Universidad Carlos III de Madrid

BACHELOR THESIS

BIOMEDICAL ENGINEERING

Use of the rPET system as an educational tool

Author: Paula Mejía De Miguel

Tutor and director: Juan José Vaquero

Madrid, June 2016

USE OF THE rPET SYSTEM AS AN EDUCATIONAL TOOL

Author: **Paula Mejía De Miguel**

Tutor and director: **Juan José Vaquero**

TRIBUNAL

President: Rosa María De la Cruz Fernández

Secretary: Adela María García Martín

Vocal: María Arrate Muñoz Barrutia

The public defense of this Bachelor Thesis took place on the 12th of July 2016 in Leganés in the campus of the Escuela Politécnica Superior of the Universidad Carlos III de Madrid.

ACKNOWLEDGEMENTS

Siempre me ha parecido muy cierta la frase de Isaac Newton:

"Si he logrado ver más lejos, ha sido porque he subido a hombros de gigantes"

Y es que efectivamente, yo sola no podría haber llegado hasta donde estoy en este momento. Por eso, quiero agradecer a mi tutor, Juan José Vaquero su apuesta por mí en este trabajo. Su confianza y sus ganas de enseñarme y hacerme aprender.

También quiero agradecer a Guillermo Vizcaíno su paciencia, sus ganas de echar una mano en todo momento y su ánimo hasta cuando las cosas se torcían.

Y no puede faltar un gracias bien grande a Santiago y a Carlos, por las horas y horas dedicadas, por aceptarme como su aprendiz, por estar siempre pendientes de mi y dispuestos a ayudar en cualquier cosa. Por ponerme las pilas cuando hacía falta y a la vez hacer los días más amenos. Ha sido estupendo poder trabajar con vosotros, sois muy grandes.

Y finalmente, quiero dar las gracias a mi familia y a mis amigos por todo el cariño que me han dado durante este tiempo. Por preguntarme incansablemente sobre el estado de "mi máquina" y escuchar pacientemente mis explicaciones. Por darme ánimos cuando las cosas iban mal y celebrar conmigo los avances.

Muchísimas gracias a todos por auparme y hacerme lograr cosas de las que me creía incapaz.

ABSTRACT

Positron Emission Tomography (PET) is a functional imaging technique that enhances clinician's ability to diagnose and treat diseases non-invasively by detecting metabolic processes within the body. Currently it is mainly used in areas such as oncology, cardiology and neurology. Getting to know how this nuclear imaging systems work is of great importance, especially for biomedical engineers who need to have a good command of the different medical imaging techniques. The goal of this project is to prepare an experimental rPET prototype and have its hardware and mechanical system ready for teaching purposes. The project was carried out in the Biomedical Engineering laboratories of Universidad Carlos III de Madrid.

The rPET was an undocumented laboratory system and it was necessary to gather all the existing information referring to the device and compile it in a user's manual to facilitate future work with the system.

In order to set up the mechanical system, the system's source supply and the external connections coming out from the control motor box were rewired. The prototype lacked of a bed system, so a completely new one was installed into the device. In order to facilitate the rPET control, a joystick that allows the user to manipulate the bed and ring of detector's movement was implemented. This joystick also contains security measures such as a deadman push button and LEDs to inform about fault states. It was also necessary to check the proper functioning of the detectors to correct offsets or any other possible failure. The mechanical system of the rPET can be controlled either with the implemented joystick or by means of commands in a Linux terminal. The software of the rPET was already implemented but it was required to verify the communication between the CPU and the control system, update the necessary parameters in order to match the renewed bed system and check the functioning of the motor controller's and acquisition software.

TABLE OF CONTENTS

INTRODUCTION

Positron Emission Tomography (PET) is a highly specialized non invasive imaging technique that produces functional images of the body by the administration of a radioactive labeled tracer. This imaging technique allows the detection of metabolic processes within the body.

PET scans are a powerful tool used in the diagnosis of cancer, brain disorders such as Alzheimer's disease and cardiovascular problems like coronary artery disease and heart damage after a heart attack. It also makes it possible to eliminate the need of surgical biopsy in certain cases because PET can detect whether lesions are benign or malignant [1]

According to the IMV 2015 PET imaging Market Summary Report, PET imaging is currently performed in ~2.380 sites within the US, including mobile and fixed PET/CT and PET scanners [2]. This accounts for about 6.5 scanners per million people [3]. Nevertheless, 96% of the fixed scanners were PET/CT [2]. This data shows the potential and enhanced capabilities of combining two imaging techniques in a single device. Other hybrid systems such as PET-MRI have been developed and launched to the market by companies like Siemens in 2010 [4]

The number of PET/CT scanners in US is about 6 times the number in all Europe, which counts with approximately 350 installations [3]. The Spanish national health system counts with 65 PET devices, from which 26% of them can be found in Comunidad de Madrid. [5]

Small animal PET acquires functional images of animals such as rats and mice. The demand of this type of devices is driven by the importance of animal model-based research, which allows the expansion of research beyond ex vivo studies and provides a better understanding of diseases common to both humans and rodents. Small animal PET devices also benefit the clinical practice improving the study of new diagnostic tracers which improve disease detection, diagnosis and the assessment of response to therapy [6].

Before the small animal PET devices were developed, preclinical data could only be obtained by sacrificing and dissecting tissues of animals but nowadays a single animal can be studied noninvasively multiple times reducing costs and number of laboratory animals [7].

It is possible to appreciate how PET imaging is a developing area and it is highly valuable for students to understand how this technique is performed and how images are acquired. The purpose of this work is to set up a rotating PET device based on an experimental prototype with experimental and teaching purposes in Universidad Carlos III de Madrid. Interacting with the PET system will provide a better understanding of the concepts taught in class.

OBJECTIVES

The main goal of this project is to prepare an experimental rPET prototype for teaching purposes.

In order to achieve this main goal, three specific objectives have been defined each of them composed of several tasks.

1. Collect all the documentary evidence regarding the rPET device.

    1.1. Organize and classify all the documents.

    1.2. Produce a user's manual that provides meaningful information simplifying the interaction with the device.

2. Adapt the mechanical system for laboratory practices and test the detector's and associated electronics performance.

    2.1. Rewire the system's main power strip.

    2.2. Examine the motor control box' external connections and rewire where needed.

    2.3. Reassemble the bed system.

    2.4. Develop a joystick to control the mechanical movement of the device.

    2.5. Test the rPET's detectors.

3. Perform an assessment of the current software with the updated hardware.

    3.1. Test the proper operation of the CENTENT CN0170 controller and the serial port connection between the motor control box and the CPU.

    3.2. Verify the proper functioning of the previously implemented software to move the mechanical system.

    3.3. Update the parameters that configure the mechanical system for the new bed system.

    3.4. Test the detection and acquisition software

BACKGROUND

INTRODUCTION TO POSITRON EMISSION TOMOGRAPHY TECHNIQUE

Positron Emission Tomography is a non invasive functional imaging technique that allows observing the development of metabolic processes in the body.

Biologically active compounds with positron emitting radioactive isotopes are introduced intravenously into the body of the patient. These compounds are distributed throughout the body by means of the blood flow and are incorporated to metabolic processes. Once the isotopes are within the organism, their distribution is measured using detectors located in the PET machine. PET images allow in-vivo observation of multiple biological processes and it is used nowadays with clinical purposes in oncology, cardiology and neurology among other disciplines.

The isotopes that have been introduced in the body are unstable. Each time a proton decays to a neutron in the nucleus, a positron and a neutrino are emitted. The emitted positron will interact with the matter surrounding the isotope and it will suffer an annihilation reaction when it interacts with an electron. This reaction produces two anti-parallel gamma rays of 511 KeV each, which will reach the detectors within the PET. This process is shown in Figure 1. The line defined by the trajectories of the gamma photons is called Line of Response (LOR). PET detectors, are equipped with a coincidence circuit that allows identifying and characterizing all the LORs obtained. LOR's characterization makes it possible to reconstruct a three dimensional image of the activity distribution within the object by using mathematical models [8].

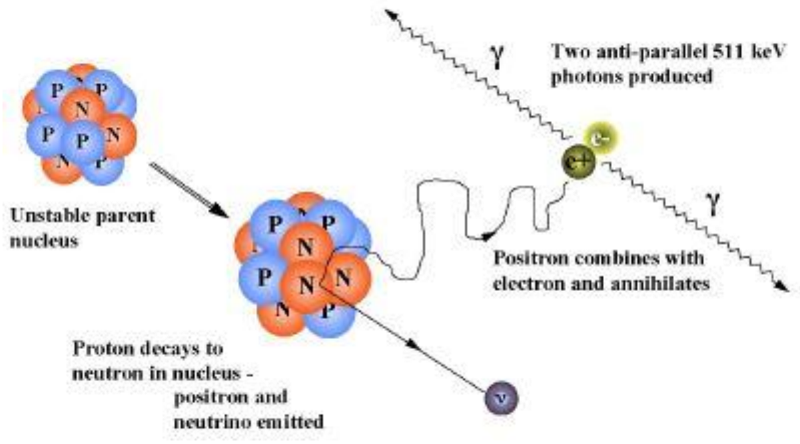


Figure 1: Positron and electron annihilation.
http://depts.washington.edu/nucmed/IRL/pet_intro/intro_src/section2.html

The radioisotopes used for this imaging technique should be positron emitters and "organic" atoms which are easily assimilated by the human body and can take part in metabolic reactions.

Some examples of radioisotopes used in PET are ^{18}F, ^{13}N, ^{15}O and ^{11}C. All of them have short lives and have to be produced in a cyclotron, which makes PET technique dependent of having access to one of those particle accelerators [9].

Isotope's half life is also a very important fact to consider. It should be long enough to allow proper tracing of the molecule but it shouldn't emit longer than the time needed for image acquisition so unnecessary radiation is minimized.

Every PET machine needs at least two parallel detectors to detect the pair of gamma rays simultaneously, but in order to increase signal to noise ratio and therefore sensitivity, the number of detectors is usually higher than two. The detectors in PET can be located in a complete circular ring and some PET machines have even more than one ring. On the other hand, increasing the number of detectors also increase the cost of the device, so other rotating models with fewer detectors like the one described in this thesis have also been developed. Figure 2 shows to possible ring distributions. The distribution on the left is composed by a pair of detectors that rotate to detect the events while the distribution on the right is made up of a continuous ring of detectors.

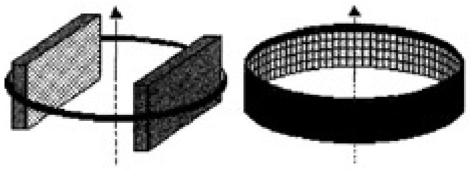


Figure 2: Examples of PET detector disposition.

http://www.globalspec.com/reference/49573/203279/html-head-chapter-8-positron-emission-tomography

When two photons are detected in close temporal proximity by opposite detectors it is assumed that both photons were originated by the same annihilation reaction and a coincidence is registered by the computer system.

Nevertheless, not every coincidence reports a true event. Within the data acquired in PET machines, it is possible to find random coincidences and scatter coincidences. Random coincidences are those produced by a pair of photons coming from different annihilation events and scatter coincidences are those pair of photons that come from the same annihilation event but with scatter. This reduces spatial resolution of images acquired this technique.

CHARACTERISTICS OF SMALL ANIMAL PET

Small animal PET posses certain unique characteristics not present in human PET devices that deal with the much smaller structures studied in rodents.

Table 1 shows a list of commercially available small-animal PET systems and its characteristics. [6]

		FOV (mm)		At CFOV...			
Manufacturer	Model	Transaxial	Axial	FWHM spatial resolution (mm)	Sensitivity (%)	Energy window (keV)	Reference
Bioscan/Mediso	NanoPET	45–123	94	1.2	8.3	250–750	(69)
Carestream	Albira	80	40–148	<1.3	3–9	Not available	(70)
Gamma Medica/GE Healthcare	LabPET	110	38–113	1.3	1.1–5.4	250–650	(15)
Philips	Mosaic HP	128	120	2.7	1.1	410–665	(71)
Raytest Isotopenmessgeräte GmbH	ClearPET	94	110	1.5	1.9	250–750	(72)
Sedecal, S.A.	rPET-1	68	47	1.5	0.5	250–650	(72)
Siemens Preclinical Solutions	microPET Focus 120	100	76	1.3	7.1	250–750	(73)
	microPET Focus 220	190	76	1.3	3.4	250–750	(74)
	microPET Inveon DPET	100	127	1.4	9.3	250–625	(32)

CFOV: center field of view

Table 1: Commercially available small-animal PET systems and main characteristics.

Yao, Rutao Lecomte, Roger Crawford, Elpida, "Small-Animal PET: What Is It, and Why Do We Need It?" 2012.

Spatial resolution becomes a crucial aspect in this type of devices. The weight of a typical mouse is around 25g while for an adult person it is around 75 kg therefore small animal PET needs a better spatial resolution. [7] The spatial resolution depends among other characteristics on the size of the detector crystal and the detector's decoding scheme. Recent small animal PET scanners have greatly improved spatial resolution by using long and thin detector crystals with the long side aligned with the radial direction and the narrow side facing the imaging field of view. Spatial resolution has also been enhanced by the use of statistical iterative reconstruction algorithms.

The use of animals to perform studies arise other issues that have to be taken into account such as the use of anesthesia during the procedure, which is administered by masking the animal. It is also important to account for environmental changes and hypothermia, to which rats and mice are more susceptible than human. Usually a heating source is incorporated in these devices and vital signs are monitored during image acquisition. Apart from that, structures to hold the animals in selected positions have to be added to the design of this type of devices.

rPET

The work presented in this project has been based on an experimental prototype placed in the biomedical laboratory of Universidad Carlos III de Madrid. The basic workflow and schematics explaining how this system works are presented in the following section. This introduction is also thought to be a basic manual to understand the system and it could be given to those who are going to interact with the device in the future providing a general overview of the system's hardware.

The device presented in this document is referred as rotating PET (rPET) system due to the fact that it contains four detector blocks instead of a continuous ring of detectors as many clinical systems do. In order to acquire images, the detectors rotate along the ring's axial axis. This type of detector's arrangement produces lower resolution images but it supposes a reduction in cost. The basic scheme of the rPET is shown in Figure 3. The actual PET is connected to a CPU which contains all the software needed for the image acquisition process. The CPU also transmits user specifications related to the process of acquisition to the PET device.

On the other hand, the rPET sends to the CPU the data acquired with the detectors. This data will be used in the process of image reconstruction. The rPET also sends data related to its physical state such as the ring or bed position, the number of control units connected etc.

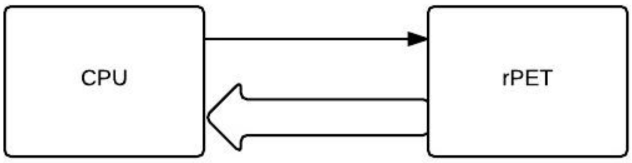


Figure 3: rPET basic scheme

Figure 4 illustrates a more detailed scheme of the rPET. The general structure can be subdivided in two smaller structures according to the process they are involved with; the control elements (showed with red dashed lines in Figure 4) and the detection elements (showed with green dashed lines in Figure 4).

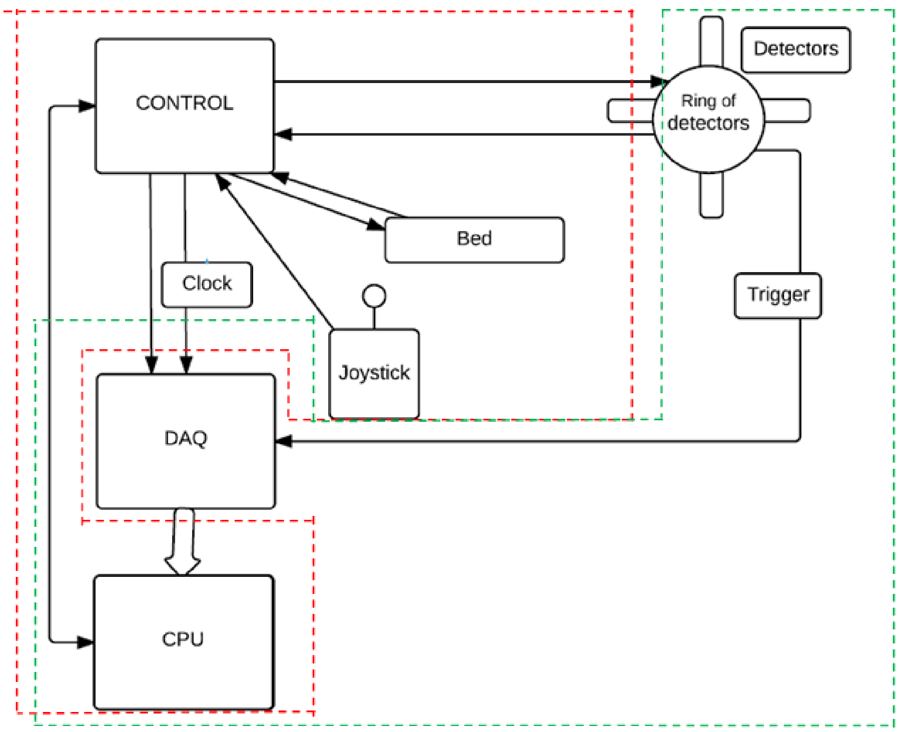


Figure 4: Detailed scheme of the rPET elements and interaction between them.

Control elements

Figure 5 shows the elements that form part of the control section of the rPET, each of them will be explained in more detail in the following section.

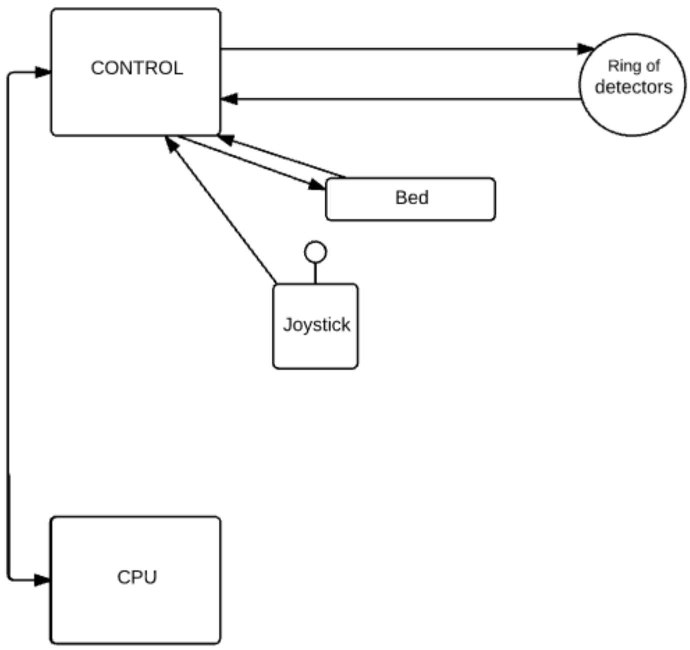


Figure 5: Control elements of the rPET

Control: Manages all the elements for data to be acquired and processed.

All the elements related to the mechanical system control, have been grouped together in a “motor control box”.

The control box receives information about the bed and ring of detectors’ position. It also allows translating joystick movements performed by the user, in movements of the bed and the ring. The control unit communicates with the CPU sending information about the state of the other components, but it also receives commands introduced by the user from the CPU.

In order to allow all this communications, the box is equipped with several connectors as it can be seen in Figure 6.

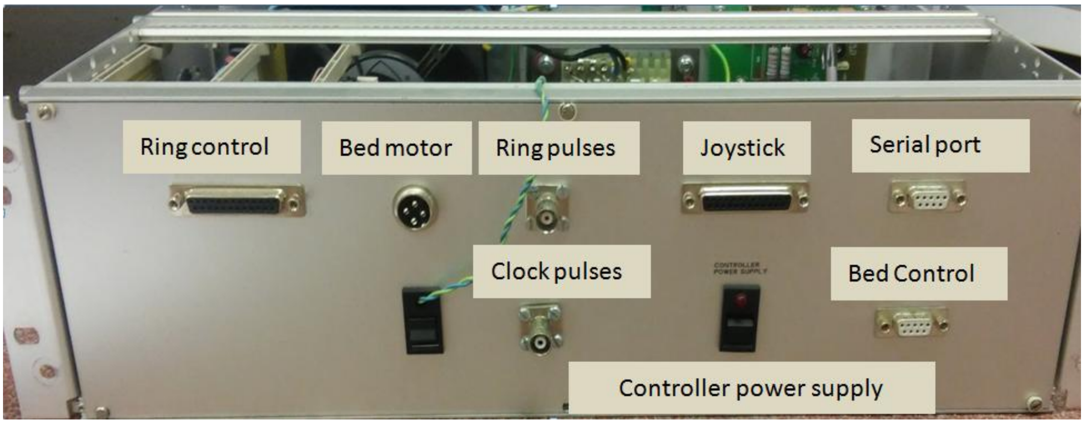


Figure 6: Motor control box of the rPET

- Ring control: Wired to this entry it is possible to find the 25 pin exit from the Newport. The phases of the step motor and the ring signals used are connected to it.
- Bed motor: Contains the phases of the bed step motor.
- Clock pulses: This is a 5 kHz clock signal used as a reference during the acquisition process.
- Joystick: This connector carries the joystick signals moving the bed and the ring.
- Ring pulses: This connector carries a square signal with a number of pulses equivalent to the ring's movement. Specifically, the relation between pulses and angular movement is 250 pulses\degree.
- Bed control: This connector contains the bed's fault and home signals. The fault signals determine the bed's moving limits.
- Serial port: Communication between the computer and the controller.
- Controller power supply: This switch carries the power supply to the motor controller and to the electronics associated to it.

The most important part of the motor control box is the cn0170, a programmable two axis motion controller for step motor systems.

When the cn0170 is connected to a computer, the computer can control the execution of the running program. The cn0170 can also be executed to run certain programs automatically. It also returns data to the computer. All these communications are performed using a communication port.

Figure 7 represents a sketch of the controller cn0170 with its main connections.

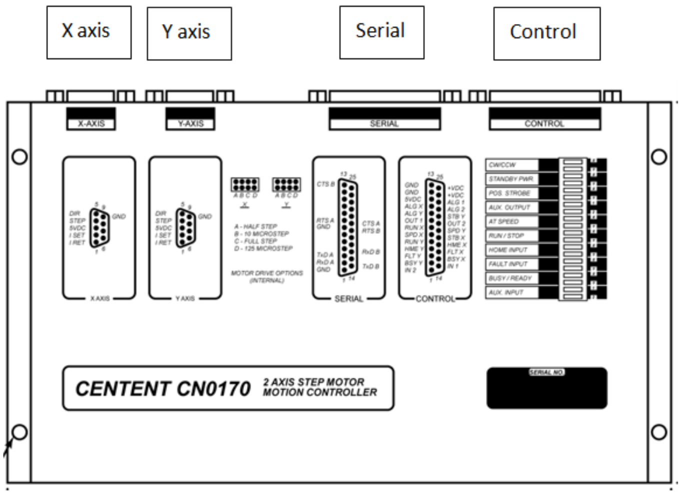


Figure 7: Centent CN0170 overview and main connections

- X and Y connectors: DB9 connectors that form the interface between the cn0170 and the motor controls
- Control connector: This DB25 connector contains all the inputs and outputs of the controller. The power supply also passes through this connector.
- Serial connector: It is a DB25 connector that process the data of two different channels, A and B. Channel A is used to connect the computer and the controller. Channel B can be connected to a channel A of a different cn0170 controller in order to extend the number of axis in the system.

