INDEX COPERNICUS INTERNATIONAL

Bio-Algorithms and Med-Systems

WWW.BAMSJOURNAL.COM ISSN: 1896-530X

ORIGINAL ARTICLE

A cross-staged gantry for total-body PET and CT imaging

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ABSTRACT

Total-body Positron Emission Tomography (PET) scanning is a promising new method for rapidly acquiring comprehensive wide-volume metabolic data with a lower radiation dosage compared to discrete whole-body PET imaging. PET scanners are generally used with Computed Tomography (CT) scanners to precisely understand tumor location and composition with the help of anatomical images. However, PET/CT sequential imaging methods for simultaneous total-body imaging are impractical for claustrophobic patients due to the enclosed gantry design and require large examination rooms because of the need for an exceptionally long patient table. To address this challenge, the Jagiellonian-PET Tomography (J-PET) Total-body scanner employs an innovative approach: utilizing both PET and CT devices on the same patient table but from different axes. The motion system of the J-PET Total Body scanner requires custom linear stages to move both PET and CT gantries. In this study, a novel cross-staged linear guiding solution is proposed by combining scanners on intersecting separable stages. The proposed sliding system is a combination of different machine elements and will be produced for the J-PET Total-body PET/CT Scanner. Concept designs are shown, and the proposed system is described. The application of the system for the J-PET total-body PET/CT scanner is discussed. The proposed solution is still in the development phase. The system holds the potential to achieve combining CT and PET scanners from different axes and enables motion artifact-free imaging for total-body imaging.

KEYWORDS

linear motion, XY gantry system, J-PET, total-body PET, PET/CT, medical imaging

Received: 03.12.2023
Accepted: 24.12.2023
Published: 31.12.2023

CITE THIS ARTICLE AS:
Kaplanoglu MT, Moskal P, "A cross-staged gantry for total-body PET and CT imaging," Bio-Algorithms and Med-Systems vol. 1, no. 1, pp. 109-113, 2023, DOI: 10.5604/01.3001.0054.1941

AUTHORS' CONTRIBUTION:
A – Study Design
B – Data Collection
C – Statistical Analysis
D – Data Interpretation
E – Manuscript Preparation
F – Literature Search
G – Funds Collection

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INTRODUCTION

Positron emission tomography is a metabolic imaging technique to monitor radiopharmaceutical activity inside the human and animal body, particularly for diagnosing cancer through the detection of electron-positron annihilation locations [1]. The method relies on injecting positron emitter linked specific radiopharmaceutical agents into the body and observing its trace by surrounding detectors. In most applications, radiopharmaceuticals are injected via blood vessels and circulate in the body. However, the simultaneously imaged area is generally partial due to the scanner's field of view (FOV). Extending the FOV and monitoring the entire body via the PET method yield very detailed metabolic information, and approaches for this purpose are called whole-body and total-body imaging techniques. Whole-body PET partially examines the body and creates a full image from combined partial images, while total--body imaging monitors the entire body volume simultaneously. Whole-body PET imaging requires a higher radiation dose and more time compared to total-body imaging. The new generation of high-sensitivity total-body PET scanners enable dynamic and low-dose imaging [2–6]. Examinations with conventional PET/CT scanners are limited for a part of the body because of the required examination time, X-ray tube lifetime, and cost of wide detectors. Nevertheless, imaging can be extended to examine the full body instead of a limited section to produce a complete anatomical view of the target with metabolic positron emission data. Monitoring the full body leads to effectively investigating the spread of cancer, side effects of treatments on different organs, and much more detailed information due to the scanned volume. On the other hand, combining an anatomical scanner with a "total-body" PET scanner requires a very long linearly moving patient table with a capacity of ~200 kg to use in examinations. Such a solution necessitates large examination rooms and is uncomfortable for patients with claustrophobic feelings, who must be shifted through a tunnel longer than 200 cm.

