the indexers, the drivers and stepper motors combined with a user interface like a host computer, a programmable logic circuit or a dumb terminal (Maloney, 1986). The indexer, also called the controller is essentially a microprocessor to generate step pulses and signals for the direction of the driver. The indexer also performs some other command functions. The driver, also called the amplifier receives signals from the indexer as command, which is converted into the power required to sensitize the motor windings. For this work, the driver was carefully selected bearing in mind its voltage and current ratings and construction technology, so as to effectively run the stepper motor used. Stepper motors operate differently from DC brush motors, which rotate when voltage is applied to their terminals. Stepper motors have multiple toothed electromagnets arranged around a central gear-shaped piece of iron, usually driven with a constant current (Humphries and Sheets, 1986). The electromagnets are energized by an external control circuit, comprising the controller (or indexer) and the driver that provides the necessary current and voltage to the stepper motor so that it has a smooth operation. Conventional electric motors rotate continuously, but stepper motors rotate or step in fixed angular increments. One revolution involves the motor taking a specific number of steps determined by the number of teeth, motor construction, and type of drive scheme used for control (Kenjo and Sugawara, 1994). This measurement, called the step angle or step resolution, can be stated as an angular measurement or a specific number of steps through which we can achieve precise positioning. A stepper motor is designed to move in small increments, making it effective for precise work. A stepper motor rotates precisely by synchronizing the pulse signals from the controller, which are given through the driver converting them in to stepper motor motion. There are three commonly used excitation modes for step motors, namely, full step, half step and micro stepping. In full step operation, a 2-phase stepper motor moves 200 steps for each revolution, or 1.8° per step. When the excitation is alternating single and dual phase operation, this results in steps that are half the basic step angle of 1.8° or half step operation. Micro stepping can divide a motor's basic step up to 256 times. Micro stepping improves low speed smoothness and minimizes low speed resonance effects. Micro stepping produces roughly 30% less torque than dual phase full stepping. Thus, a stepper motor divides a full rotation into a number of equal steps so that the motor's position can be controlled or commanded to move or stay at any of these steps without any position sensor for feedback, if the size of the motor is carefully selected to meet the required application in respect to torque and speed. This stepper motor system being developed, will move a rectangular lead frame shield housing a radionuclide and detector system for scanning underground object scatterer for Compton scattered tomographic imaging.

2. Materials and Methods

In this work, a rectangular lead frame to house the gamma-ray emitting radionuclide source and detector is constructed. The dimensions of this rectangular lead frame is 1.5m x 0.1m x 0.1m. From the two ends of this frame (at source S and detector D) are two lead frame arms of dimensions 1.0m x 0.05m x 0.1m each, welded. The welding was done such that the lead frame arms were each inclined at 600 to the rectangular frame. The lead frame arms serve as collimation for the emitted gamma-ray from the radionuclide source to the scatterer (object to be imaged) and collimation for the scattered radiation from the scatterer to the detector. Europium-152 (^{152}Eu), a gamma-ray emitter was selected as the radionuclide source and a sodium iodide, NaI (Tl) scintillator detector used as the detector. The radionuclide is available at the Centre for Energy Research and Development, CERD, of the Obafemi Awolowo University, Ile-Ife, Nigeria. Adejumo and Balogun (2012) in an earlier work on using dual energy Gamma-Ray transmission technique to measure soil bulk density and water content of central southwestern Nigerian soils reported that this radionuclide, is disc shaped, prepared on 1st March, 1992, by Isotope Products Laboratories, Burbank, California, U.S.A. It was marketed with a series number 296-89-8 with some other radionuclides as "Gamma disc set". The activity of this source at the date of preparation was given as 1.064μCi (3.94×10^4 Bq). Very small openings were drilled in the rectangular lead frame at the positions of the source and detector to allow "near" monochromatic photons to be emitted from the source and scattered photons from the scatterer detected at the detector. The NaI (Tl) scintillator detector is a cylindrical shaped BICRON Corporation manufactured model 3M3/3 with serial number FF-

669, coupled to a photomultiplier which is also BICRON Corporation manufactured, model number PA-14 and serial number AG-472; all available at CERD, Ile-Ife, Nigeria (Adejumo and Balogun, 2012). From the detector, connections are made to an analogue-to-digital converter, ADC, and then to a computer display with the developed electron density distribution software interfacing to display object scatterer images on the computer screen. The overall set-up frame is shown below in Fig. 1.