Ring of detectors: The rPET has a total of four blocks of detectors grouped in two pairs and located perpendicularly in a ring. The ring is moved by a step motor and the angle and direction of rotation is determined by the user that controls the movement of the ring by means of the joystick.

Bed: The rPET has a Velmex LG BiSlide moved by a step motor. The movement and direction of the BiSlide is controlled by the user by means of the joystick. Velocity and acceleration of the bed can also be set up by the user.

Joystick: It is used as an interface between the user, the bed and ring of detectors. Moving the joystick in the Y direction, the bed moves towards or away from the ring of detectors. Moving the joystick in the X axis, the ring of detectors rotates.

CPU: Within the CPU there is a shell capable of executing commands related to the movement of the mechanical system of the rPET. This shell called `motor_shell_centent` has been programmed in C language and has been designed to work in a UNIX terminal.

Detection elements

Figure 8 shows the elements that form part of the detection section of the rPET, each of them will be explained in more detail in the following section.

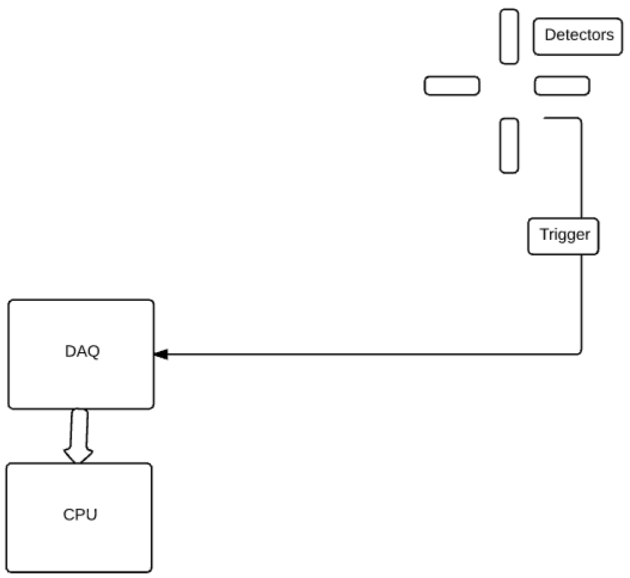


Figure 8: Detector elements of the rPET

Detectors: As it was said before, the rPET has four blocks of detectors grouped in two pairs and located perpendicularly in a ring.

Each of the detectors is formed by the following components:

- Scintillation crystal matrix: It is located on the surface of the photomultiplier and it transforms the incident gamma photons into light photons. The crystals used in the present rPET are LSO crystals. LSO crystals or $Lu_2SiO_5[Ce]$ posses excellent physical properties that make them suitable to be used in PET systems. They have high density (7.4 g/cm^3) and high effective atomic number (65) which makes them efficient in gamma ray detection. Apart from this physical properties, LSO crystals also count with an optimum combination of short decay constant (40 ns) and high relative emission intensity (75) that together with the absence of secondary decay component make them suitable for this type of applications.[20]

- Photomultiplier: Collects the light generated by the crystals and it is transformed into an equivalent electrical signal.

- Associated electronics: It is located at the photomultiplier's exit and it not only amplifies the signal coming out from the photomultiplier but also reduces the number of signals to be digitalized.

- Internal protection case: Removable case that contains the PS-PMT and the crystal matrix. It provides protection to both elements and ensures that the crystal matrix is fixed to the main case and the photomultiplier won't move with respect to it.

- Main case: Metallic case that contains all the previous elements attaching them to the ring of detectors. The main case also allows adjusting the position of the detector and isolating it from the ambient light.

A picture of one of the detectors used is shown in Figure 9.

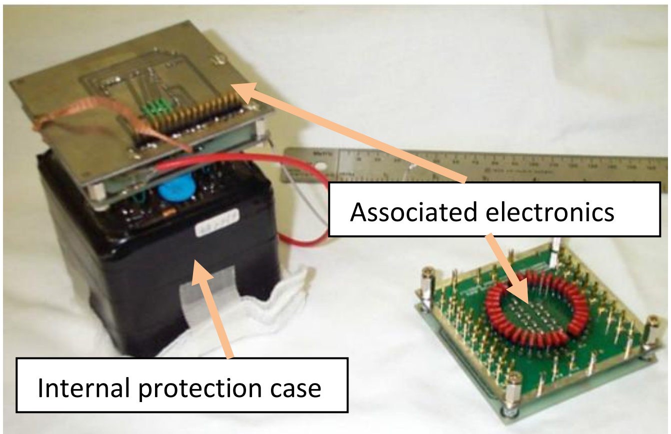


Figure 9: rPET detectors

The event detection in the rPET is based on the Anger Principle [12] which allows detection and allocation of true events within the scintillation crystal matrix. The method used to read the output signal coming from the position sensitive photomultipliers (PS-PMTs) is the calculation of the center of gravity using photomultipliers with cross-wire anodes [13]. Within the detector electronics there is a charge distribution network that collects the signal obtained after each detected event. Position of the event can be calculated depending on the outputs coming from each channel. An example of a cross-wire anode is depicted in Figure 10.

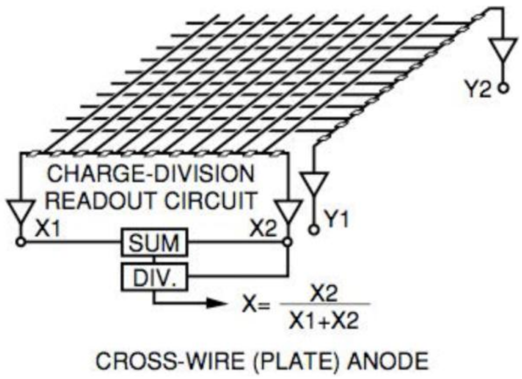


Figure 10: Detector's charge distribution network

Coming out from the detector’s main case there are four cables as it is shown in Figure 11, which is a sample picture of the outer view of one of the detector’s blocks.

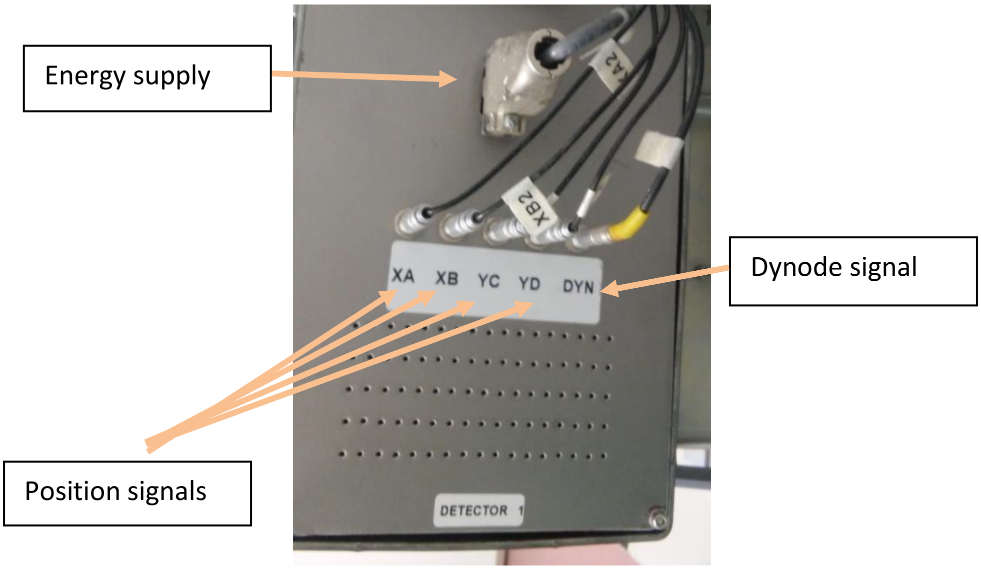


Figure 11: Outer view of the rPET detector blocks

Channels XA and XB allow to allocate the event in the X position while channels YA and YB give the Y position of the event. Energy information can be obtained by summing all the four channels. Finally, the dynode signal doesn't go through the charge distribution network circuit and goes directly into an amplification step. This signal will have positive polarity and will be used as a time sensitive signal to temporally locate the detected events.

It is possible to appreciate in Figure 11 that several cables need to be connected to the block of detectors in order to collect the corresponding signals and transmit them to the DAQ. Apart from that, the electronics of each detector need to be supplied. The energy supply of the detectors is carried by a wire connecting the block of detectors by means of a DB9 connector. All this wires make it impossible for the ring of detectors to complete a rotation of 360 degrees; therefore in order to acquire images the ring will perform two rotations of 180 degrees in opposite directions. In order to operate in the described way, the ring counts with two limit switches that should be always active to avoid damage of the equipment. When the switches are active, each time the ring reaches one of the End of Range (EOR) limits, a fault signal will be produced. Figure 12 shows the different positions the ring can be at: home, positive end of range (EOR) and negative end of range.

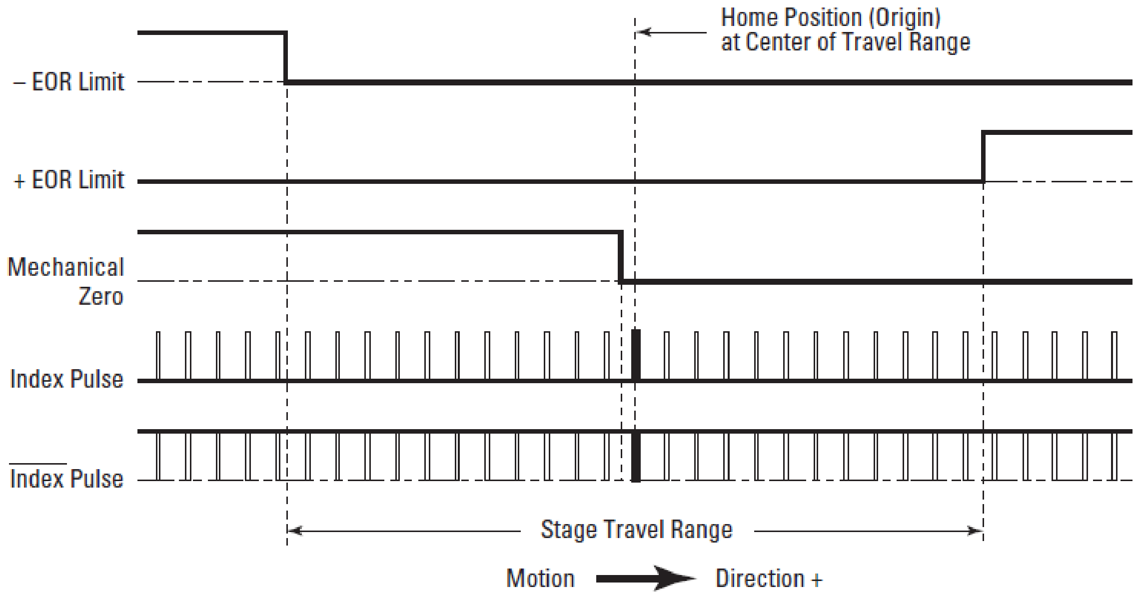


Figure 12: Ring fault detection. Each time the ring reaches one of the End of Range (EOR) limits, a fault signal triggers.

The detectors send two types of signals to the Data Acquisition System (DAQ):

Trigger signal: Produced each time a valid coincidence signal is detected. A signal is considered valid when it fulfills the following conditions:

-Two events are detected in opposite detectors within a time equal or lower than the interval determined by the coincidence window.

-Both events are within a certain energy range.

The first condition allows to reject single events and the second conditions avoids considering as valid noisy events and piled-up signals.

The trigger signal activates the data acquisition process.

Data signal: Contains the information about the detector and the position within the detector where the event has occurred.

DAQ: The Data Acquisition System digitalizes the coordinates indicating where the valid events have occurred in each pair of opposite detectors and sends this information to the CPU.

The data acquisition system is capable of:

- Differentiate between single events (where a photon reaches just one detector) from true events (where two photons are detected in opposite detectors within a time interval)
- Differentiate between noise signals, pile-up signals and valid events. Pile-up signals are those that occur within a short time interval and they are detected as a single high valued signal.
- Digitalize signal positions of each photomultiplier and send them to the CPU where the control program is executed.

The DAQ is composed of two main blocks:

1. A group of modules externally connected to each other and powered by a CAMAC chassis

2. A PCI interface connected by a LVDS BUS to some of the modules within the chassis that provides the control application with the data coming from the acquisition system.

TASK IMPLEMENTATION

In this section, the procedures followed to accomplish the objectives specified before are explained. The work needed to achieve each specific objective, has been divided in several tasks which are detailed in this section.

1. - DOCUMENTATRY EVIDENCE GATHERING

1.1. - Organize and classify documents

The rPET prototype was an undocumented experimental laboratory device. Because of its purpose is merely educational and it is not a commercial device, it lacks of the corresponding regulatory documents. There was information referring to the rPET coming from different sources. All of them were necessary to understand the various elements of the prototype but information was scattered among circuit diagrams, component manuals and previous senior thesis among others. All this information needed to be gathered and organized to facilitate future work with the rPET.

A list of the different sources used to develop the manual and understand the functioning of the device is presented below:

- D. Eduardo Lage Negro senior thesis "Sistema de adquisición de datos para Tomografía por Emisión de Positrones".
- rPET – CETIR project SUINSA.
- CN0170 Hardware manual.
- CN0170 Software manual.
- RV Series Newport User Manual.
- Laboratory notebooks from previous work with the rPET
- Individual circuit diagrams referring to:
    - Joystick.
    - Control motor box.
    - BiSlide and Newport motor connection.
    - Main power strip.
- Joystick and BiSlide technical specifications.

1.2. - User's Manual

Apart from organizing and classifying the existing information referring to the rPET a unique and easy to follow user's manual was developed. This manual provides the basic general information to interact with the device. If further insight about any particular topic is needed, more specific information can be obtained by accessing the documents and manuals used to develop the user's manual.

The manual is divided in two main sections concerning the hardware and the software respectively. It also contains several appendixes with technical specifications about the different items embedded in the rPET that may be useful for the user.

2. - MECHANICAL SYSTEM ADAPTATION

This section details the procedures followed in order to set up the mechanical system of the rPET. Only the changes and updates performed to the rPET prototype are mentioned here.

2.1. – Main Power Strip

The first step performed to set up the mechanical system was to rewire the main power strip of the rPET. The electricity supply line goes through a differential switch and it is distributed among the motor control box, the detector's supply source and the data acquisition system by the use of three thermo magnetic switches. The basic scheme of the rPET being supplied to the 220 KV supply line is shown in Figure 13.

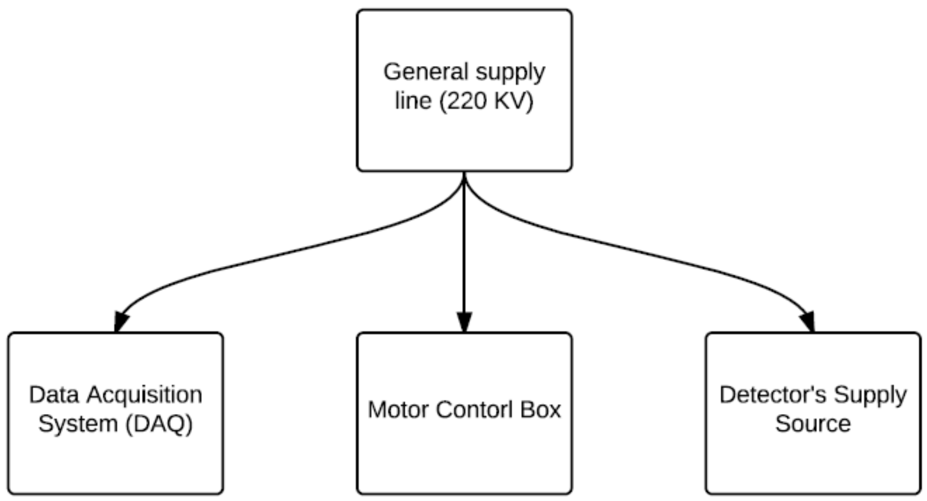


Figure 13: Scheme of the rPET supply system

The main power strip was successfully wired to feed all the components of the rPET. The electric diagram designed for the power strip can be found in Appendix II.

The three thermo magnetic switches were reconnected using the standard color code: brown for the phase cables, blue for the neutral ones and green/yellow for ground.

2.2. - Motor Control box external connections

As it was explained in the rPET background section, the motor control box groups together all the elements related to the mechanical system control. Within the motor control box it is possible to find the Centent CN0170 controller as well as the drivers for the bed and the ring of detectors. These elements communicate with the external elements by means of the connectors specified in rPET the background section. In this project it was not necessary to change anything within the motor control box but it was required to make up some missing external wires that allowed communication between the motor control box and external elements. The basic scheme of the connections between the motor control box and its external elements is presented in Figure 14:

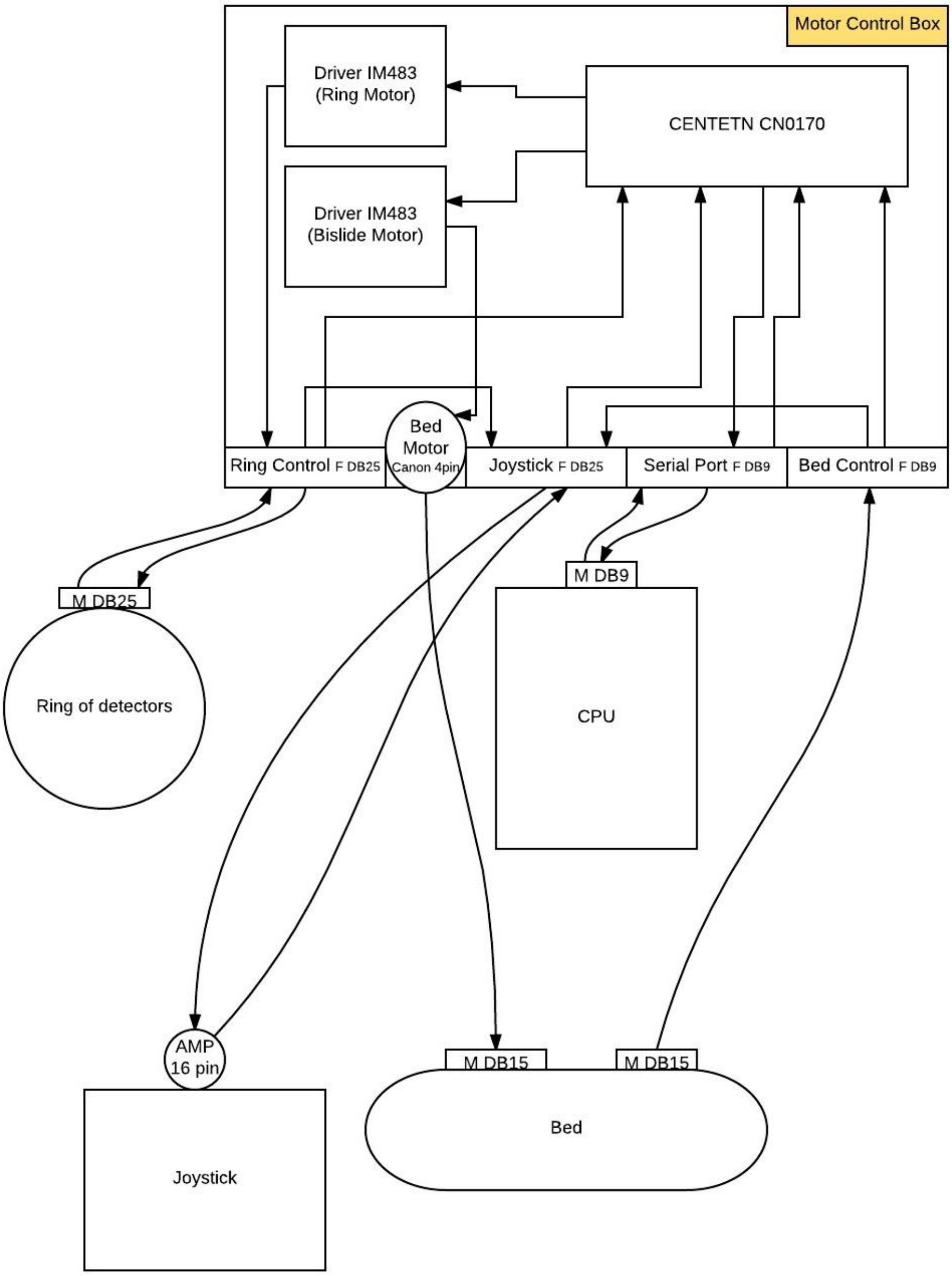


Figure 14: Connections between the motor control box and its external elements

Ring of detectors: It is possible to appreciate in the diagram of Figure 14 how the Centent communicates with the ring motor driver which in turn controls the ring of detectors. Communication between the ring and the motor control box is given by a wire with DB25 connectors at both sides. This communication is double-way because although the ring is controlled by the Centent, it also sends signals both to the Centent and the joystick system about home and fault positions.

Bed system: The bed system needs two cables to function properly instead of just one. First, the BiSlide step motor communicates with the motor control box by means of a cable connected to the motor control box by a 4 pin Cannon-DB25 connector. This wire carries signals from the BiSlide motor driver which is controlled by the Centent; therefore, it provides a one-way communication. On the other hand, the communication for the BiSlide control system is carried out with a cable connected to the motor control box by means of a DB9 connector and to the BiSlide with a DB15 connector. This wire carries the home and fault signals provided by limit switches contained within the BiSlide. The signals provided by this switches are carried into the Centent or the joystick system.

Joystick: The joystick box communicates with the motor control box with a cable that connected to the motor control box using a DB25 connector and to the joystick box using an AMP 16 pin connector. The communication given in this case is double-way. The joystick receives fault inputs from both the ring of detectors and bed systems but it also needs to communicate with the Centent to transmit the user inputs that allow interacting with the mobile parts of the rPET device.

CPU: Finally the motor control box communicates with the rPET CPU using a serial port communication. This communication is also double way because the rPET sends information about the state of the mobile system to the CPU but it is also possible for the user to control the Centent by means of a terminal window and move both the ring of detectors and the bed using certain commands.