The J-PET group is developing a new total-body PET scanner with axially arranged long plastic scintillators [7–12]. The J-PET total--body PET scanner will have PET and CT scanners on different axes, and both devices will move to the same stationary patient table by scanning the patient sequentially. It stands out from the Siemens SOMATOM CT sliding Gantry [13] and the United-Imaging uEXPLORER®: The total-body PET/CT [4] has a multi-axis sliding system and special PET detector features. Thanks to its unique design, the J-PET total-body PET/CT scanner provides several enhancements to physical limitations raised by using conventional PET/CT imaging methods for total-body PET/CT scanning. The term "stationary patient table" refers to a patient table without motion features during CT and PET scans. In contrast to common PET/CT scanners, the patient remains in a stationary position on the fixed table until the end of the examination. Fig. 1. illustrates the approach of the J-PET total-body scanner; double arrows show the direction of axes for the PET and CT gantries. The PET gantry will clamp on the stationary patient table after arrival and unclamp to go back after examination. This approach removes the requirement of a long patient table, occupies less space and is mechanically much more compact. In addition to enabling total--body imaging, it also offers an advantage over moving beds to minimize artifacts caused by motion. Patient movement is a direct factor in acquiring false data during an examination; it causes motion artifacts on CT images and inaccurate annihilation position information for PET.

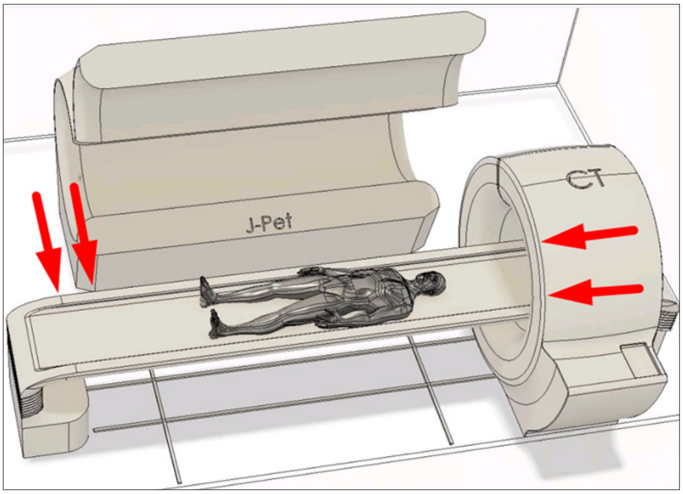

Fig. 1. J-PET/CT: Concept of the modal total-body imaging. This system consists of moving CT and J-PET scanners and a stationary patient table. Red arrows show the direction for axes.

Synchronizing the patient table with a rotating gantry is a precise task, and the table should move forward by the slice thickness length for each half rotation of the CT gantry. If the patient cannot remain still during the examination, motion artifacts on the image may occur. Movement of the patient causes unadaptable traces on the final image. Motion artifacts are generally more visible on slice transitions, but they can also occur within the same slice data. The artifact on partial imaging may be bypassed by rescanning but a CT rescan during total-body examination accumulates much more ionising radiation dose in a patient compared to partial imaging. Occurrence of the body motion artifact also delays PET examination where timing is very important to acquiesce enough metabolic data. The key point to minimise occasional motion artifacts is keeping the patient in a stand-still position as much as possible. Providing a comfortable examination experience for the patient and not moving the table are key points. For this purpose, keeping the patient table in a fixed position is a solution. This approach may reduce the possibility of involuntary patient movement during scanning due to the stable position of the table and the patient.

To integrate both scanners from different axes into the stationary patient table, two linear movement roads should be inserted perpendicularly to each other. However, there is currently no commercial stage available to perform this operation. Two-axis linear motion systems move an object from a point through X or Y locations, but bringing two different objects from Y or X locations to a certain point is a complicated task due to geometrical limitations.