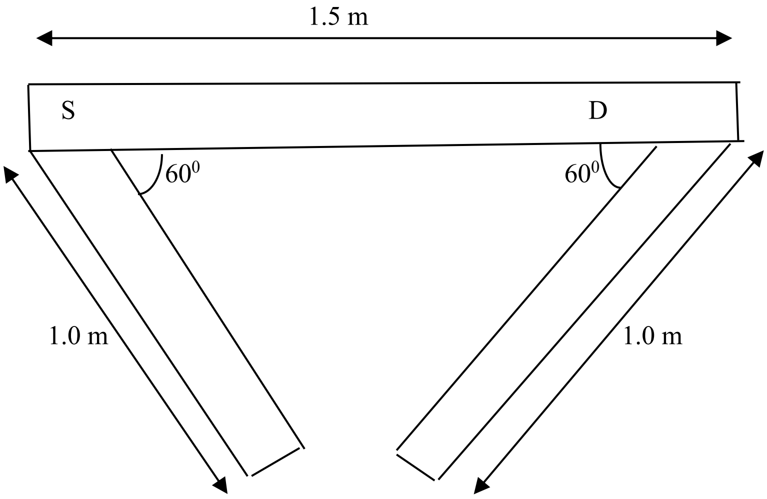

Fig. 1 Lead Collimator set-up Frame

To scan the object to be imaged, the motion and positioning of the whole set-up must be precisely controlled, and is achieved using a stepper motor arrangement attached to the rectangular lead frame of the set-up. The decision for the choice of stepper motor type requires a good understanding of the design, working and operations of stepper motors to arrive at the best choice of stepper motor for the envisaged task. For our envisaged task, the approximate weight of a 1.5 m x 0.1 m x 0.1 m rectangular lead frame is about 21.5 kg, for each of the two (2) lead frame arms of dimensions 1.0 m x 0.05 m x 0.1 m, the weight is about 18 kg (or about 36 kg for both), giving us about 60 kg for the entire frame set-up when the detector and radionuclide are inserted. An AP8918L9504 Stepper Motor, IP (Ingress Protection) rated IP-65, US-based National Electrical Manufacturing Association, NEMA 34 (except shaft output), was carefully selected to perform the task of moving the lead shield frame for the purpose of scanning the object to be imaged. The mounting face of the motor is 3.4 inches square (86 x 86 mm), delivering a torque of 8.53 Nm, shaft speed of 75 rpm, 1.8^0 step angle (full step) (nanotec, 2019). Other useful technical data for this motor include: current per winding, 6.4 – 9.5 A; holding torque, 594 Ncm – 933 Ncm; rotor inertia, 3000 gcm^2; inductance per winding, 2.74 mH. The block diagram for the stepper motor system is shown below in Fig. 2.

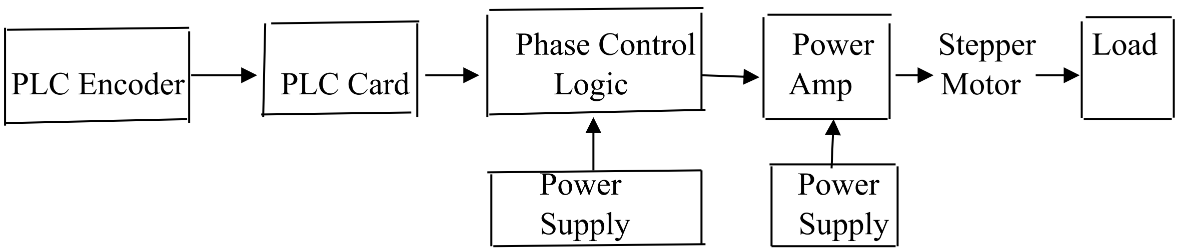

Fig. 2: Block Diagram for Programmable Logic Controlled stepper motor system

3. Results and Discussion

Findings

From the assembled materials and the set-up methodology, this programmable logic controlled stepping motor system for this motion-controlled positioning equipment will achieve precise 3-D scan of objects buried under the ground. Phantom images obtained using the CST image reconstruction code earlier developed by Adejumo et al. (2019) are shown in Figs. 3a – 3d. Scattered photons from an object scatterer (whose image is desired) are received at the detector, D and the electron density distribution of the object is directly imaged by Compton scattering tomography, CST. By connecting the detector to a display computer, interfaced with the developed CST image reconstruction software, desired images of objects under the ground can be displayed on the computer screen.