2.3. - Bed system reassembly

The prototype lacked of a bed structure, so a completely new one was installed. A Velmex LG MN10-0200-M01 BiSlide was selected to perform this function. After performing research among different distributors and companies, this model was selected due to the fact that it could be custom made to meet the rPET requirements. The BiSlide was delivered by Velmex, INC [11].

The BiSlide is a linear motion stage that consists on a worm gear coupled to a fixed support which is screwed to the device chassis surface. The worm gear is triggered by the movement of a step motor which is coupled in the front part of the BiSlide. In

Figure 15 the step motor is designed as “Motor plate”. Within the worm gear it is possible to find a support for the linear movement of the system which goes forward or backwards depending on the rotating direction of the attached step motor. The relation between the motor’s rotation movement and the support translation is 1 turn per millimeter. Figure 15 shows the features of the linear motion stage selected for the rPET.

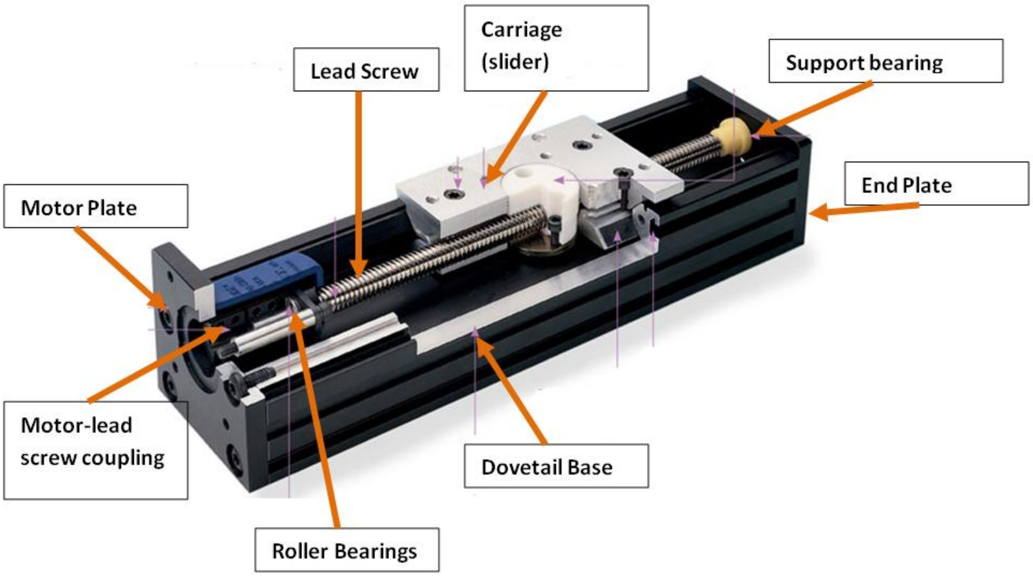


Figure 15: rPET's linear motor stage features

The travel distance of the BiSlide and therefore its linear movement capacity is 20’’ (508 mm). Figure 16 shows the elevation, plan and section of the BiSlide.

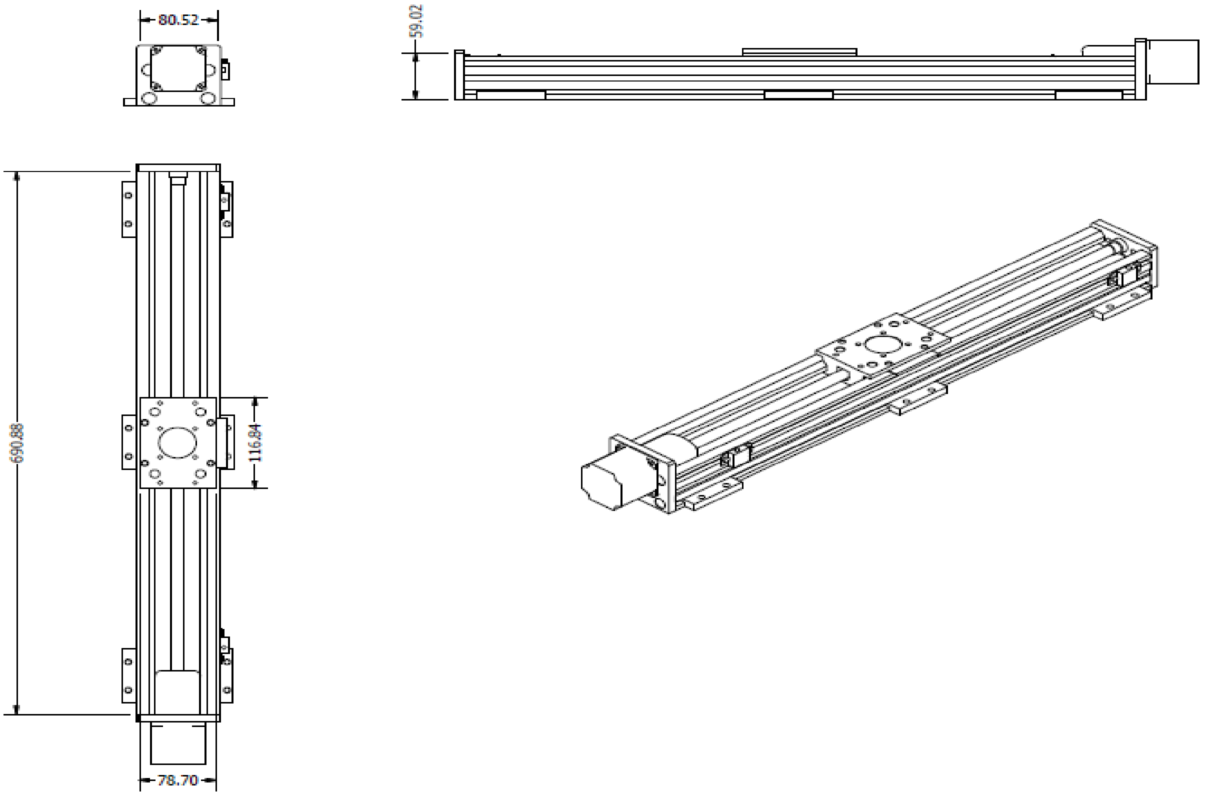


Figure 16: BiSlide's elevation plan and section

The BiSlide is also provided with three limit switches like the ones shown in Figure 17.

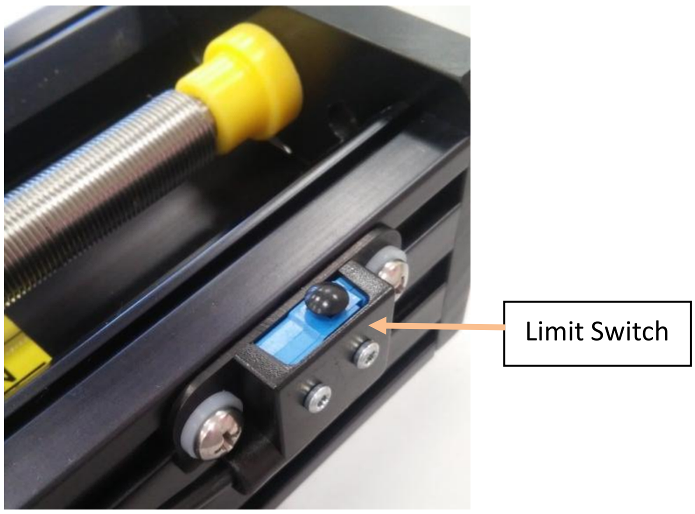


Figure 17: BiSlide limit switches

One of the switches marks the limit for the forward movement of the bed, another one is used as the limit for the backward movement and the last one marks the home position. The switches are triggered when the hook screwed to the mobile support goes over the switch's actuator. These switches communicate with the Centent and the joystick system and depending on the one that has been activated the rPET will respond in a different way. The three signals coming from the limit switches enter the motor control box by means of a wire connected to it with a DB9 connector. The fault signals coming from the movement limit switches communicate with the joystick system and turn on a LED notifying the user that a limit switch has been reached. It also stops automatically the system until it is started in controlled conditions. Table2 shows useful characteristics related to the BiSlide.

Characteristic	Value	Further comments
Reference position	0.0	Location of the backward limit switch
Home position	32 mm from 0.0 position	Minimum bed's departure position before carrying out a study
Travel distance	508 mm	Long enough to acquire whole body images of small animals
Control interface	Manually using a joystick or via software	
Motor steps/mm	400	The negative direction will move the bed towards the detectors

Table 2: BiSlide characteristics

The cables for the BiSlide control and power supply were implemented and welded to the respective connectors. The BiSlide limit switches which are normally closed become open when they are triggered. It was necessary to connect the two fault switches in series so any time one of them is triggered because the bed reaches the limit either in the forward or the backward direction the user is not able to move the bed anymore. This connection in series creates an electrical AND.

It was also necessary to design a structure to fix the BiSlide to the rPET device. The structure is made of steel and it is mounted on the chassis of the rPET. The supporting structure was designed and implemented in the technical office of Universidad Carlos III de Madrid. The BiSlide is fixed to the structure by means of six cleats also designed and implemented in the technical office of Universidad Carlos III de Madrid. The cleats were allocated three at each side of the BiSlide providing the desired attachment to the support structure. The layout of both the BiSlide support and the cleats can be found in Appendix III and Appendix IV respectively.

The circuit design for the BiSlide control system and the power supply was also developed and it can be found in Appendix V and Appendix VI respectively.

The BiSlide installation into the rPET was successfully performed. It will allow the movement of the sample to be imaged in the forward and backward direction. The BiSlide therefore permits locating different parts on of the sample to be imaged within the FOV as well as the performance of dynamic range studies. Figure 18 shows the BiSlide installed into the rPET.

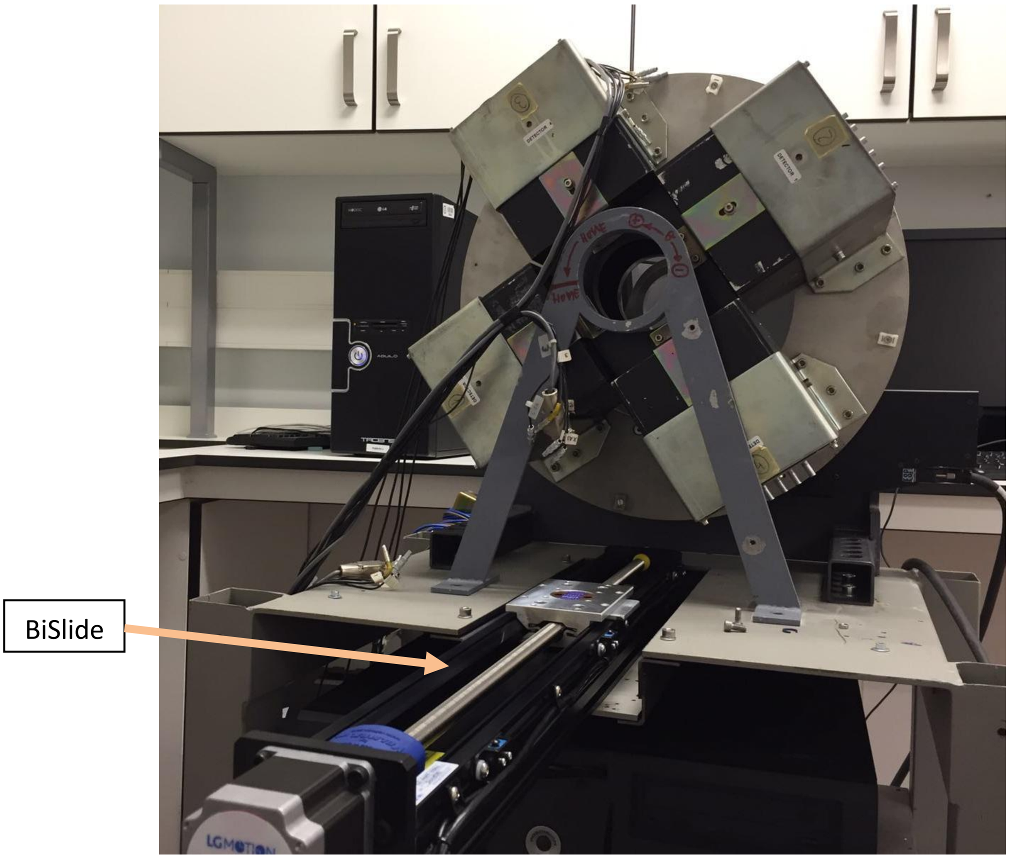


Figure 18: BiSlide installed into the rPET

2.4. - Joystick development

A joystick system was also implemented from scratch to facilitate the user's control of the rPET. With this purpose, an M-series miniature resistive joystick was selected. The joystick counts with three movement axes although only two of them are used in this project. The joystick axes are potentiometers in which the stick's movements made by the user adjust the voltage dividers. Moving the X axis it is possible to rotate the ring of detectors. Moving the handle in the Y axis the user will move the bed forward and backward. Dimensions of the joystick used are shown in Figure 19.

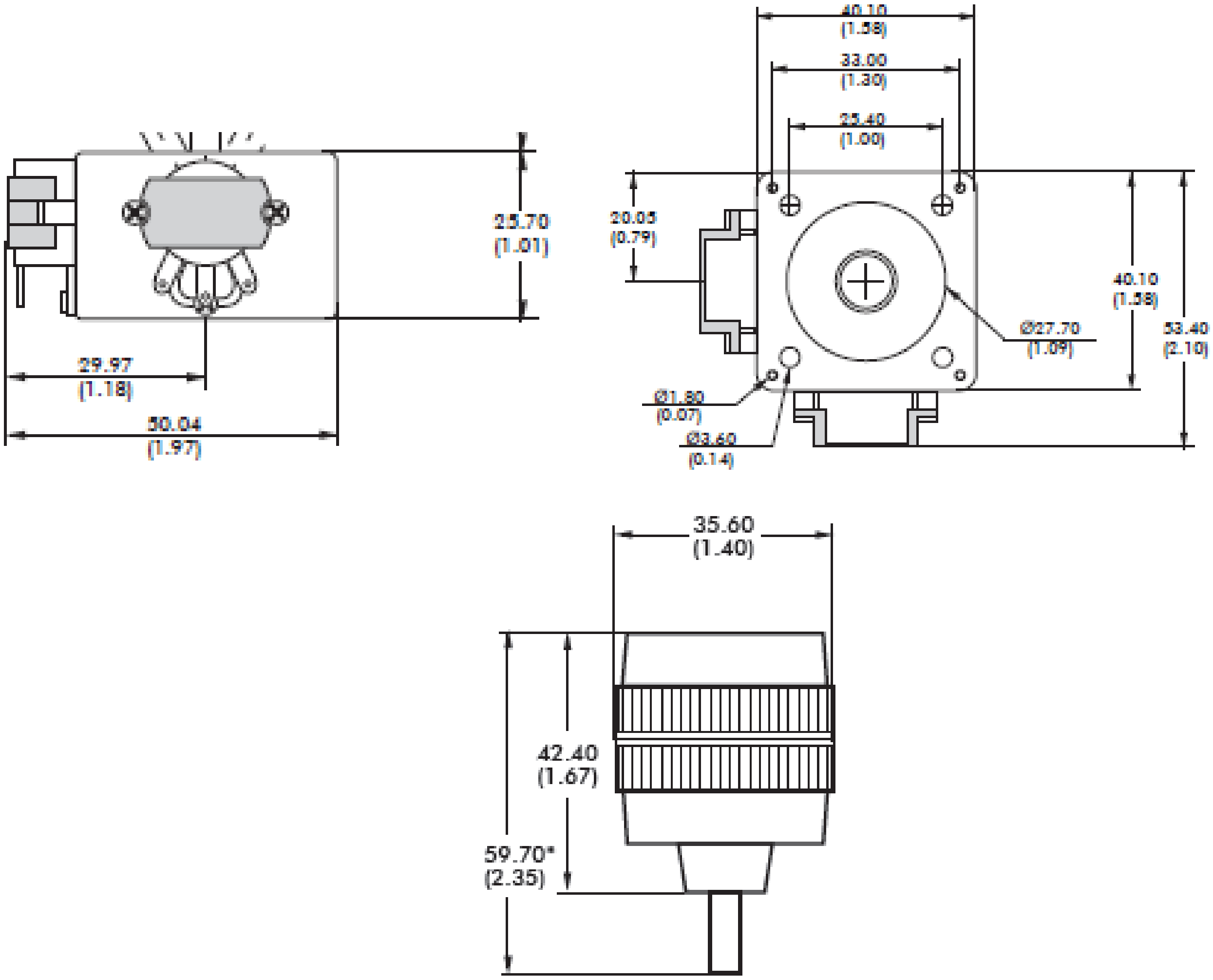


Figure 19: Joystick dimensions

The joystick was allocated within a metallic box that was mechanized in the technical office of Universidad Carlos III de Madrid. In Appendix I it is possible to find the detailed layout of the implemented box. The inner wiring of the joystick system was performed and the cable connecting the joystick to the motor control box was implemented. The electric diagram of the inner circuits within the box can be found in Appendix VII. Figure 20 shows the result after implementing the wiring.

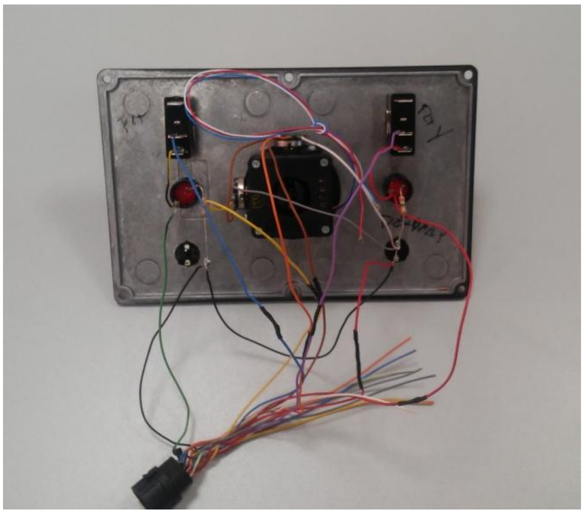


Figure 20: Joystick inner circuit view

The electric diagram for the wiring of the joystick box to the motor control box can be found in Appendix VIII. All this wiring process was properly documented and the correspondence between cable colors and connector pins can be found in Appendix IX. The final product after joystick implementation is shown in Figure 21.

Figure 21: Joystick box

The joystick gives the opportunity of controlling the rPET movement without entering commands in the computer. Its implementation is thought to improve user's interaction with the device making it quicker and more intuitive. The joystick system was designed to perform the following functions:

- Bed movement produced by Y-axis movement.
- Ring of detector's movement produced by X-axis movement.
- Notify the user when a fault state is reached. Depending on where the fault state has been produced (either in the bed, the ring of detectors or both) a different LED will be turned on. Fault states mark the End-Of-Run (EOR) of either the BiSlide or the ring of detectors.
- Blockage of the corresponding element (bed or ring of detectors) when a fault state is reached.
- Recovery of the capacity to move either the BiSlide or the ring of detectors after a fault state has been reached by the deactivation of the corresponding switch within the joystick box.

As it is possible to observe in Figure 21, the box containing the joystick is equipped with two pushbuttons, two LEDs and two switches as well as a handle to facilitate user's operation with it. One of the pushbuttons acts a deadman that needs to be pushed in order to move either the bed or the ring of detectors. As the rPET is thought to be used with teaching purposes, the deadman acts as a security measure that avoids moving either the rPET's bed system or the ring of detectors by accident or under uncontrolled conditions. The other pushbutton is left unwired but the reason to implement it within the joystick box was to leave space for future improvements or additional features needed to control the rPET.

On the other hand, the joystick box is equipped with two LEDs and two switches that make up the fault system. Each time the bed or the ring reaches a fault position like the end of the travel range a fault signal will enter the joystick and turn on one of the two LEDs. Further movement of the corresponding axis won't be translated into movement of the ring or the bed if it has reached a fault state until the user turns off the corresponding switch. By turning the switch off, it is assumed that the user has knowledge of the fault state, that he/she knows how to correct it and that he/she will perform further movements under controlled conditions.

The fault signals for the BiSlide system are produced when the bed reaches the end of the travel range either in the forward or the backward direction. In the case of the ring of detectors, the fault signals are produced when the ring reaches the End of Range (EOR) position. It is very important to have the limit switches that activate the End of Range limits turned on. A switch that enables the limit switches can be found in the Newport to which the detectors are attached. It is located on the right side of the rPET. Figure 22 shows the location of this switch on the rPET.

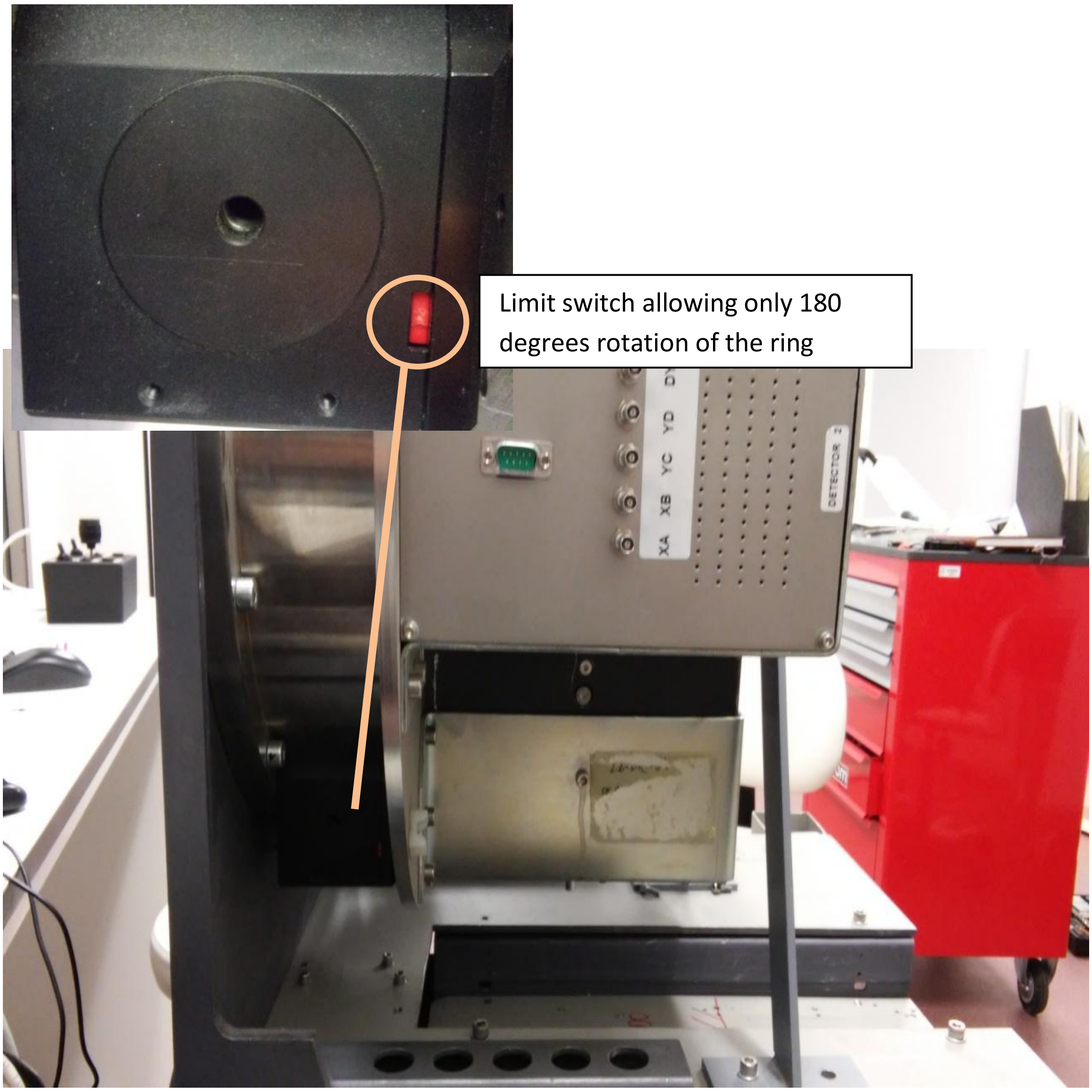


Figure 22: Location of the limit switch that enables the EOR switches

When the switch is in the disposition showed in Figure 22 (completely red), the ring will only perform rotations of 180 degrees. If it is tried to rotate the ring more than 180 degrees, the fault system will become active. When the switch showed in Figure 22 is seen half red and half white, the End of Range switches are deactivated and the ring can be rotated 360 degrees or more.