In the J-PET total-body scanner each device has a weight of over 1000 kg and requires precise movement in sub millimetres. Conventional linear systems utilize motor-coupled screw bearings with linear guides for movement, but none of the additional axes intersect with the other. The required linear system should move each device independently, precisely and by covering the same patient table. Since the CT gantry consists of a rotating X-ray tube and detector array, it is necessary to keep the circular ring as a single piece, but the PET scanner can be used like a clamp. The CT scanner should be allocated between the legs of the stationary patient table, while the PET scanner comes from the other axis. The mechanical structure of the linear motion system should be taken into account to sustain the design.

Since there is no commercial same-surface system available to drive heavy objects precisely for medical imaging purposes from different axes, a custom system should be developed for the J-PET total-body PET/CT scanner. Developing separable and relatively short-size linear stages and combining them along two axes on the same surface can be a solution. The aim of this study is to investigate and propose a linear carriage machine element for using it as the base slider of the J-PET total-body PET/CT scanner. This system features independent and moving PET and CT gantries from different axes to the same patient table. Current work covers an initial idea for the motion, but the main objectives are to figure out a novel machine element to precisely carry PET and CT gantries of the J-PET total-body PET/CT scanner, converting concept designs into detailed computer-aided design (CAD) and construction of the system.

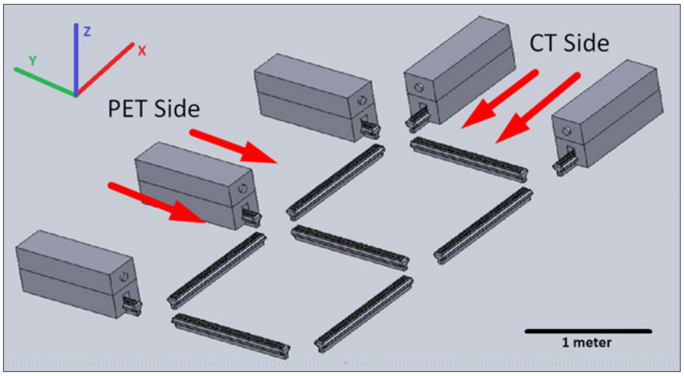

Fig. 2. Preliminary 3-D design of the system. Motion blocks and their fixed discrete rails. Red arrows show the directions for gantries.

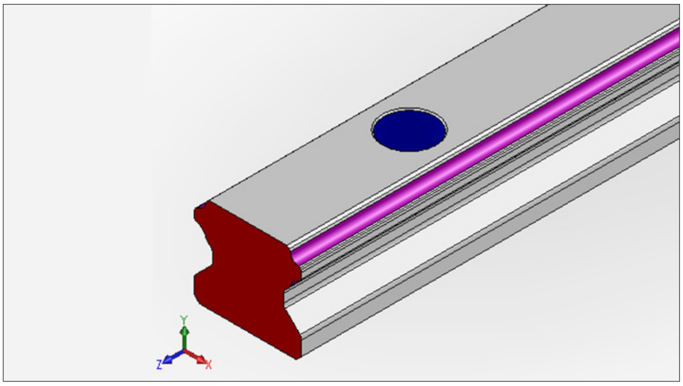

Fig. 3. Partial isometric view of a linear slider rail which will be improved (the red surface is the endpoint, blue surface is for fixing and purple surface the location of ball bearings).

THE PROJECT METHODOLOGY

There are design, simulation, prototyping, scaled production and automation steps from concept to final construction of the cross-staged motion system. The current stage of the work is concept design and it should be carried into a CAD design.

Design of crossed stages

Combining two different objects from two different axes on the same surface is an engineering puzzle because of crossed linear stages. Linear bearing systems and conventional linear stages assume that each object on a line does not intersect with another object from another axis on the same surface. To overcome this the classical way one axis should be above the other, but weights of scanning devices and area limitations make it hard to apply. As an alternative to the conventional approach, we propose discrete linear stages that meet two different axes on the same surface by separable linear stages.