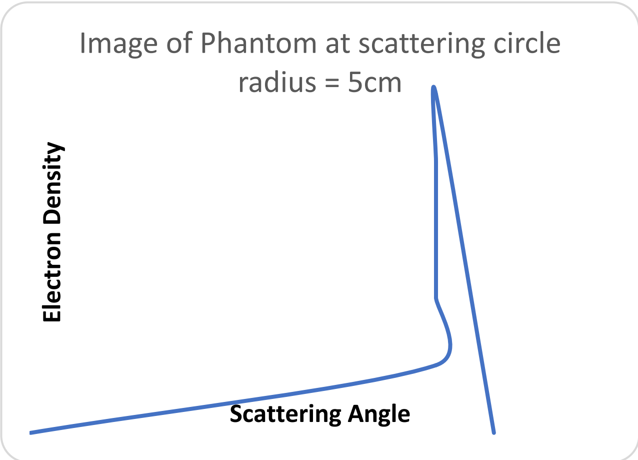

Fig. 3a: Image of a Phantom at scattering circle radius, 5cm (Adejumo et al., 2019).

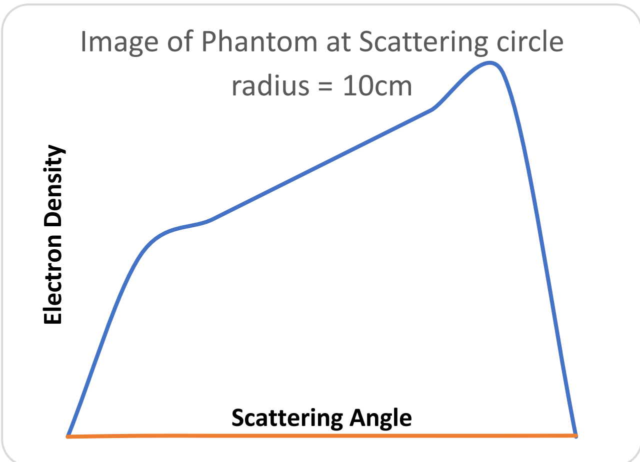

Fig. 3b: Image of a Phantom at scattering circle radius, 10cm (Adejumo et al., 2019).

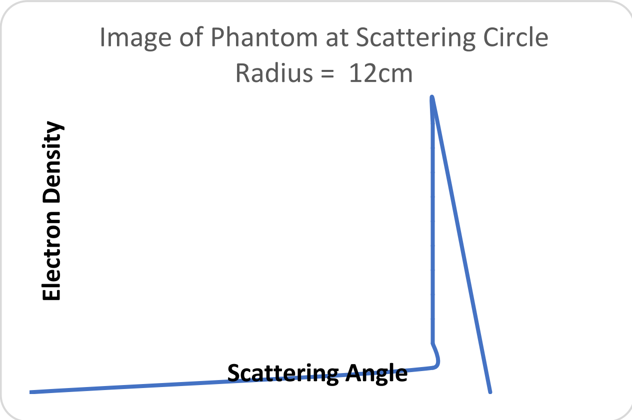

Fig. 3c: Image of a Phantom at scattering circle radius, 12cm (Adejumo et al., 2019).

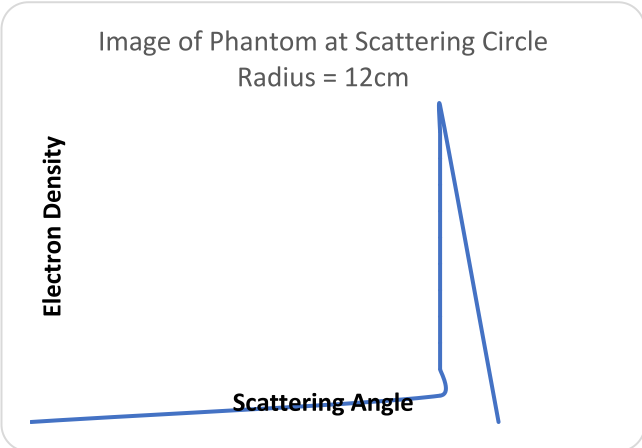

Fig. 3d: Image of a Phantom at scattering circle radius, 13cm (Adejumo et al., 2019).

Discussion

The choice of the use of a 2-phase, bipolar stepper motor over a 5-phase stepper motor for this motion controlled positioning system was taken consequent of technical considerations of the design of these motors.

First, to move the envisaged load of about 60 kg of lead frame housing the radionuclide source and detector system, the 1.8^0 step angle for a 2-phase stepper motor will be more appropriate to conveniently perform the envisaged task.

Second, the fact that in this work, scans of large and fairly large objects are envisaged, the lower resolution of the 2-phase motor (having 200 steps per rotation, or 1.8° per step when compared with the 5-phase motor of 500 steps per rotation, or 0.72° per step) is not a priority.

Third, we, as designers of this particular motion-controlled positioning system, appreciate the fact that the 2-phase motor produces much more vibration than a 5-phase motor on account of the higher step angles in the 2-phase motors; 1.8° versus 0.72° in a 5-phase motor. This increased vibration is again not a priority since this system is for outdoor use, where extra vibration noise poses no special problem.