2.5. - Testing the rPET detectors and associated electronics

The proper operation of the rPET detectors needed to be checked to correct possible offsets or other errors that may be present. In order to do that, the signals coming from the outputs XA, XB, YC, YD, which provide position information, were measured for each detector with an oscilloscope. The measurement procedure described in the technical specifications was followed. The photomultiplier tubes were supplied with a voltage within the recommended range (900 V). When the measurement was performed, the temporal divisions were set to 100ns and the voltage divisions to 500mV. Figure 23 shows the setup arranged for the detector's performance measurement.

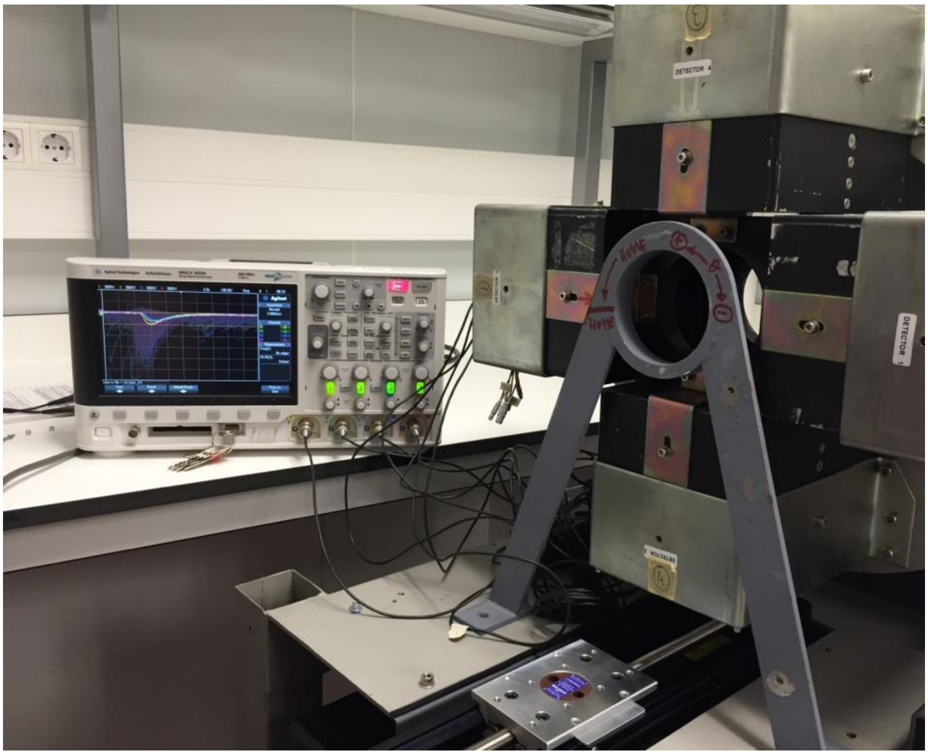


Figure 23: Setup for the detector's performance measurement

The signal coming from the dynodes of the detector's photomultipliers, which provides temporarily information, was also measured. To do that, the specifications detailed in where also followed.

Figure 24 and 25 show the signals recorded for the four positioning signals coming out from detector number 1. The signals where acquired both with and without persistence.

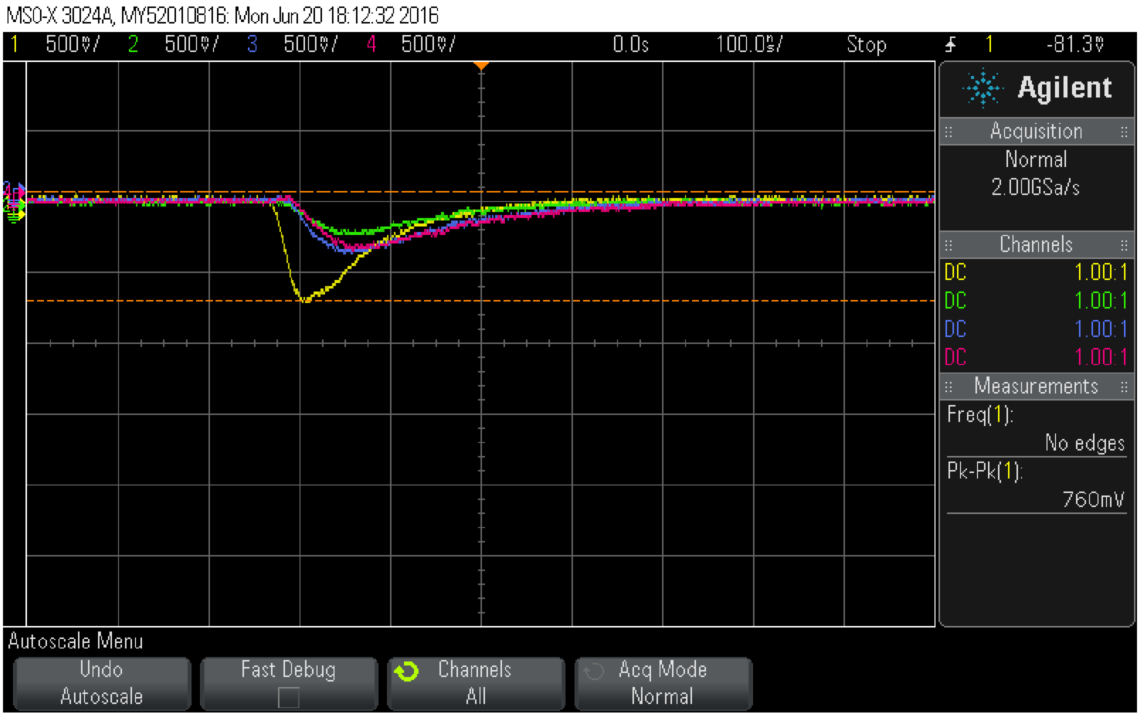


Figure 24: Output signals from detector block 1 without persistence

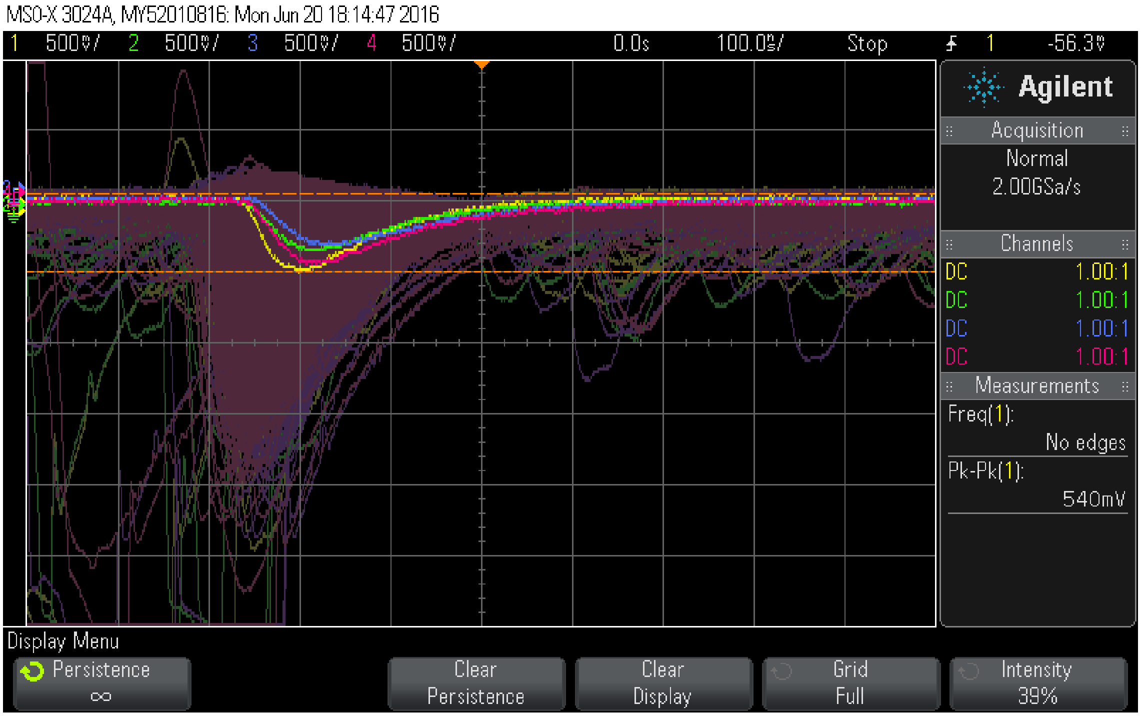


Figure 25: Output signals from detector block 1 with persistence

The signals are found to be within the desired detector's dynamic range. The results obtained for the rest of detectors were similar to the ones showed in Figure 24 and 25. Figure 26 shows the signal obtained from one of the dynodes. The image was acquired in persistence mode.

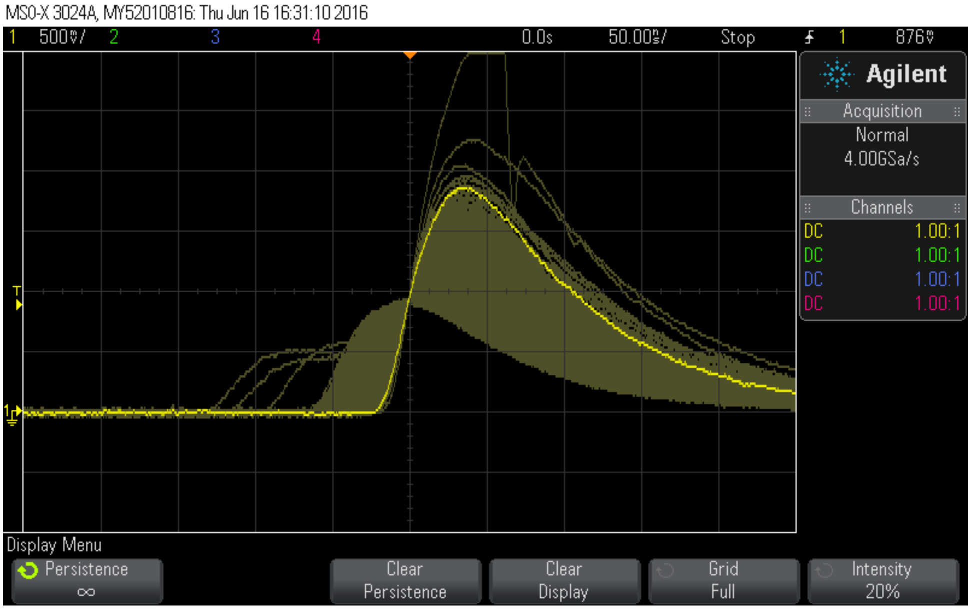


Figure 26: Dynode signal

The rest of the dynode signals were also within the desired dynamic range and therefore valid to perform acquisitions with the rPET.

3. - PERFORMANCE ASSESMENT OF THE CURRENT SOFTWARE WITH THE UPDATED HARDWARE

The rPET prototype counted with previously implemented software. This software can be divided into calibration software and acquisition software. The calibration software can still be subdivided into software controlling the mechanical system and the acquisition and detection software. Controlling the mechanical system there is a shell named *motor_shell_centent* capable of executing specific commands over the movement system of the rPET. This shell counts with a series of user functions that allow controlling the movement system of the rPET by means of a computer terminal and without using the joystick. The detection and acquisition calibration software counts with several implemented functions. All this structure is depicted in the diagram shown in Figure 27.

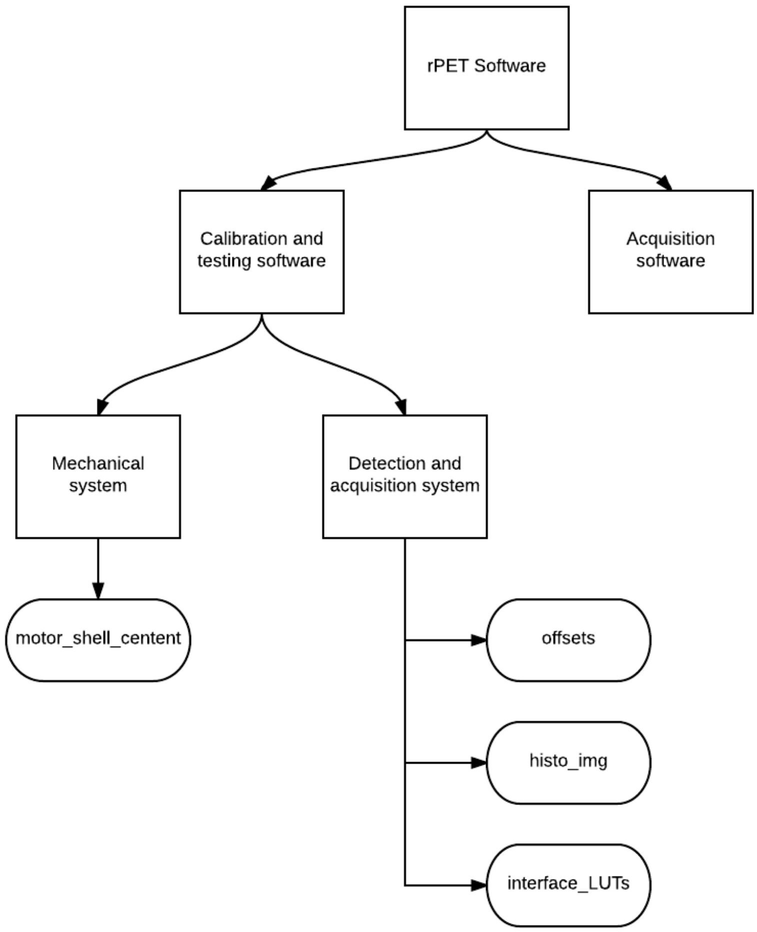


Figure 27: rPET software

The functions of the programs shown in Figure 27 are listed in Table 3 [8]:

Program	Function
offsets	Obtains offset levels from the acquisition system
histo_img	Characterizes each of the detector blocks in the system
interface_LUTs	Obtains the crystal map of each detector
Daq	Tomographic acquisition program

Table 3: Main rPET's programs function

3.1. - Testing the CENTENT CN0170 Controller and serial port communication

The first step concerning the software assessment was to check the proper operation of the Centent controller that manages the movement of the bed and ring step motors. In order to do that, a serial port communication was established between the Centent and a laptop. The Centent was controlled using an open-source, free software named Tera Term. Tera Term is a terminal emulator that supports telnet, SSH1 and SSH2 connections besides serial port connections [15]. Using this software, simple commands found in the Centent software manual [10] were sent to the Centent and movement of both the ring of detectors and the bed system was achieved.

Once it was checked that the Centent controller was working properly, it was necessary to verify that the serial port communication between the motor control box and the Linux CPU of the rPET was working properly. A serial port communication was established between both of them and using the computer's terminal window, it was possible to access the `motor_shell_centent` and detect the Centent unit connected to the CPU.

3.2. – Software moving the mechanical system

Once the serial port communication was proved to be working properly, the operation of the `motor_shell_centent` that controls the movement of the bed and ring step motors was tested. Using the computer's terminal window, it was possible to access the program and verify the operation of the user functions found in [8]. All the functions controlling the movement of the rPET system produced the desired outcomes.

The mechanical system of the rPET was configured using the function `configcnsystem` implemented within the `motor_shell_centent`. This function initializes the X and Y axes motors and introduces into the motor controller the configuration values given as argument. The file used as default if no other configuration file is specified is "`motor_params.txt`". This file is located within the executing directory and it contains information concerning: velocity, acceleration, home direction, controller's step resolution, acceleration profile and joystick mode among others.

Configuration of the rPET's mechanical system was also proved to be correct. It was also verified that a change in the configuration file used by the former function is translated into the desired change in the mechanical system operation.

3.3. - Mechanical system parameter update

The installation of a new bed system within the rPET, made it necessary to change some parameters within the rPET's software to meet the characteristics of the new step motor. The parameters steps/mm and steps/ degree are used in the file `microshell.h`, which is a component of the `motor_shell_centent` file and contains the definition of the functions used on it.

From the BiSlide specifications [11] it was possible to know that the worm gear moves 1mm per motor turn and the motor within the BiSlide rotates 1.8 degrees per step. The BiSlide driver can be configured to control the step motor at full resolution (1.8 degrees/step) of half resolution (0.9 degrees/step). Checking the driver's disposition it was observed that the half resolution configuration was selected. With all this information it was possible to compute both the steps/mm and steps/degree and update the file `miscroshell.h`.

$$\frac{Steps}{degree} = \frac{1}{1.8} = 0.55$$

$$\frac{Steps}{mm} = \frac{1turn}{mm} * \frac{0.55\, step}{degree} * \frac{360\, degree}{turn} = 400$$

3.4. - Detection and acquisition software

The detection and acquisition software was tried to be launched too. When executing the functions implemented in the detection and acquisition system of the calibration and testing software, an error was obtained repeatedly:

```
Error opening pfba
```

pfba together with pfbb are special files used for communication with the system making reference to physical devices or services of the operating system.

This error corresponds to failure of the Peripheral Component Interconnect (PCI) interface. A PCI interface is a standard computer bus used to connect peripheral devices to the motherboard [16].

In the case of our system, the PCI is connected to a Low Voltage Differential Signaling (LVDS) bus. LVDS buses operate at low power and can run at very high speeds [17]. Its function is to capture and package the events coming from the acquisition system. The PCI includes the driver's source code (`pfb.c` and `pfb.h` files).

In order to solve the PCI problem, the instructions found in [8] that explained how to reinstall the PCI interface were followed:

- Create the special files pfba and pfbbb using the following commands:

  ```
  mknod-m 0666/dev/pfbs c 60 0
  mknod-m 0666/dev/pfbb c 61 0
  ```

  The parameters *–m 0666* show the mode of the corresponding file */dev/pfba* and */dev/pfbb* which in this case is 'a+rw' (all users can read and write [18]. The parameter *c* indicates that the device is a special character file and not a special block file. The numbers following the file type show the bigger and lower device numbers.

- Copy the driver (*pfb.o*) to the appropriate path which in our case is `/lib/modules/2.4.20-8smp/kernel/drivers/char/`. Once these steps has been completed, it could be possible to connect the module (.o file) to the nucleus of the operating system by executing the command `/sbin/insmod pfb`, but in order to avoid having to connect the module to the operating system each time the system is initialized it is necessary to follow one last step.

- Add to the script `/etc/rc.d/rc.local` the line `/sbin/insmod.pfb`. By doing this, each time the system is started the module will be connected to the operating system.

The pfb.o file was recovered from a former backup copy of the rPET system.

Despite of carrying out the previous steps, the detection and acquisition system of the calibration and testing software could not be executed.

Taking a deeper insight into the system, it was discovered that the kernel within the rPET system had changed. The actual kernel in the system is 3.2.0-23-generic while the kernel compatible with the pfb.o driver was 2.4.20-x. The system had gone through some system actualizations since the implementation of the software and the driver and the kernel are not compatible anymore producing the failure of the PCI interface and the subsequent lack of communication between the data acquisition system and the rPET's CPU.

DISCUSSION AND CONCLUSIONS

LIMITATIONS

The main limitation that needs to be overcome before this device can be used by students of Universidad Carlos III de Madrid is the incompatibility of the PCI driver with the CPU Linux kernel. Until this problem is not solved no acquisitions can be made because the PCI is the element that captures and packages the events coming from the acquisition system.

In order to solve this condition, three possible solutions are proposed:

1. To compile again the driver's source code to match the kernel's new version (3.2.0-23-generic).
   Although this is a possible solution, it would be almost impossible to accomplish it in the present situation because when the source code for this system was implemented, it was not documented and it is not available nowadays.

2. To program again the driver using reverse engineering.

3. Change the computer's kernel to make it compatible with the driver.

It would be necessary to carry out the pertinent assessment to determine which of the three solutions is the more convenient.

FUTURE WORK

The first step that should be followed in order to leave the rPET prototype ready for teaching purposes is to resolve the compatibility problem between the PCI driver and the rPET kernel. This will allow making acquisitions and using the device as a test bank to exploit iterative reconstruction and explore angular sampling techniques.

Although the mechanical system of the rPET was set up and is ready to use after this project, further improvements can be added to it enhancing the rPET's performance. One of these improvements would be to substitute the current cables collecting the signals from the detector blocks by elbowed connectors. This will increase the distance between the BiSlide and the detector system increasing the travel range of the bed system because the sample could be moved under the connectors. Figure 28 shows the limited space between the BiSlide and the connectors.