Fig. 2. shows the current concept design, consists of two motion blocks to carry the CT and three motion blocks to carry the PET devices. Each device will move on only one axis (X or Y) and be driven by servo motors inserted into moving blocks. The empty space between the rails allows block transitions for objects coming from both the X and Y axes.

Proposed materials

For a common precise linear stage, there should be linear sliders to carry load, rotating ball screws to move the load and motors directly coupled with ball screws to give motion. In our approach, sliders and ball screws should be combined as separable modules. To realize the mentioned concept design, machine elements should be customized, since conventional linear sliders only provide a carrier for the load and a turning motion contact part for linear movement. Standard sliders cannot be used in discrete positions with empty spaces between each serially arranged rail.

A standard rail shape, shown in Fig. 3., is the path for the carrier which moves a load. The carrier has bearing units, i.e., balls to minimize the friction between the carrier and the rail. The purple surface on the image shows where the balls fit. Low friction may reduce the required power for motion and make it possible to use the same rail for the long term. However, the working distance of the carrier is limited by the length of the rail; conventional linear-slider carriers keep their ball bearings inside of the carrier only if a rail is inserted into it. The red surface in Fig. 3. shows the end point. If the balls exceed the red surface they fall from the rail. The rail should be redesigned with a special carrier to keep the balls even if they leave the rail.

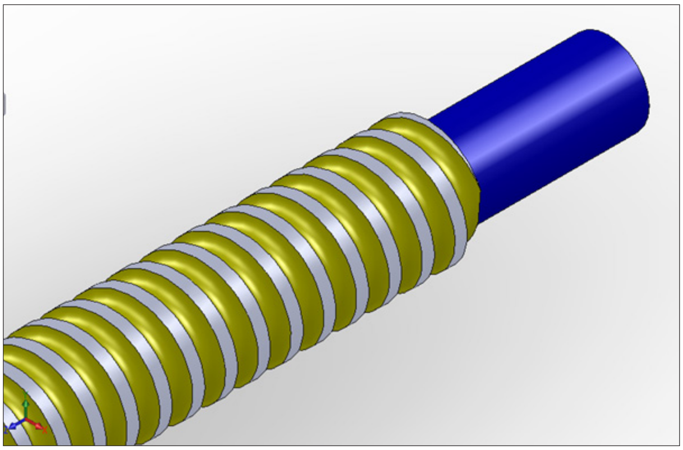

Fig. 4. Partial isometric view of the ball design screw to be improved (yellow surface shows the ball settling area; blue surface shows the motor coupling area).

The carrier moves via a force applied by a motor-coupled ball screw. Similar to conventional carriers, ball screws are designed to operate on a continuous but limited line rather than discrete rails. In Fig. 4., a normal ball screw is shown with an isometric view. The screw nut moves forward or backward when the shaft shown in blue rotates. Conventional linear-motion machine elements, with their known structures, cannot be applied on discrete rails on the same axis. Designing a new ball-screw system with a combined carrier is required to construct a system suggested in Fig. 2. The core of this new system should consist of two main parts: a stable block and a motion block. The stable block is the fixed rail part on ground to carry moving blocks. It should contain channels for the balls and a housing for to keep them in the stable block. The motion block, which is the moving part between the linearly arranged stable blocks, should have a screw shaft on the motion block. The motor will be also coupled via gears to the screw shaft to enable the shaft to move. In contrast to the normal carrier and ball-screw system, the screw shaft should not be covered with nuts but a semi-housing to allow motion blocks to move from one stable block to another. This method may be used in a J-PET total--body PET/CT scanner if a new nut is designed to keep the balls inside and allow the shaft to separate from the nut.