Fourth, there is little difference between the output torque of a 2-phase motor and a 5-phase motor, although, the 5-phase motor does have more "useable" torque, the primary requirement from the motor is the generation of sufficient torque to perform this envisaged task.

The choice of either a unipolar or bipolar stepper motor was arrived at after considering the merits of each of these winding configurations. With a unipolar driver, the current can only be sent through the windings in one direction, which means less flexibility in how the driver can be used, but it offers an advantage when it comes to performance at high speeds. In contrast, the bipolar driver can send current through the windings both ways, which means that there are more ways to connect a stepper motor to such a driver, but creates a drop in high speed performance compared to the unipolar driver; at high speeds, the bipolar winding setup is less effective than the unipolar set-up. A unipolar motor has twice the amount of wire in the same space, but only half used at any point in time, hence it is 50% efficient (or approximately 70% of the torque output available. On the other hand, though a bipolar stepper motor is more complicated to drive, the abundance of driver chips means this is much less difficult to achieve (Wikipedia, 2019b). At lower speeds, we have less torque from the unipolar configuration, and are therefore specifically useful for motors that will be run at high speeds most or all of the time. On the other hand, in the bipolar winding configuration, the full coil is used, and this produces more torque at lower speeds. This type of setup is much more effective when we have one or multiple motors that will be operating primarily at low to moderate speeds. At low speeds, high inductance is not a problem since current can easily flow into the motor windings fast enough that the stepper motor maintains its rated torque. Since our stepper motor for this particular task is expected to operate at low speeds, we do not anticipate the problem of high inductance.

Mechanical and Electrical errors in a stepper motor system can adversely affect the smooth operation of the motor, and such need to be properly addressed. There are several components to mechanical error; the major one is tooth configuration. Once the motor completes a full 360° rotation, the same tooth is now lined up at the original starting point, eliminating mechanical error. Although the teeth on a motor are supposed to be square, the stamping process and age of the die can cause some of the teeth, or portions of the teeth to be rounded. Instead of the magnetic flux flowing directly, it can flow elsewhere when the teeth are rounded. Using a Full-Step drive, a 2-phase motor repeats its state every 4th step, while in a 5-phase motor the states repeat every 10th step. Any electrical error caused by imbalances in the phases is negated every 4th step in a 2-phase and every 10th step in a 5-phase, leaving only mechanical error. In terms of synchronization, since the 5-phase motor only moves 0.72° per step it is nearly impossible for the 5-phase motor to miss a step due to overshooting/undershooting. A motor will lose synchronism or miss a step when the teeth on the rotor do not line up with the correct teeth on the stator. For a 2-phase motor which moves 1.8° per step, the probability of overshooting/undershooting is higher than in the 5-phase motor. However, the advantages of the 2-phase, bipolar stepper motor outweighs that of the 5-phase motor for this particular task at hand.

It is apparent, from the foregoing that the configuration of a 2-phase, bipolar stepper motor will be better applied than the 5-phase motor for our task of moving the rectangular lead frame shield housing a radionuclide and detector system for scanning underground object scatterer for Compton scattered tomographic imaging.

A Stepper Motor's IP rating, also known as Ingress Protection or International protection rating is defined in international standard EN 60529 (British BS EN 60529: 1992, European International Electrotechnical Commission, IEC 60529). These standards are used to define the levels of sealing effectiveness of electrical enclosures against intrusion from foreign bodies such as dirt and water (Rainford, 2019). The rating consists of the letters IP followed by 2 digits; the first digit stands for the level of protection that the enclosure provides against solid bodies, the second digit describes the degree of protection of the equipment inside the enclosure against water. For example, for IP 65, the first digit referring to the protection against solids offer protection from total dust ingress, and the second digit referring to protection against liquids offers protection from low pressure water jets from any direction. The physical size of stepper motors are usually described via a US-based National Electrical Manufacturing Association, NEMA standard, which describes the bolt-up pattern and shaft diameter. NEMA refers to the frame size of the motor as standardized by NEMA in its publication ICS 16-2001 (NEMA, 2001). It specifies the 'face' size of the motor. For example, NEMA 34 stepper has a face of 3.4 x 3.4 inches with screw bolts to match (Wikipedia, 2019c).

4. Conclusion

We conclude from this ongoing work on the development of a motion-controlled positioning system for use in radiation experiments that with the successful development and testing of the CST image reconstruction code to be used by this equipment. This programmable logic controller, PLC based stepping motor system being developed will achieve precise 3-D scan of objects buried under the ground and desired images of these objects can be displayed on a computer screen.

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