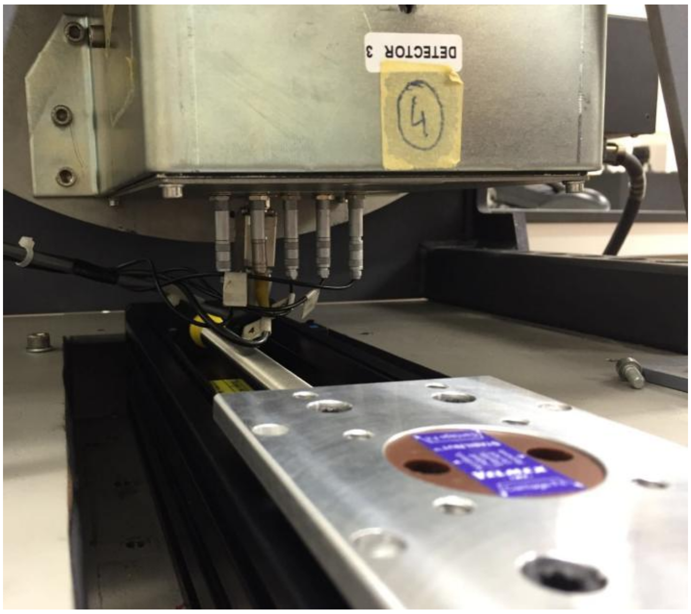


Figure 28: Limitation of space between the BiSlide and the connectors

Another improvement that could be made to the device concerns the joystick fault system. The actual system can receive 4 fault signals, two of them coming from the BiSlide and other two coming from the ring of detectors. The system is able to differentiate if the fault state has been produced in the BiSlide or in the ring of detectors, but it is not possible to differentiate where the fault state has been reached within the element producing a fault signal. For example, if the bed reaches its limit in the forward direction, a LED light will turn on and the user will not be able to further move the bed in any direction until the corresponding switch has been deactivated. Once the user deactivates the switch, the fault signal is ignored and he will be able to move the bed again in any direction. This system assumes user's knowledge of how to interact with the device in such a way that if a fault state is reached because the bed has arrived to its forward limit, the user will deactivate the corresponding switch and will move the bed backward and not forward. Further security measures could be introduced into this fault system by not allowing the user to move the bed in the forward direction if a fault state has been reached even if the fault switch is deactivated. This configuration could be achieved by incorporating a controller into the joystick such as an Arduino device which will control this situation.

Finally, it is known that many systems are equipped with a laser positioning system that enhances alignment of the patient and allows signaling of reference markers over the sample as well as reproducibility of the acquired image [19]. Implementation of a system like that in the rPET prototype will provide a more realistic version of the device. This laser system could also be connected with the joystick device in order to allow remote control by the user

MAIN CONTRIBUTIONS AND CONCLUSIONS

The availability of an rPET system within the laboratories of the Universidad Carlos III the Madrid will be highly valuable for both students and teachers of the Biomedical Engineering Degree. It will give the opportunity to get further insight into the PET imaging technique, consolidate concepts taught in class and it will provide firsthand experience with nuclear imaging.

The work developed in this Final Degree Project has set up the mechanical system of an rPET prototype and the rPET's hardware is ready for future work with the system. The main improvements implemented within the device are listed below:

- Development of a bed system that provides support to the samples that will be imaged and move them within the FOV.

- Implementation of a joystick system that facilitates user interaction with the rPET's mechanical system. The joystick system carry out movement of the bed and the ring of detectors, informs of the presence of a fault state within any of the axes and it is provided with security measures (deadman) to avoid accidental movement of the rPET's mechanical system.

Apart from the former improvements some testing and renovation work was also performed:

- Rewiring and labeling of the system’s main power strip.
- Manufacture of the necessary wires to connect the motor control box to the corresponding elements of the rPET.
- Testing of the detector system performance.
- Verification of the Centent CN0170 proper operation.
- Testing of the serial port communication between the CPU and the controller.
- Testing of the software controlling the mechanical system’s movement.

In order to carry out this project, it has also been necessary to document the whole system by collecting all the existing information regarding the rPET developed before this project was started and by making record of all the new features added to the device. All this information has been ordered and gathered in a manual which describes the rPET whole system and gives the user the necessary information to interact with it. This manual could be used by those continuing the set up of the rPET in the future and also by students interacting with the rPET who are the final recipients of this work. The manual can be found in Appendix XI.

The final goal of this rPET prototype is to be used by teachers of the Universidad Carlos III de Madrid with teaching purposes. The use of this rPET system by future students will complement the teaching materials in several subjects of the Biomedical Engineering Degree of Universidad Carlos III de Madrid. It will be possible for students to get to know how a small animal PET system looks like and how it operates without leaving the university. It could also be used by them with testing and research purposes of different reconstruction techniques.

BIBLIOGRAPHY

[1] Podoloff DA, Advani RH, Allred C, Benson AB, "Pet Professional Resources and Outreach Source," Nov, 2009.

[2] IMV, "IMV 2015 PET imaging market summary report," May, 2015.

[3] Buck AK, Herrmann K, Stargardt T, Dechow T, Krause BJ, Schreyögg J, "Economic Evaluation of PET and PET/CT in Oncology: Evidence and Methodologic Approaches," Oct, 26, 2009.

[4] Siemens, "Aportación de Valor de las tecnologías en el sector sanitario," Oct., 2014.

[5] Equipos de alta tecnología disponible por Comunidad Autónoma. Available: http://www.msc.es/ciudadanos/hospitales.do?tipo=equipos. Dec, 2015.

[6] Rutao LY, Crawford R, "Small-Animal PET: What Is It, and Why Do We Need It?" Feb, 2012.

[7] Douglas JR, Simon RC, "Small-Animal Preclinical Medicina Instrumentation and Methodology," May, 2008.

[8] Lage E, "Sistema de adquisición de datos para Tomografía por Emisión de Positrones," 2009.

[9] Introduction to PET physics. Available: http://depts.washington.edu/nucmed/IRL/pet_intro/intro_src/section2.html. Dec, 1999.

[10] Software Manual CN0170. Available: http://www.centent.com/Manuals/cn0170s.pdf.entent Company.

[11] BiSlide. Available: http://www.velmex.com/Products/BiSlide/bislide_manual.html?tab=3#TabbedPanels1. Jan, 2016.

[12] Imaging Based on the Anger Principle. Available: http://oftankonyv.reak.bme.hu/tiki-index.php?page=2D+Imaging+Based+on+the+Anger+Principle. Jun, 2010.

[13] Miles NW, Aarsvold JN, Emission Tomography: The Fundamentals of PET and SPECT. Elsevier, 2004.

[14] Power Transistors and Heat Sinks. Available: http://www.learnabout-electronics.org/Amplifiers/amplifiers51.php. March, 2016.

[15] *Tera Term Home Page*. Available: https://ttssh2.osdn.jp/index.html.en. May, 2016.

[16] PCI. Available: http://techterms.com/definition/pci. Apr, 2016

[17] Goldi J, "An overview of LVDS Technology," Jan, 1998.

[18] Linux and Unix chmod command. Available: http://www.computerhope.com/unix/uchmod.htm. Han, 2015

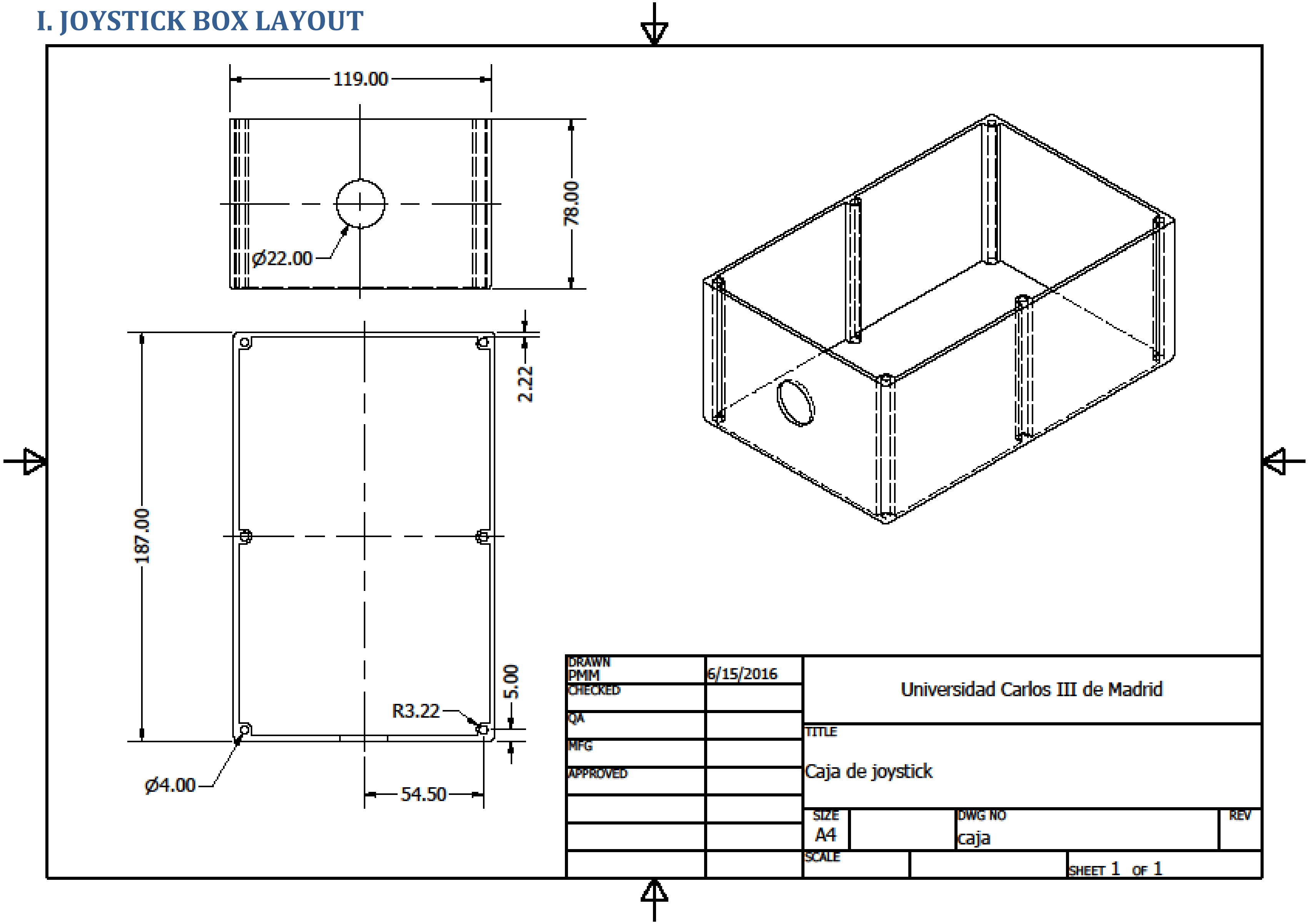
[19] Perea B, Cabrera A, Delgado JM, "Recomendaciones para el uso de la PET-CT con 18F-FDG en la planificación de radioterapia,".

[20] Melcher CL, "Scintillation Crystals for PET," pp. 1051-1052-1055, 2000.

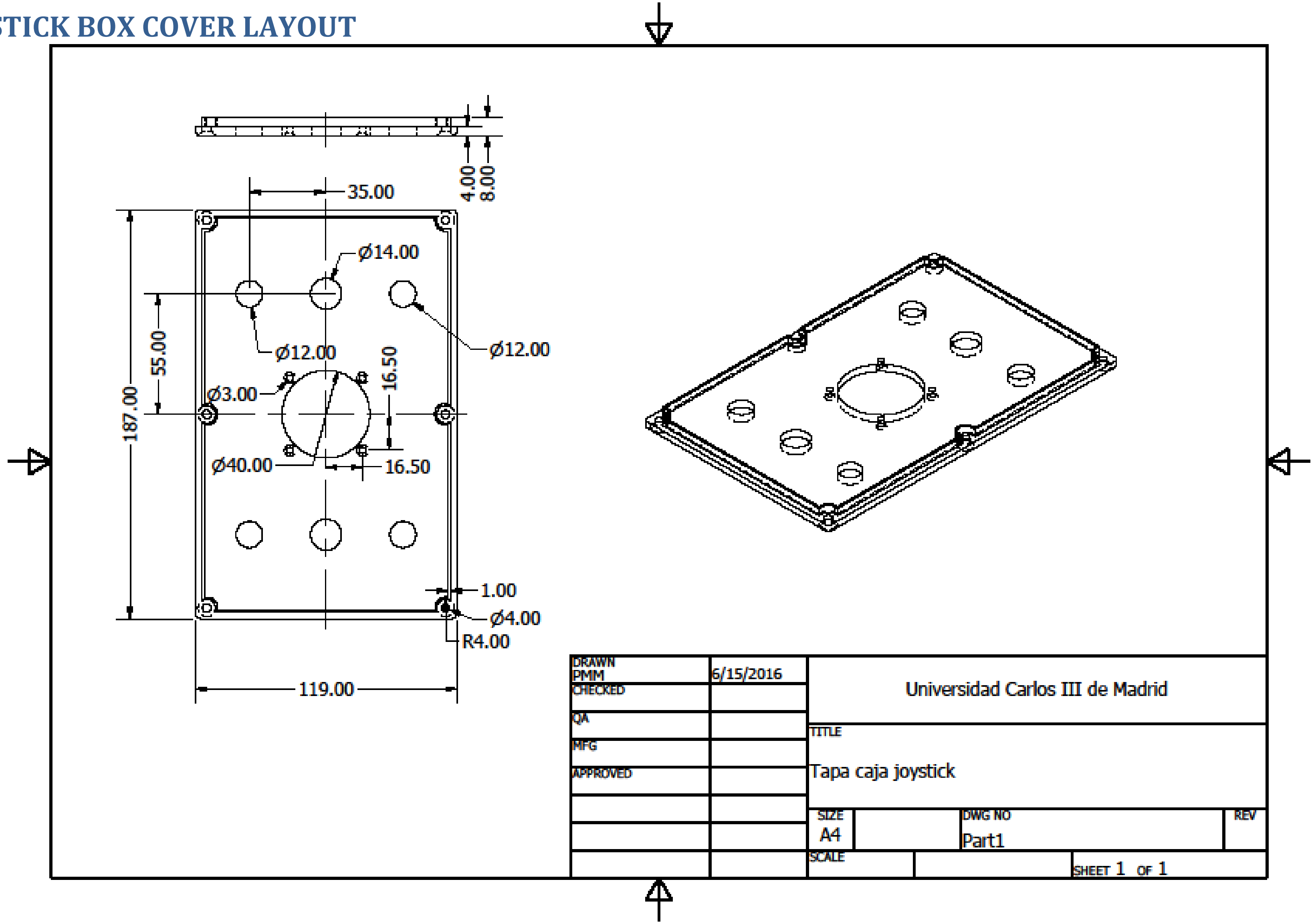
[21] Motores paso a paso. Available:
http://platea.pntic.mec.es/vgonzale/cyr_0204/cyr_01/robotica/sistema/motores_p-p.htm.