Motors and encoders

Motors can be inserted inside the motion block to drive the ball screws. The required power is related to the load and gear ratios. There are several motor types, but precise motion with high loads points to servo motors, which are closed-loop systems and can be driven by speed or position control algorithms. It's also possible to combine most servo motors with planet gears to increase the given torque by the motor. These motor-control units are called "servo drivers", and they should be kept in separate cabinets because of their large size. Electrical signals to the motors should be carried out with flexible cable channels. Cables should also be moving during examination. Servo motors contain rotary encoders to give their angle position to the controller, but this information may not always match the exact position of the gantries. An additional encoder system, such as magnetic linear tapes, can be installed. Magnetic bands are linear measuring devices to read a magnetic band to take out micrometre-resolution position information. A magnetic band on the ground surface and a reader on the motion block can be considered as a position feedback sensor. Improved designs for ball screws and rails can be used for motion and stable blocks. A prototype will be produced for one motion block and two stable blocks to verify the approach of applicability for separable linear sliders.

DISCUSSION

The proposed solution for the design and construction of the cross-staged gantry system, as outlined in this study, introduces a pioneering approach to address the challenges associated with moving both a total-body PET scanner and a CT scanner from different axes on the same surface. The key motivation for this work is overcoming the limitations in commercial linear machine elements, to prompt the exploration of a discrete sliding system through the design of specific machine elements capable of allowing parts to separate from the rails. As mentioned earlier, this system is still in the development phase, and the current transition is from concept design to a detailed CAD design.

The significance of this approach is particularly highlighted in the context of the J-PET total-body PET/CT scanner, which demands a unique solution due to the distinctive geometrical challenges associated with its design. The proposal of a discrete sliding system, if successfully implemented, holds promise not only for the J-PET scanner but also for various other motion systems, providing a potential solution to the limitations encountered with multi-axis linear stages.

The detailed discussion of the rail shape and ball design screw reveals a meticulous consideration of the intricacies involved in the construction of a cross-staged motion system. The emphasis on low friction, working distance limitations and the need for a redesigned rail to prevent ball displacement underscores the attention to efficiency and reliability in the design. The introduction of a combined carrier with stable motion blocks showcase an engineering solution to overcome challenges associated with conventional ball-screw systems.

Unlike traditional PET/CT scanners that necessitate the movement of patients through a lengthy tunnel, the J-PET total-body scanner's stationary table eliminates the need for patients to traverse extended distances. This design choice aligns with the commitment to enhance the overall patient experience during imaging procedures. The stationary patient table plays a pivotal role in minimizing motion artifacts during imaging. In total-body PET/CT scans, maintaining patient stillness is critical for obtaining accurate and artifact-free images. The stationary position eliminates potential sources of motion artifacts, ensuring the precision of both CT and PET scans.

This is particularly crucial for achieving reliable anatomical and metabolic data simultaneously. The J-PET total-body scanner's approach to employing a stationary patient table results in a more compact and space-efficient design compared to traditional PET/CT scanners. The elimination of the need for a long, moving patient table contributes to a more streamlined and mechanically compact imaging system. This can have practical implications for installation in medical facilities with spatial constraints.

SUMMARY

This work proposes a new solution for designing and constructing a two-axis sliding system on the same surface to carry both a total-body PET scanner and a CT scanner from different axes. In this paper, we discuss the limitations of commercial linear-machine elements and propose a new method for linearly moving two objects from different axes to a stable bed to overcome geometrical issues for the J-PET total-body PET/CT scanner. A discrete sliding system can be possible if particular machine elements are designed to allow parts to separate from the rails. These new elements can be used to move the J-PET total-body scanner's PET and CT parts separately on the same surface. This system can also be used for different motion systems to overcome limitations of multi-axis linear stages.

ACKNOWLEDGEMENTS

We acknowledge support from the National Science Centre of Poland through grant nos. 2021/42/A/ST2/00423 and 2021/43/B/ST2/02150, Jagiellonian University via Project No. CRP/0641.221.2020, and the SciMat and qLife Priority Research Area budget under the auspices of the program Excellence Initiative – Research University at Jagiellonian University.

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