ANNEX INDEX

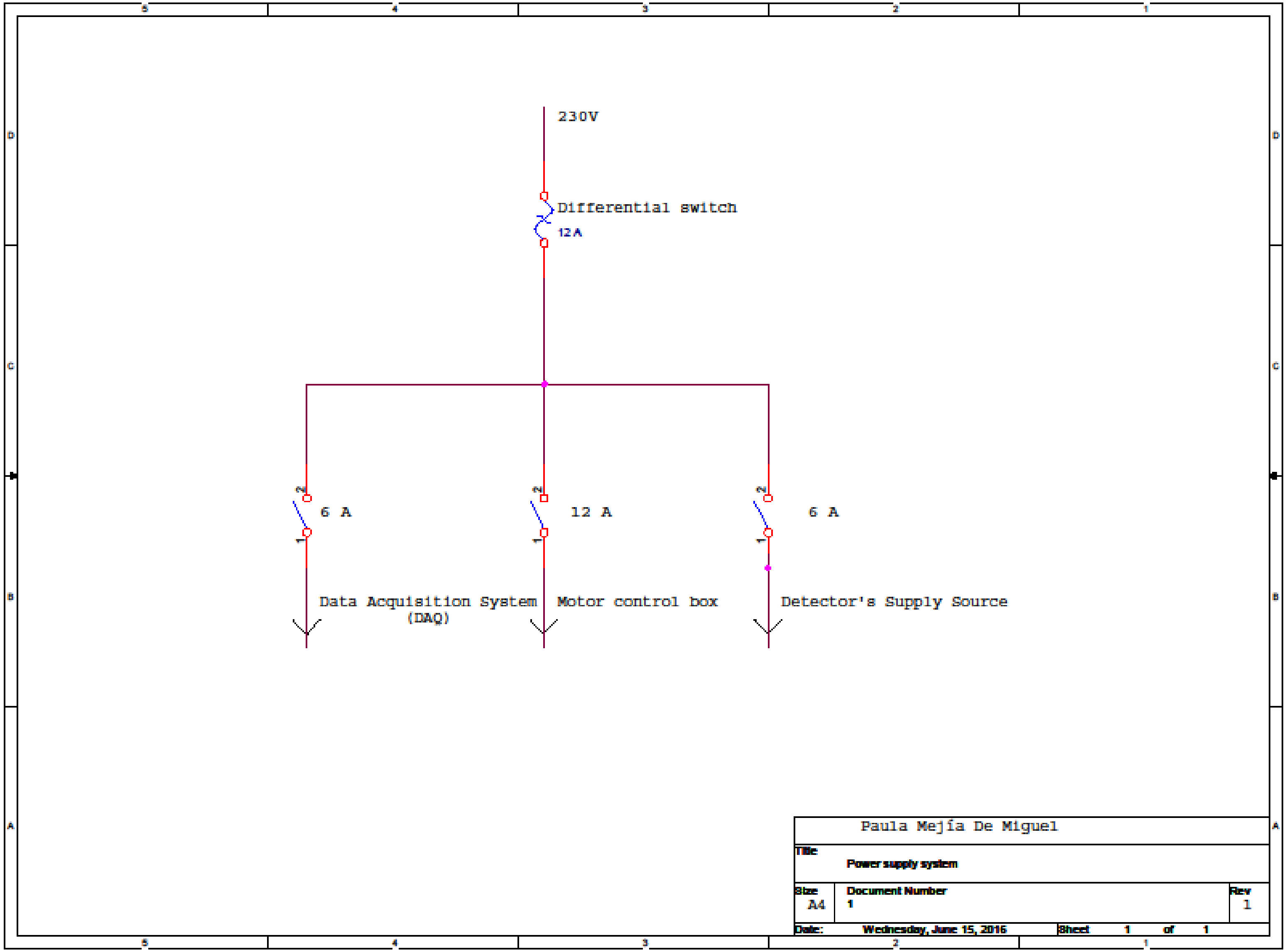
I. JOYSTICK BOX LAYOUT



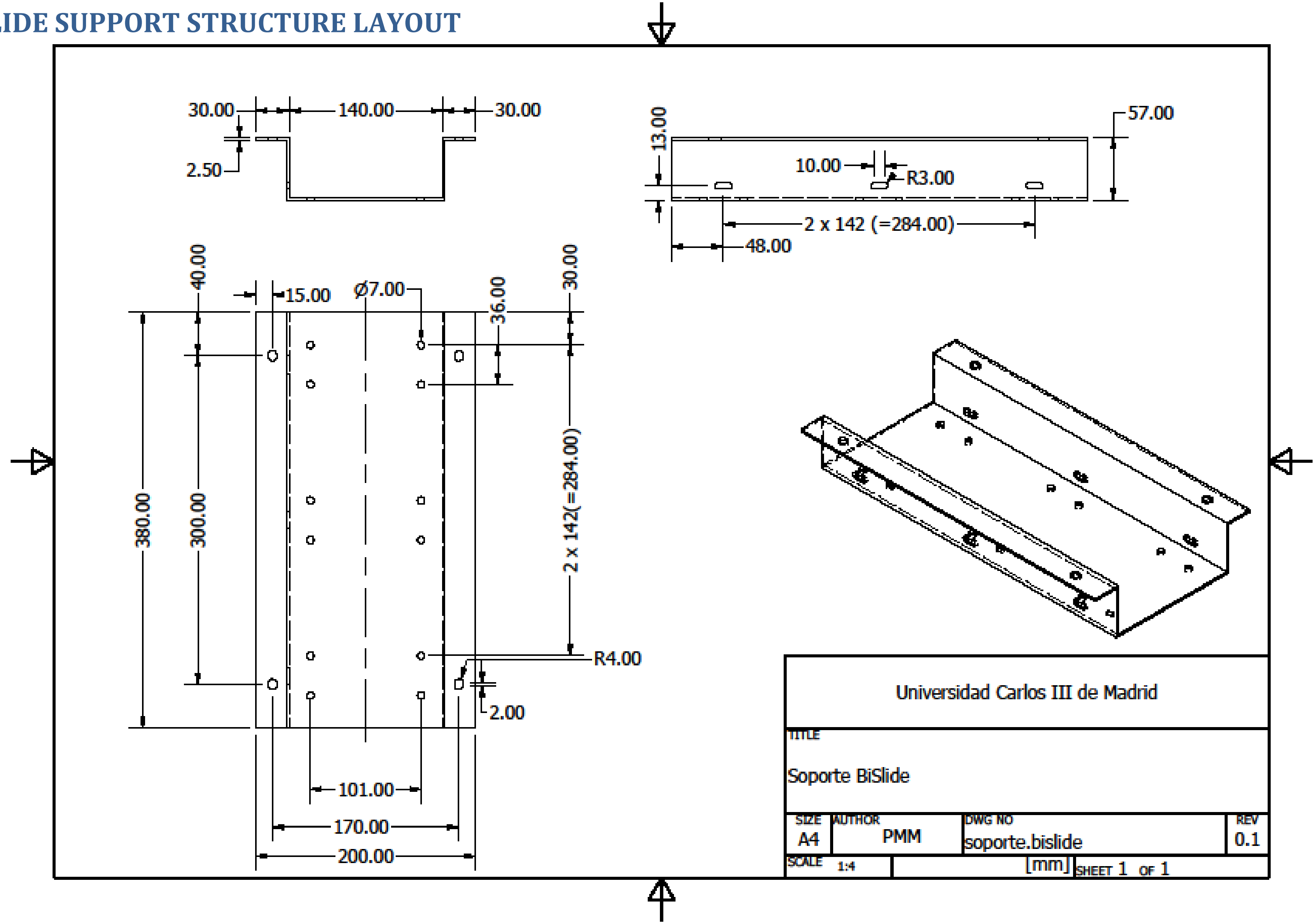
II. JOYSTICK BOX COVER LAYOUT



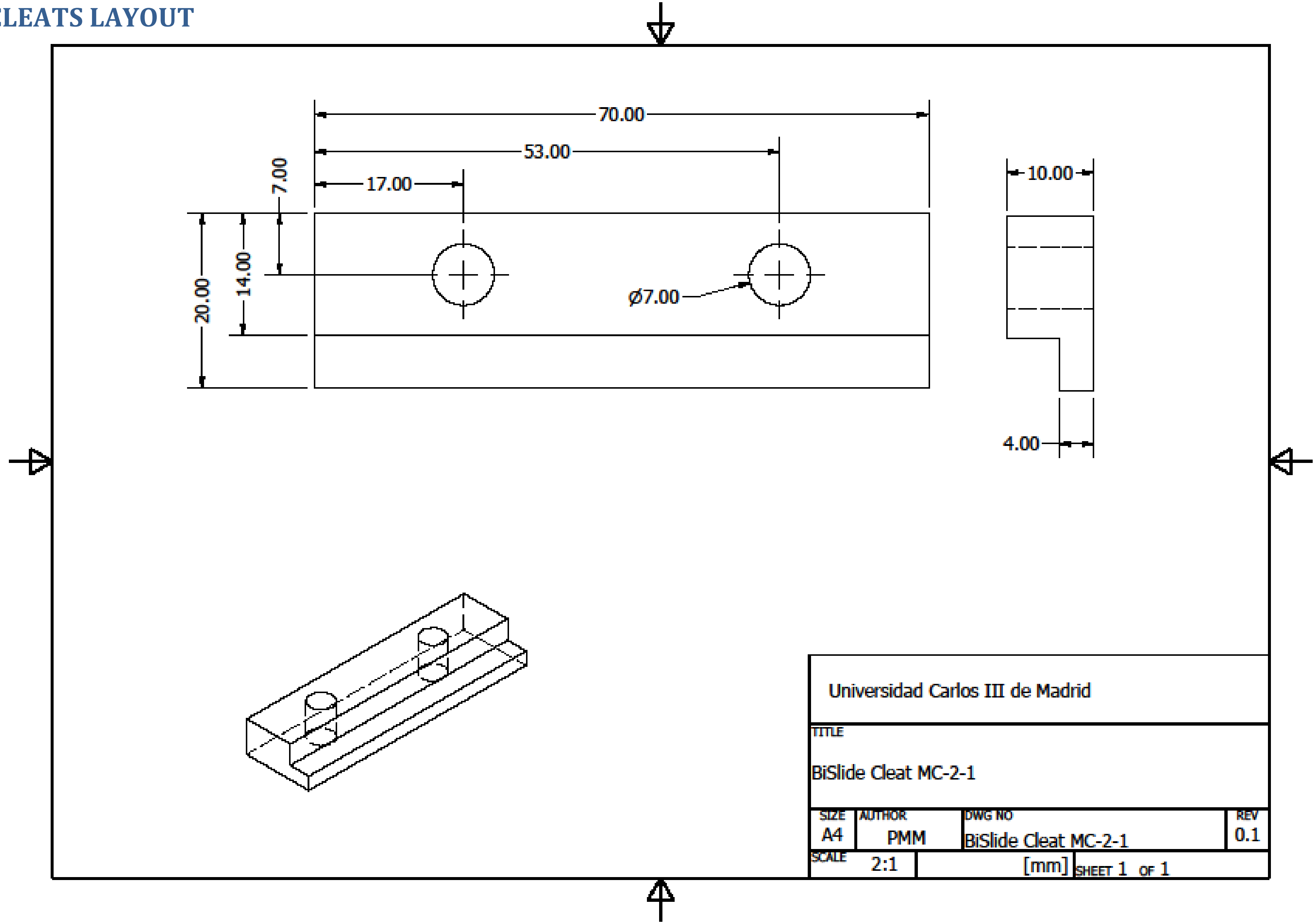
III. MAIN POWER STRIP CIRCUIT



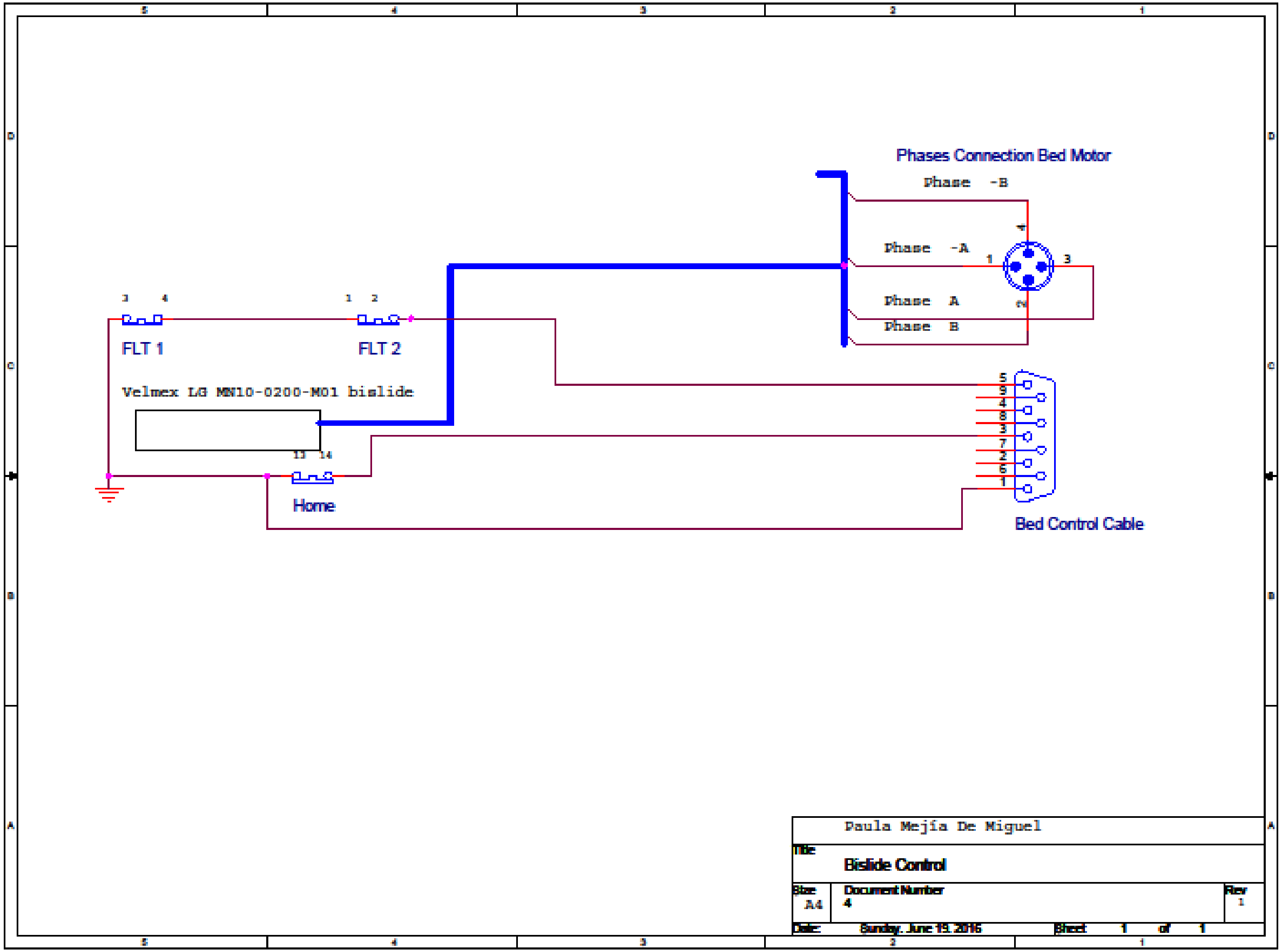
IV. BISLIDE SUPPORT STRUCTURE LAYOUT



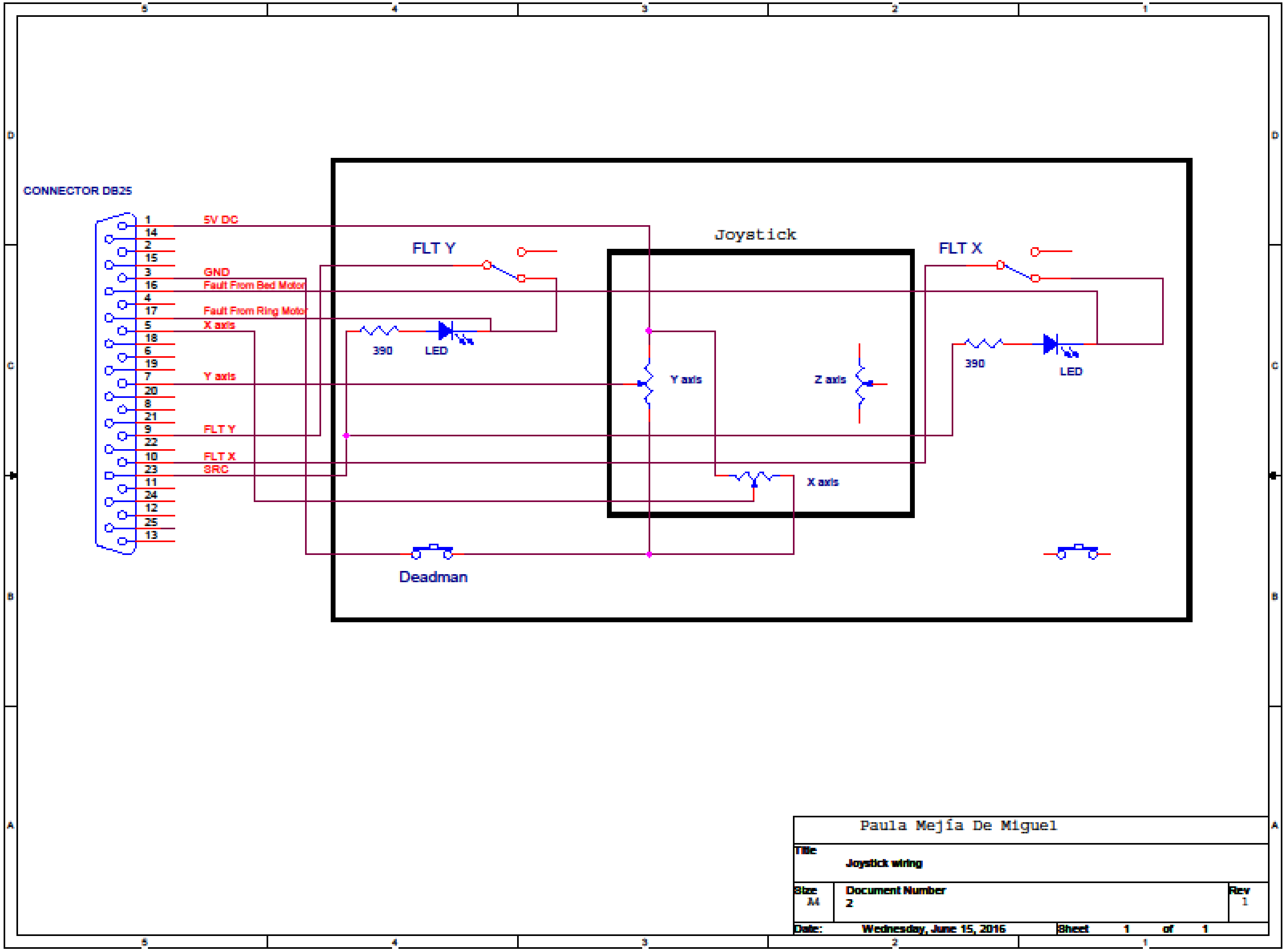
V. CLEATS LAYOUT



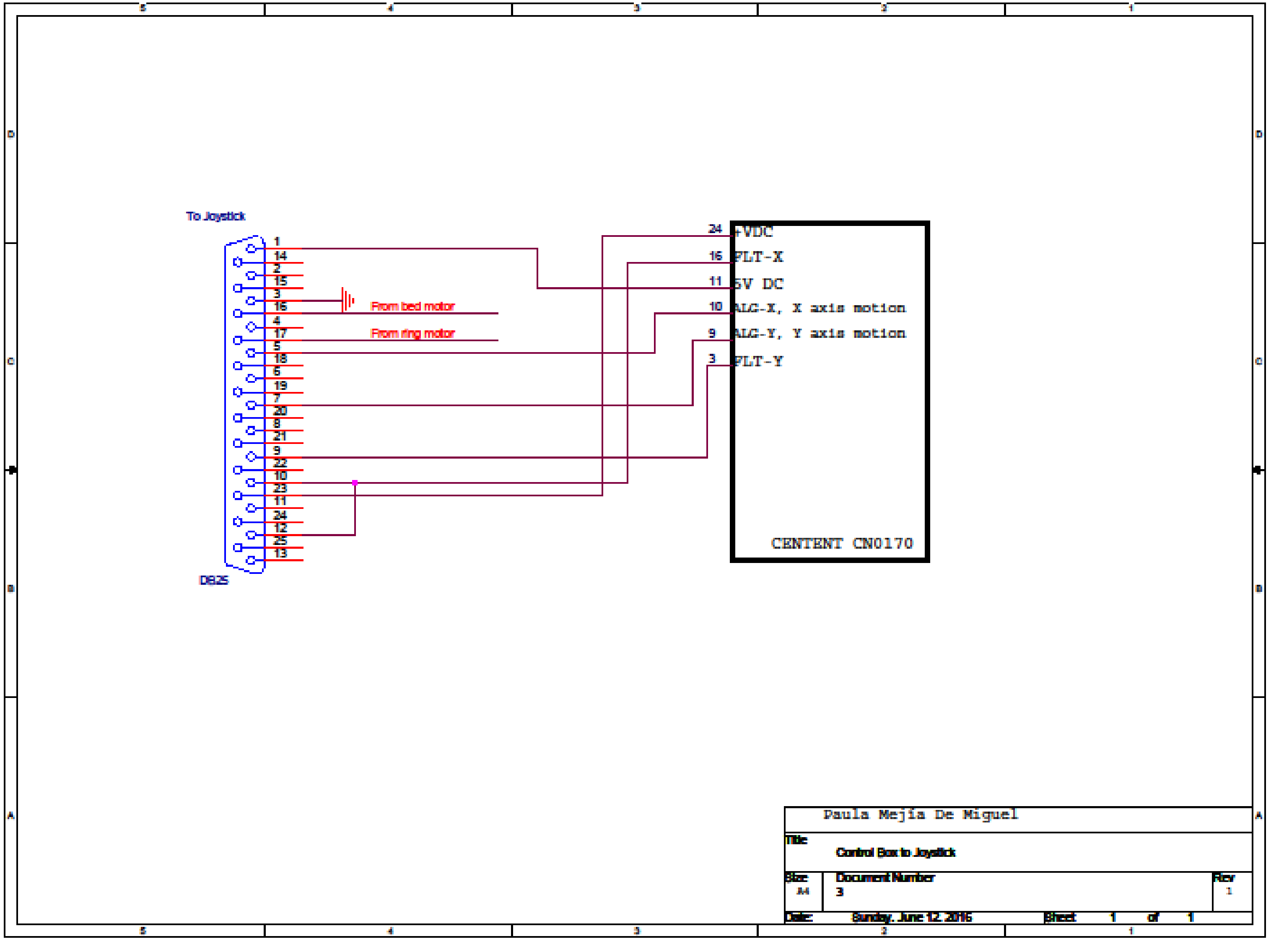
VI. BISLIDE CONTROL SYSTEM CITCUIT



VII. JOYSTICK CIRCUIT



VIII. JOYSTICK TO MOTOR CONTROL BOX CIRCUIT



IX. JOYSTICK PIN AND CABLE COLORS

AMP 16 pin		Function	DB 25 pin
1	brown	5V DC	1
2	red	GND	3
3	orange	X axis	5
4	yellow	Y axis	7
5	purple	FLT Y	9
6	blue	FLT X	10
7	green-black	Fault from bed motor	16
8	red-black	FAULT from ring motor	17
9	black	SRC	23
10	white	-	-
11	grey	-	-
12	orange-red	-	-
13	yellow-red	-	-
14	grey-black	-	-
15	light green	-	-
16	red-blue	-	-

X. COSTS

Project duration: 6 months

Project budget (€): 31414

BUDGET BREAKDOWN

Human resources

Category	Hours employed	Cost per hour	Cost (€)
Project coordinator	150	35	5250
Technical engineer 1	150	20	3000
Biomedical Engineer	800	15	20000
		Total	23000

Material cost

JOYSTICK BOX			
Description	Units	Unit price (€)	Cost (€)
Toggle switch	2	1,2	2,4
Led frame	2	0,79	1,58
LED´s	2	0,55	1,1
Contact removal tool	1	1,51	1,51
Circular Male connector contact. Size 16, 22 series 6000 3A, Wire size 26 → 20 AWG	16	0,72	11,52
Series 6000 Male straight connector. Aerial assembly. Frame size 32mm 16 pins, female contacts	1	8,67	8,67
Series 6000 Male straight connector. Panel assembly. Frame size 32mm 16 pins, male contacts	1	6,22	6,22
Circular Female connector contact. Series 12960 5A, Wire size 26 → 24 AWG	16	0,66	10,56
Metallic box	1	21,78	21,78

BED MOTOR			
Description	Units	Unit price (€)	Cost (€)
LG-MN10-0200-M01 BiSlide	1	1750,00	1750,00
Extra limit switch	1	50,00	50,00
Courier	1	132,00	132,00
BiSlide tray	1	150,00	150,00
Cleats	6	9,00	54,00

ELECTRONICS			
Description	Units	Unit price (€)	Cost (€)
L297D	1	7,37	7,37
L298	1	4,16	4,16
IMS IB463	1	99,99	99,99

OTHERS			
Description	Units	Unit price (€)	Cost (€)
Connectors	1	7,80	7,80
Cables	1	5,30	5,30
Screws	1	2,37	2,37
Connectors	1	7,80	7,80

TOTAL	**2328,33**

Other direct costs

Description	Duration (months)	Cost (€)
Personal computer (20% depreciation)	6	200,00
Internet	6	640,00
Windows 7	6	99,95
Office 2013	6	79,99

TOTAL	**1019,94**

General cost and industrial benefit

The general costs and industrial benefits correspond respectively to 16% and 6% of the material costs.

Description	Cost (€)
General cost (16%)	372,54
Industrial benefit (6%)	139,70

TOTAL	**1019,94**

Summary of costs

Description	**Budget on total costs (€)**
Personnel	23000
Materials	2328
Functioning costs	1020
Indirect costs	5066
Total without IVA	24817
IVA 21%	6597
Estimated total	31414

XI. rPET MANUAL

r-PET

UNIVERSIDAD CARLOS III

Paula Mejía De Miguel

100303869

Index

1.-INTRODUCTION TO POSITRON EMISSION TOMOGRAPHY

The Positron Emission Tomography is a non invasive functional imaging technique that allows observing the development of metabolic processes in the body.

Biologically active compounds with positron emitting radioactive isotopes are introduced intravenously into the body of the patient. These compounds are distributed throughout the body by means of the blood flow and are incorporated to metabolic processes. Once the isotopes are within the organism, their distribution is measured using detectors contained in the PET machine. Therefore, PET images allow in-vivo observation of multiple biological processes and it is used nowadays with clinical purposes in oncology, cardiology and neurology among other disciplines.

The detectors identify pairs of gamma rays that are produced when a positron and an electron collide. The annihilation reaction produces two gamma photons with opposite directions that reach the detectors. The line defined by the trajectories of the gamma photons is called Line of Response (LOR). By identifying and characterizing all the LORs obtained, it is possible to obtain all the information necessary for the later reconstruction of the image.

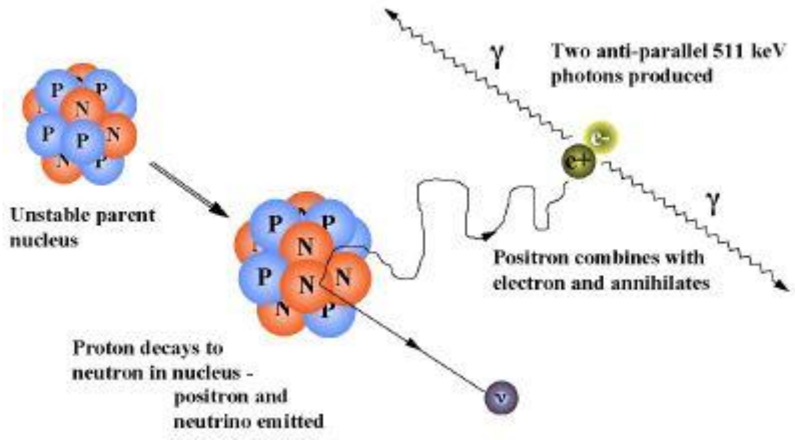


Figure 29: Positron anhilitaion

The detectors in PET can be located in a complete circular ring but the PET machine described in this manual is a rotating PET (rPET) with two pair of detectors rotate in order to obtain information about a certain area.

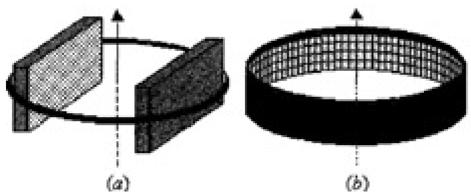


Figure 30: PET detector's arrangement

When two photons are detected in close temporal proximity by opposite detectors it is assumed that both photons were originated by the same annihilation reaction and a coincidence is registered by the computer system.

2.- rPET MAIN SCHEME

The basic scheme of the rPET is shown in Figure 3. The actual PET is connected to a CPU which contains all the software needed for the image acquisition. The CPU also transmits to the PET the user specifications for the process of acquisition.

On the other hand, the rPET sends to the CPU the data acquired with the detectors that will be used later in the process of image reconstruction. The rPET also sends data related to its physical state such as the ring or bed position, the number of control units connected etc.

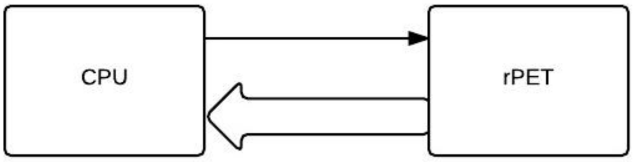


Figure 31: rPET main scheme

Figure 4 illustrates a more detailed scheme of the rPET. The general structure can be subdivided in two smaller structures according to the process they are involved; the control elements (showed with red dashed lines in the figure 4) and the detection elements (showed with green dashed lines in figure 4).

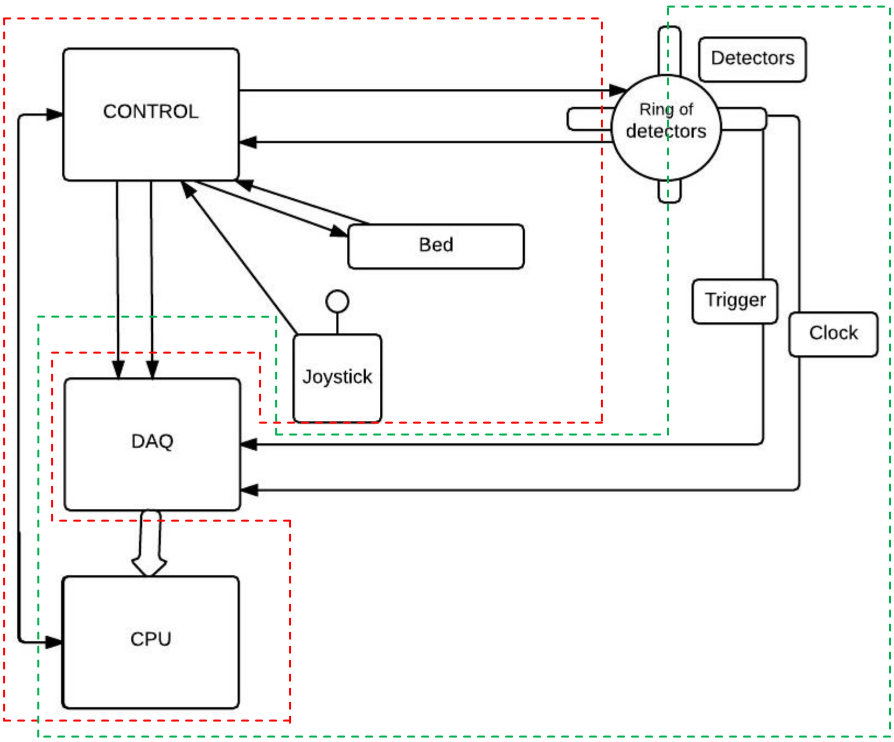


Figure 32: rPET detailed schematic

2.1.- Control elements

Figure 5 shows the elements that form part of the control section of the rPET, each of them will be explained in more detail in the following section.

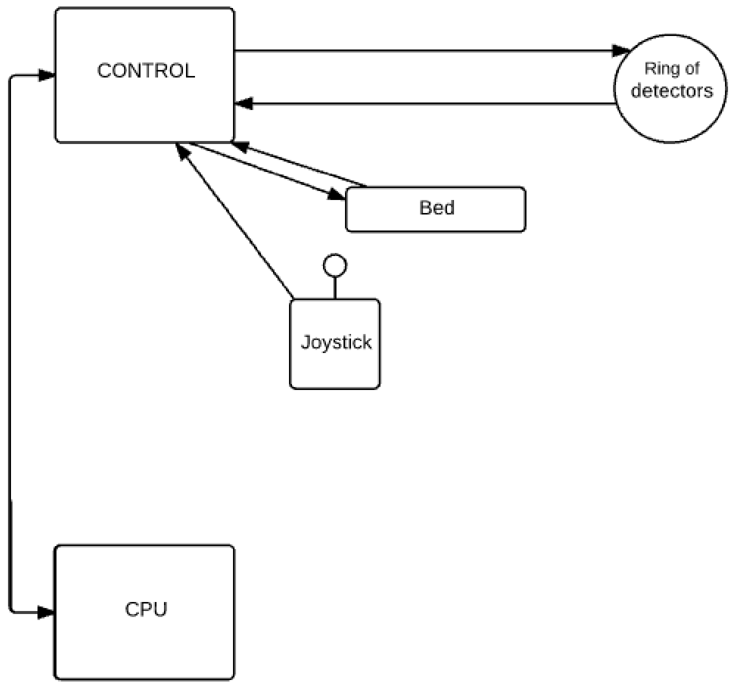


Figure 33: rPET control elements

Control: Manages all the elements for data to be acquired and processed.

All the elements related to the mechanical system control, have been grouped together in a “motor control box”.

The control box receives information about the bed and ring of detectors’ position. It also allows translating joystick movements performed by the user, in movements of the bed and the ring. The control unit communicates with the CPU sending information about the state of the other components, but it also receives commands introduced by the user from the CPU.

In order to allow all this communications, the box is equipped with several connectors as it can be seen in Figure 6.

The function of each of these connectors can be found in Apendix I

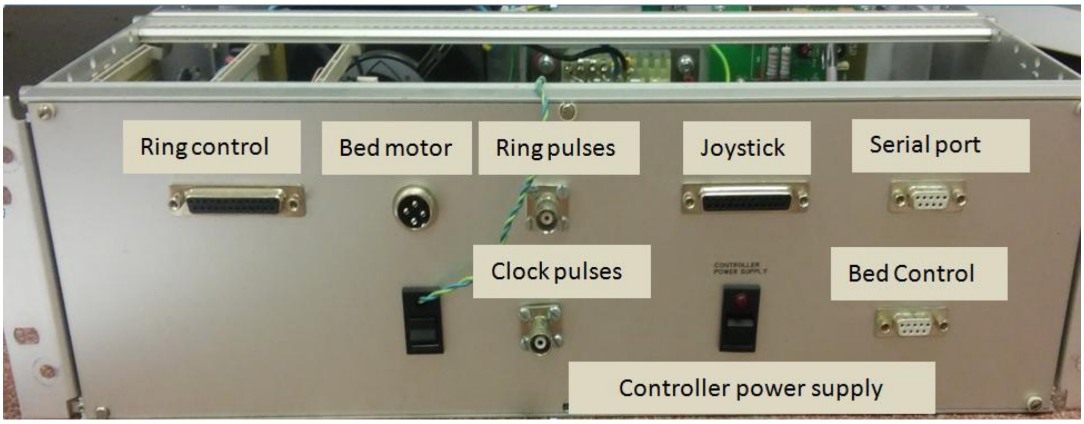


Figure 34: rPET motor control box

The most important part of the motor control box is the cn0170, a programmable two axis motion controller for step motor systems.

When the cn0170 is connected to a computer, the computer can control the execution of the running program. The cn0170 can also be executed to run certain programs automatically. It also returns data to the computer. All these communications are performed using a communication port.

The controller can be operated in three different modes:

- Mode 1, “Immediate mode”: The controller executes the instructions as soon as they are received
- Mode 2, “Program mode”: The commands sent to the controller are stored and queued sequentially.
- Mode 3, “Operation mode”: A program previously stored in the controller’s memory is executed.

Figure 7 represents a sketch of the controller cn0170 with its main connections.

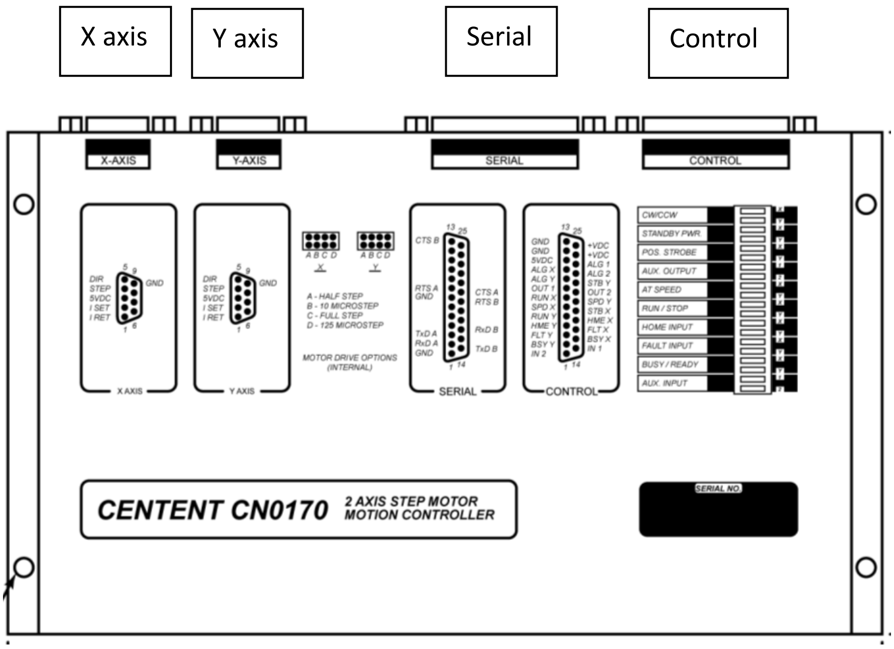


Figure 35: Centent cn0170 main connections

- X and Y connectors: D9 connectors that form theinterface between the cn0170 and the motor controls
- Control connector: This D25 connector contains all the inputs and outputs of the controller. The power supply also passes through this conector.
- Serial conector: D25 connector that process the data of two different channels, A and B. Channel A is used to connect the computer and the controller. Channel B can be connected to achannel A of a different cn0170 contorller in order to extend the number of axis in the system.

Ring of detectors: The rPET has a total of four blocks of detectors grouped in two pairs and located perpendicularly in a ring. The ring is moved by a step motor and the angle and direction of rotation is determined by the user that controls the movement of the ring by means of the joystick.

Bed: The rPET has a Velmex LG BiSlide moved by a step motor. The movement and direction of the BiSlide is controlled by the user by means of the joystick. Velocity and acceleration of the bed can also be set up by the user.

Joystick: It is used as an interface between the user, the bed and ring of detectors. Moving the joystick in the Y direction, the bed moves towards or away from the ring of detectors. Moving the joystick in the x axis, the ring of detectors rotates.

Technical data about the joystick is detailed in Apendix II

CPU: Within the CPU there is a shell capable of executing commands related to the movement of the mechanical system of the rPET. This shell called motor_shell_centent has been programmed in C language and has been designed to work in a UNIX terminal.

2.2.- Detection elements

Figure 8 shows the elements that form part of the detection section of the rPET, each of them will be explained in more detail in the following section.

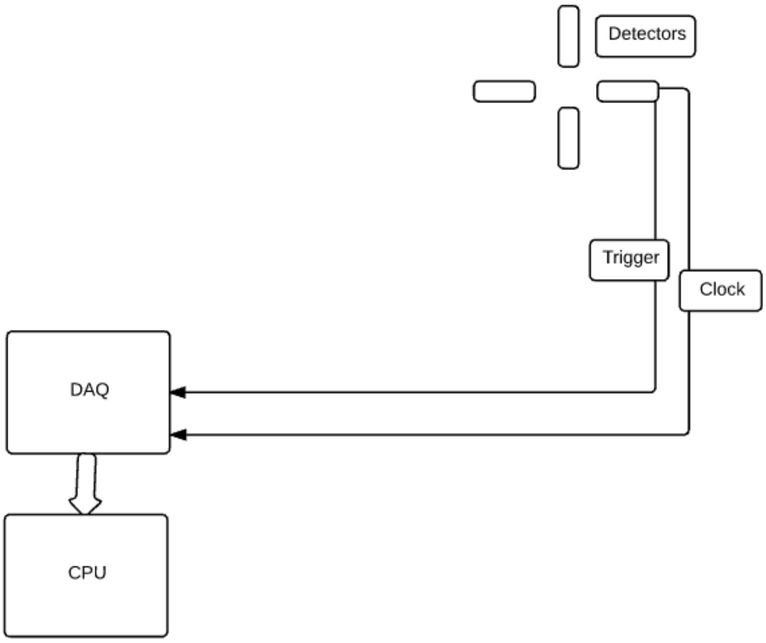


Figure 36: rPET detection elements

Detectors: As it was said before, the rPET has four blocks of detectors located perpendicularly in pairs in a ring.

Each of the detectors is formed by the following components:

- Scintillation crystal matrix: It is located on the surface of the photomultiplier and it transforms the incident gamma photons into light photons.
- Photomultiplier: Collects the light generated by the crystals and it is transformed into an equivalent electrical signal.
- Associated electronics: It is located at the photomultiplier's exit and it not only amplifies the signal coming out from the photomultiplier but also reduces the number of signals to be digitalized.

- Internal protection case: Removable case that contains the PS-PMT and the crystal matrix. It provides protection to both elements and ensures that the crystal matrix is fixed to the main case and the photomultiplier won't move with respect to it.

- Main case: Metallic case that contains all the previous elements attaching them to the ring of detectors. The main case also allows to adjust the position of the detector and isolates it from the ambient light.

Each of these elements are shown in Figure 9

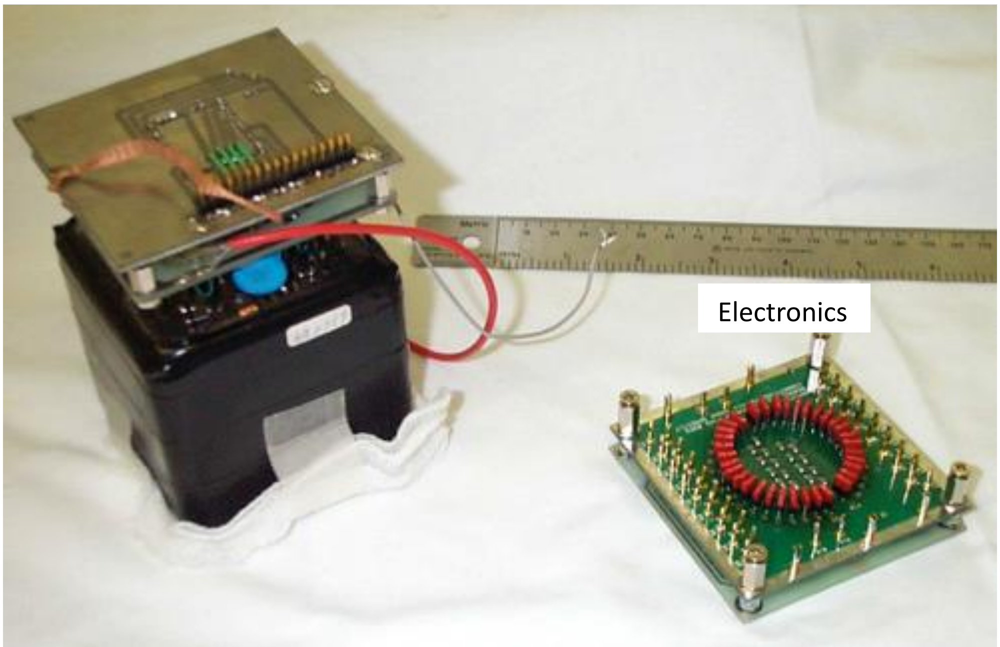


Figure 37: Internal view of rPET detectors

The detectors send two signals to the Data Acquisition System (DAQ):

Trigger signal: Produced each time that a valid coincidence signal is detected. A signal is considered valid when it fulfills the following conditions:

-Two events are detected in opposite detectors within a time equal or lower than the interval determined by the coincidence window.

-Both events are within a certain energy range.

The first condition allows to reject single events and the second conditions avoids considering as valid noisy events and piled-up signals.

The trigger signal activates the data acquisition process.

Data signal: Contains the information about the detector and the position within the detector at which the event has occurred.

DAQ: The Data Acquisition System digitalizes the coordinates indicating where the valid events have occurred in each pair of opposite photodetectors and sends this information to the CPU.

The data acquisition system is capable of:

- Differentiate between single events (where a photon reaches just one detector) from true events (where two photons are detected in opposite detectors within a time interval)
- Differentiate between noise signals, pile-up signals and valid events. Pile-up signals are those that occur within a short time interval and they are detected as a single high valued signal.
- Digitalize signal positions of each photomultiplier and send them to the CPU where the control program isexecuted.

The DAQ is composed of two main blocks:

1. A group of modules externally connected to each other and powered by a CAMAC chassis
2. A PCI interface connected by a LVDS BUS to some of the modules within the chassis that provides the control application with the data coming from the acquisition system.

Figure 10 shows the general structure of the system as well as the connection that exist between the signals coming from the detectors and the different modules that form the DAQ.

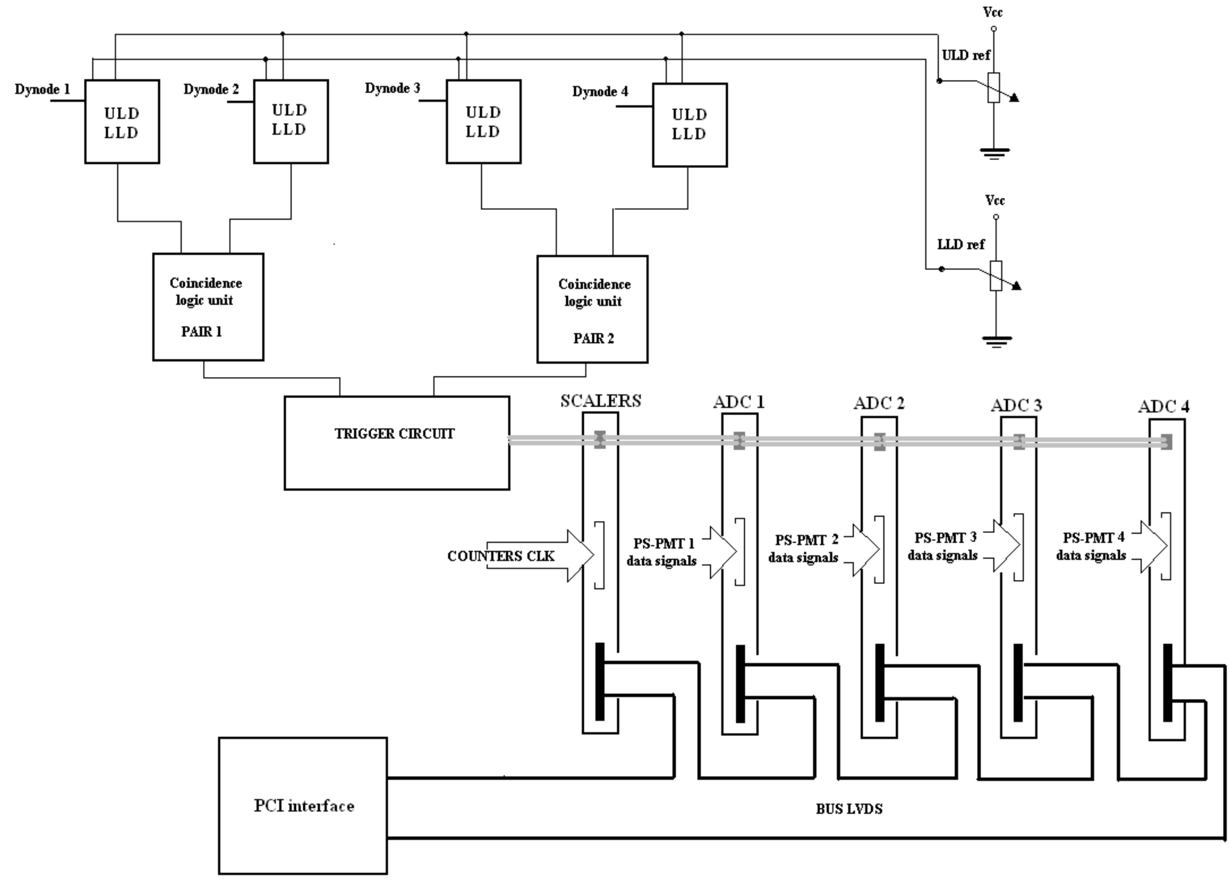


Figure 38: Main scheme of the rPET trigger circuit and connection between signals going from the detectors into the DAQ

- **ULD AND LLD**

  ULD and LLD are the initials of Upper Level Discriminator and Lower Level Discriminator. The signals coming from the dynode pass individually through these two comparators.

  Using a potentiometer, two thresholds are set up (LLD ref and ULD ref) in order to only let pass the dynode signals with characteristics exceeding the restrictions imposed by those thresholds. Those signals are transformed into pulses with the desired width by means of a flip-flop

- The **modules** that form the system can be classified in 3 different types:

  - <u>Data acquisition modules</u>: These modules are in charge of the analog to digital conversion of the signals coming from the PS-PMTs. Those signals are sent afterwards to the PCI interface.

    More information about the system's acquisition event format can be found in Apendix III

  - <u>Scalers module</u>: It is a card with a 28 bits latch and four 28 bits counters. These counters contain the information of each event detected by the acquisition system and it will be sent to the PCI interface.

    Technical information about this module can be found in appendix IV

  - <u>Trigger module</u>: This module controls all the previous elements and it is able to:

    1. Distinguish the signals that don't fulfill the required characteristics.
    2. Generates the coincidence windows between detectors of the same pair.
    3. Trigger in the right moment and in the right order the acquisition of the signals in the detectors of interest.

As it can be seen in Figure 10, the inputs of this module are the signals coming from the last detector's dynode and the outputs are the trigger signals of the ADCs and scalers module.

This module groups the detectors in pairs depending on the dynodes that are connected to its input. This allows detecting coincidence events in opposite detectors and generating the trigger signal of the appropriate ADCs.

Each time a coincidence signal coming from the pair of detectors 1 or 2 is activated, the following actions in the system will occur:

- Both the counter and ADCs (1-2 or 3-4) trigger signals are simultaneously activated.
- The trigger module blocks its entries so it will not accept more coincidences until the signal "End of transference" is sent by the scalers module.

- The trigger signal from the scalers module acts as a flag that will be passed from module to module. If the module to which the flag arrives is sensitized (its trigger signal has been activated), it will pass its data to the BUS and the flag to the following module. If the module to which the flag arrives is not sensitized, the flag will automatically pass to the next module.
- Once the flag arrives to the last module (ADC4), it will return to the scalers module which activates the "End of transference signal" and the system will be able to process more coincidences.

The trigger module posses extra functionalities that are explained with more detail in Appendix V

For more information about ADC technical specifications can be found in Appendix VI

- **Interface PCI**

  This part of the system is composed of a PCI tag connected to a LVDS BUS that collects and packs the events coming from the acquisition system. This device is used to group the events that arrive in 128 Kbytes "chunks" and by means of the DMA allocate the events in a memory position accessible for the control system.

  The DMA (Direct Memory Access) allows peripheral components to access the system's memory and read or/and write into the memory independently of the CPU. A DMA transference consist on copying a memory block from one device to another but it is the DMA the one initializing the transference instead of the CPU.

  The source code of the driver is within the card. It is necessary to compile the driver and later install the built module. The module or modules are .o files that can be connected or disconnected to the Linux kernel in execution time.

  In appendix VII it is possible to find the steps needed to install the PCI interface and the implemented functions used to manage the data that goes into the PCI card.

3.-SOFTWARE

3.1.- Mechanical system

Motor_shell_centent: shell capable of executing specific commands over the movement system of the rPET.

3.1.1-Source files

cnt0170.h: contains the definition of the functions that allow interacting with the motor control box CENTENT 0170.

cnt0170.c: implements the functions that allow interacting with the motor control box CENTENT 0170

3.1.2.-User functions

closecnsystem (close): resets COM1 port to its original configuration stopping communication between the computer and the motor control box.

configcnsystem (config): starts the X and Y axis introducing in the motor control box the configuration parameters that appear in the file that is used as an argument. If no file is used, this function will use as default option the parameters found in *motor_params.txt* (See section 3.3.1 Input and output files)

Example: [motor_shell]$ config ./parametros.txt

*In the screen will appear the number of CN0170 units detected. If the motor control box is off or disconnected, the computer could lock up. In this situation, control over the system could be recovered pressing ctrl+C.

get: This function returns the position (in steps) of any of the axis.

Example: [motor_shel]$ get X

If the motor control box is off or disconnected, the computer could lock up. In this situation, control over the system could be recovered using ctrl+C.

home: It takes to the home position any of the axis (X/Y/XY)

Example [motor_shell]$ home X

*In order to use this command it is necessary to execute function (config) first.

initcnsystem (init): shows the number of CN0170 units detected. In our case it should always be 1. If the returned value is 0, connection between the motor control box and the computer should be checked. If the problem still persists, the motor control box should be reset.

joystick (joy): activates or deactivates the X axis joystick depending on the chosen option (ON/OFF).

Example: [motor_shell] $ joy ON

In order to use this command it is necessary to execute function (config) first.

kill (k): this function instantaneously forces the stop of the motors ending the function that is being executed and resetting the motor control box CNT0170

This function is used as an emergency stop tool.

onfault: this function recovers the motor system from a locked out state produced by a FAULT situation (black out due to activation of a limit switch)

This function needs the deactivation and later activation of the limit switches by the user. A message in the screen will appear when these actions are needed.

If the motor control box is off or disconnected, the computer could lock up. In this situation, control over the system could be recovered using ctrl+C.

quit (q): this function will instantaneously stop the system. The axis will decelerate to 0 with the acceleration profile previously stored in the system.

This function is used as an emergency stop tool

relmove: moves the specified axis relative to its actual position. For the X axis the movement is given in millimeters and for the Y axis the movement is given in degrees.

For the X axis, a (-) sign moves the bed closer to the ring and for the Y axis, a (-) sign moves the ring CCW.

Example: [motor_shell]$relmove X -100

In order to use this command it is necessary to execute function (config) first.

resol_int: this command is used to perform studies of the detector's intrinsic resolution through the Z axis of the PET system. The user needs to introduce two parameters:

arg[1]= bed's travel distance between consecutive positions

arg[2]= times that the bed travels the distance shown in arg[1]

Example: [motor_shell]$resol_int -0.25 10

This command indicates 10 steps resolution of 0.25 mm per step. The (-) sign implies that the bed moves toward the ring of detectors.

sequence (seq): This function configures and starts the system to perform the sequence of events specified by the introduced parameters.

The meaning of each parameter is:

arg[1]= frame duration (in minutes)

arg[2]=beds number

arg[3]=frame number

arg[4]=number of overlapped image slices

Example: [motor_shell]$ seq 6 3 1 3

This command will perform a 6 minute study per frame, 3 beds, 1 frame and 3 overlapped slices in between successive beds.

set: sets the value of the CNT0170 digital outputs, CN_OUT1 and CN_OUT2

Example: [motor_shell]$ set CN_OUT1 0

If the motor control box is off or disconnected, the computer could lock up. In this situation, control over the system could be recovered using ctrl+C.

speed: Sets either the maximum or minimum speed for any of the axis.

Example: [motor_shell]$ speed X max

version (v): Shows in the screen the actual version of the motor_shell

3.2.- Detection and acquisition system programs

offsets: obtains the offsets of each channel of the DAQ. This prevents the system from taking into account noisy components.

User specifications:

-t N: N defines de acquisition time in seconds. The default time is 60 seconds

-oS: S defines the name of the generated offset files. The default name is ADC_offsets

-**h**H: H defines the histogram name. The option –h0 prevents the generation of an histogram. The default name is histo.out

-**?** Shows the help screen

After running the program the value of the offsets and the estimated value of the Full Width at Half Maximum (FWHM) for the value distribution in the histogram are shown in the screen.

Indications for the user:

1.- Disconnect the detectors' power supply

2.- Select position 3 (down) for the trigger module

The following files are generated after running the program offsets:

ADC_offsets.txt: file containing the value of the offsets for each channel of the DAQ. The order in which the data is presented is: ADC1-ch1…ADC1-ch16, ADC2-ch1…ADC2-ch16, […], ADC5-ch1…ADC5-ch16.

histo.txt: histogram in ASCII format created after running the program *offsets*. The order in which the data is presented is: ADC1-ch1…ADC1-ch16, ADC2-ch1…ADC2-ch16, […], ADC5-ch1…ADC5-ch16.

histo_img: this program allows checking the correct functioning of the detectors and the DAQ characterizing them by the generation of histograms, crystal maps and projection images among other data.

User specifications:

-v:	-Shows in the screen the program version and stops the program
-t N:	-N defines de acquisition time in seconds. The default time is 60 seconds
-**i**nombre:	-Determines whether raw files with the crystal maps are generated or not. Typing –**i0** prevents the files generation. The default name of the files is *nombreID_tubo*.out
-**l**nombre:	-Determines whether a .LIST file containing the data of the detected events is generated or not. The default state is that the files are not generated. If created, the file's name is *nombre*.LIST
-**h**nombre:	-Determines whether a file with the values of the detected events is generated or not. Typing –**h0** prevents the files generation. The default name of the file is *nombre*.out.
-oX:	-Determines wheter offset correction is applied to the acquisition system or not. Typing **–o0** prevents offset correction.
-cX:	-Determines whether a raw file with the values for the digitalized channels for each detected event is generated for each detector or not. The default option is that these files are not created. Typing **–c1** generates the files named *coordsID_tubo*

-xnombre:	-Determines whether raw files with crystal maps?? of the collimated crystals are generated or not. Typing **–x0** prevents the file generation. If generated, the name of the file is *image_xtalID_tubo*.out.
-?:	-Shows the help screen

Table 4: histo_img user specifications

The following files are generated after running the program histo_img:

coords_A…cords_D: These files contain the direct data dump (without offset correction) of the digitalized data of each PSPMT.

histo.out: This file it contains the histogram of each of the 64 channels of the DAQ.

histo.out.coordinates: This file contains the event position histograms for the crystal map images. This file allows relating the object real position with the software references.

histo.out.energy: This file contains the energy histograms of each detector

imagenA.out…imgenD.out: This is a raw file containing the crystal maps of each detector.

imagen_xtalA.out…imagen_xtalD.out: These files contain histograms of crystal maps for collimated crystals. These images help to get the intrinsic resolution of each detector.

tubeA.pdf…tubeD.pdf: file obtained after running the program histo_img. These files contain the histograms of each digitalized signal (16 in total) and the crystal map of the detector.

.LIST files: These files contain data events about the studies that have been carried out and the synchronism information needed for reconstruction. There are two types of files with this extension depending on the event they relate to.

-Synchronism events

Synchronism event files have the following structure:

Field	1.a Stop	1.b	1.c Time	1.d Angle	1.e Prompts	1.f Sync
Size	2 bits	2 bits	12 bits	8 bits	16 bits	8 bits

Table 5: Structure of synchronism events

The meaning of the field each field is detailed below:

1.a. Indicator of the gantry stop. When the bits of this field are '00'b, there is no angular stop, but when this field contains '11'b, it indicates that there will be a change in the scanning direction. This two bits allow to distinguish between clockwise and counterclockwise scans done within the same study.

1.b. Filling bits. These two bits are always zero and are used to obtain a size multiple of eight.

1.c. Time counter. It is expressed in time step variation with respect to the previous synchronism event. The clock used to determine the time reference has a frequency of 5 Khz.

1.d. Angular counter. It is expressed in angular step variation with respect to the previous synchronism event. The counter resolution is 250 steps per degree.

1.e. Prompts counter. It is expressed in variation with respect to the previous synchronism event. It states the number of detected coincidences taking into account those that are not processed due to the dead time of the acquisition system.

1.f. Synchronism signal. Coming from a ADC channel and divided by a 16 factor.

Data events

This type of events are generated each time a coincidence is processed.

Data event files have the following structure:

Field	**2.a Heading**	**2.b Energy**		**2.c Position**			
Content	ID	E1	E2	Y1	X1	Y2	X2
Size	2 bits	6 bits	8(6+2) bits	8 bits	8 bits	8 bits	8 bits

Table 6: Structure of data events

The meaning of the field each field is detailed below:

2.a. Pair ID. It allows to identify the pair of detectors that have reported the coincidence.

'01'b correspond to detectors 1 and 2.

'10'b correspond to detectors 3 and 4.

2.b. Event energy. Stores the energy value calculated for each gamma ray in coincidence that reaches opposite detectors. The value of E1 correspond to the energy of detectors 1 or 3 and the value of E2 correspond to the energy of detectors 2 or 4.

2.c. Coincidence event coordinates. Each of the fields correspond to the coordinates at the detector's surface where the photons interacted

interface_LUTs: this program generates LUTs (look up tables) of crystals for each detector. These tables can be used to identify the crystals that define the line of response (LOR)in each event.

User functions:

The first window shown once the user runs the application is presented in Figure 11, where the only possible option is to select **“Open calibration source”**

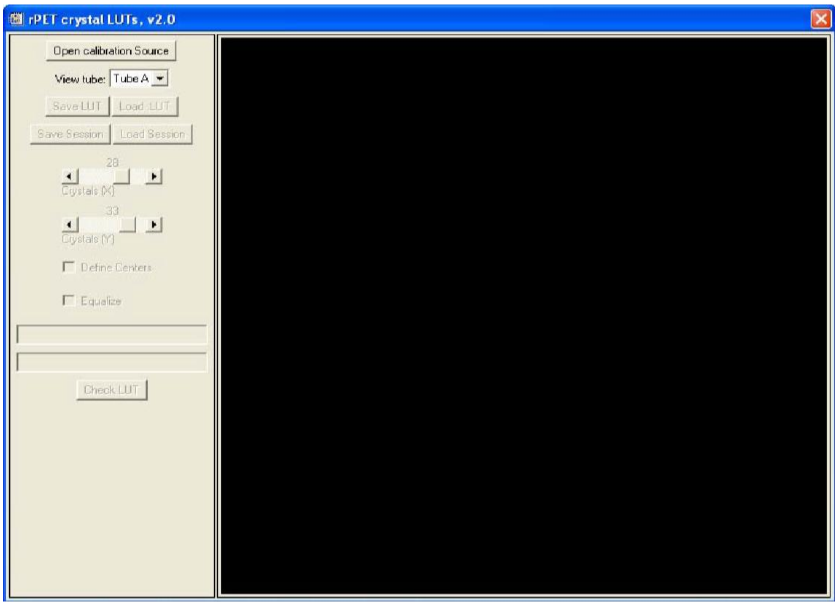


Figure 39: Initial window showed by the program interface_ LUTs

Once that option is chosen, the user can search for a LIST file. Once the file is selected, the program will read it and crystal images of the detectors will be generated using the information contained in the LIST file.

Once the program finishes reading the file, the crystal maps are loaded in the main window. Each of these images can be selected changing the option that appears in **“View tube”** in the user’s window.

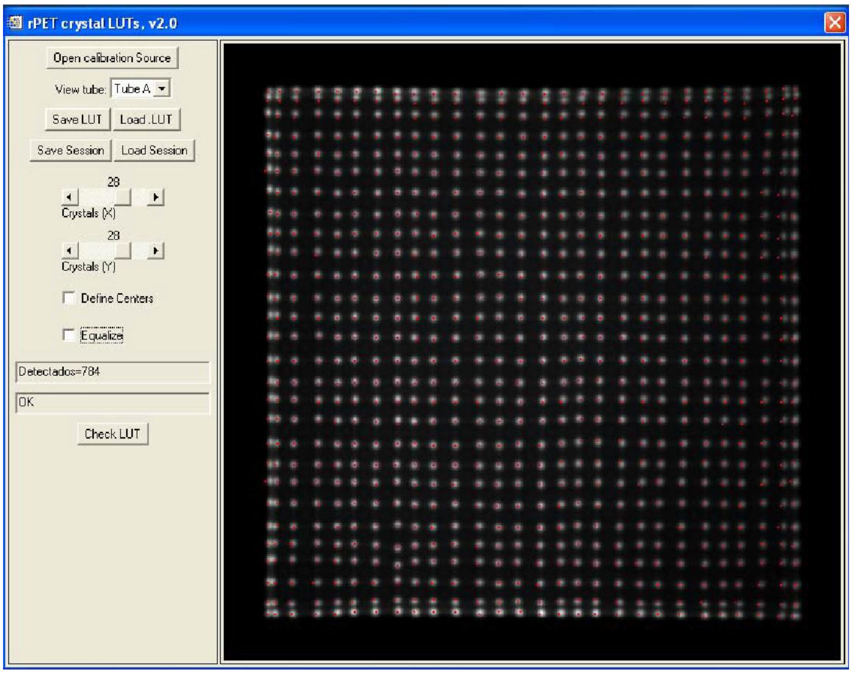


Figure 40: Selecting "View Tube" option, thecrystal maps of the different tubes are displayed in the screen

The program automatically calculates the position of the crystals. The algorithm used to perform this task looks for the maximum in the image and locates a red point in all of them.

The number of maximum points that the program locates can be selected using the sliders in the user window (**Crystals X** and **Crystals Y**). The program will mark the (Crystal X * Crystal Y) points with maximum value in the image. Changing the value of any of these sliders will make the program recalculate the maximum.

It is possible to manually adjust the position of the maximum in the image. To do that, it is necessary to check the option **"Define Centers"**. Once this option is selected, the user will be able to define a maximum with the left button of the mouse and to eliminate a maximum with using the right button.

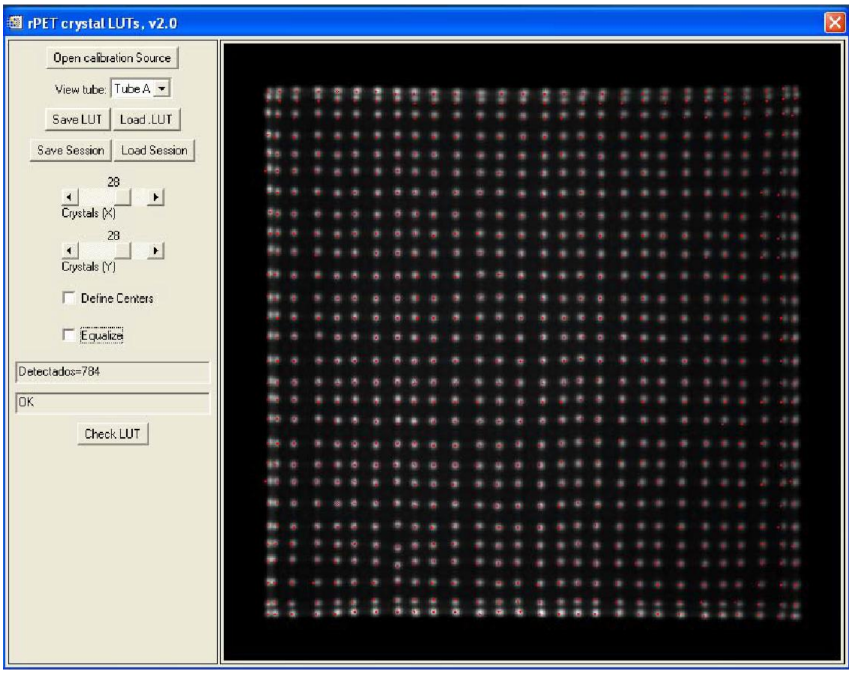


Figure 41: The options Crystal X and Crystal Y allow to change the number of maximum points shown in the image. The option Define Centers allow to manually create and delete maximums.

The option **"Equalize"** performs an image equalization; which is useful when the crystal images of the LIST file don't show the maximums clearly enough.

Once all the maximums have been located, it is necessary to check that the distribution follows the desired pattern. This is done by clicking the option **"Check LUT"**. If the LUT is correct, two images like the ones showed in Figure 4 will appear in the screen and the option **"Save LUT"** will activate, allowing the user to save the LUT of the selected tube.

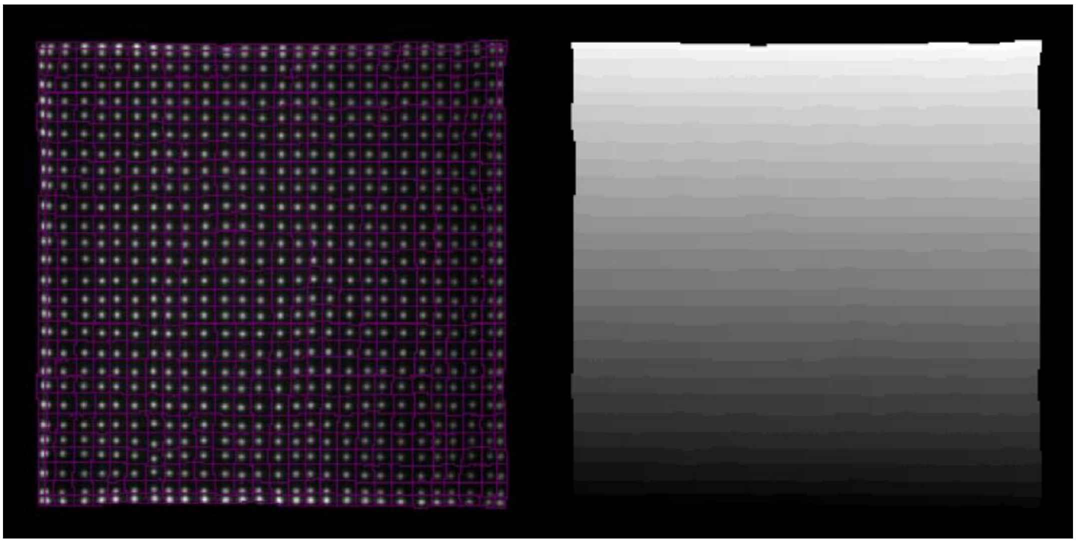


Figure 42: : Images that appear in the screen once a LUT has been verified and no errors exist. The left image shows the defined limits for the crystals. The right image shows the LUT created for a tube.

If an error is found, an image like the one shown in Figure 5 will appear in the screen:

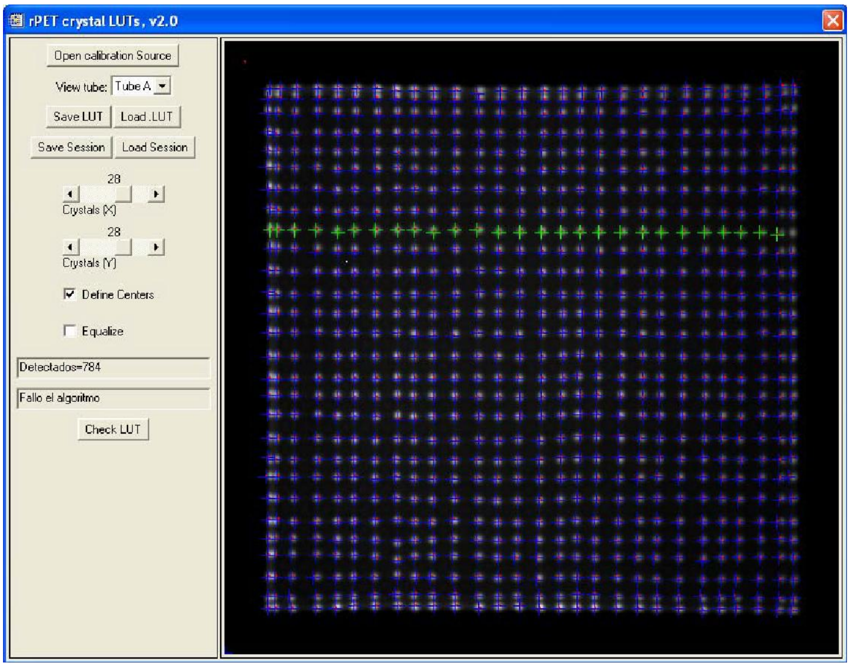


Figure 43: Image that appear in the screen once a LUT has been verified and an error is found. The row in green corresponds to the row with errors.

Other option that can be selected from the main window are:

Load LUT: Previously created LUTs are loaded

Save Session: Saves the work done even if no LUT has been saved.

Load Session: A previously saved session is loaded.

3.3.- Tomographic acquisition program

daq: this is the main program to control the rPET. It coordinates every element of the rPET (mechanical, detection and acquisition systems) and generated the files with the obtained data.

The user can call this program from the script daq_only using the user's console. The script daq_only executes the daq always under the same conditions.

A few examples on how to execute the tomographic acquisition program are shown below:

daq_only-f1-z1-d1500.00-m25.00-i18-k2-bRAT_TST_Apr07_Acq01

This command will perform a static study of 25 minutes

daq_only-f4-z1-d300-m20.00-i18-k2-bRAT_TST_Apr07_Acq01

This command will perform a dynamic study with 4 frames of 300 seconds each and a total duration of 20 minutes.

daq_only-f1-z4-m120.00-i18-k2-bRAT_TST_Apr07_Acq01

This command will perform a whole body study with 4 bed positions and a total duration of 2 hours

The execution parameters of the daq program are listed in Appendix VIII

3.3.1-Input and output files

OUTPUT

.ACQ files: These files are created once data acquisition finishes. They contain the information needed to locate the files that were used during the acquisition as well as those needed to apply reconstruction corrections.

.ACQ files are divided in four sections as it can be seen in Figure 6, an example of how a .ACQ file can look like.

```
NOMBRE_ADQUISICION
dd/mm/yyyy hh:mm.ss

[acquisition]
       slices_overlap = int
       bed_positions = int
       timed_frames = int
       time_per_frame = int
       gated_frames = int
       num_files = int
       total_time = int
       base_filename = "string"

[calibration]
       coincWin = int
       angle_offsets = int
       file_offsets = "string"
       file_alignments = "string"
       file_LUTs = ["string1","string2","string3","string4"]
       file_ERs = ["string1","string2","string3","string4"]
       file_sensib_xtal = "string"
       file_sensib = "string"
       file_sensib_trans = "string"

[isotope]
       isotope_name = "string"
       halflife = int
       beta_branching = float
       keVmin=int
       keVmax=int

[log]
       rPET acquisition finished OK.
                        Sector 1   Sector 2   Sector 3   Sector 4   Sector 5
       total            int        Int        int        int        int
       valid rate       int        Int        int        int        int
       overflows        float%     float %    float %    float %    float %
       Total acquired chunks = int, total flood warnings = int
       Total valid events = int
       Total processed events = int
       Time= float seconds. Processing Rate =  int events/sec,

       A total of  int events were read
       a total of  int bad events found

       REPORTED sync= int, sync(end_spin)= int, events= int
```

Figure 16: Example of .ACQ file

Each of the sections is explained below:

Every file has a heading with the name that the user has given to the whole study. This name is followed by the date and time at which the study was performed.

[Acquisition]:

-**Slices_overlap:** number of overlapped slices between consecutive positions of the bed

-Bed_positions: number of bed positions explored during the study. Each of them generates a different .LIST file.

-Timed_frames: Number of frames in which the acquisition is divided (>1 for a dynamic study and =1 for a static study). Each of them generates a different .LIST file.

-Time_per_frame: Time in seconds per frame.

-gated_frames: not used yet.

-num_files: Number of .LIST files that compose the study.

-Total_time: Total duration of the study in seconds.

-base_filename: determines the names of all the .LIST files generated and stored in the same directory as the .ACQ file.

The nomenclature used is the following:

base_filename_N_M.LIST

Where N is the bed position and M is the frame.

[Calibration]

-coincWin: coincidence window duration in nanoseconds

-angle_offsets: shows the value in degrees of the initial angle between the pair of tubes 1 and 2.

-file_offsets: offset file used for the creation of the .LIST files.

-file_alignments: file where misalignments between detectors with respect to its ideal position in YZ plane in reference to the detector's own reference system are stored.

-file_LUTs: this vector specifies the names of the crystal assignment files corresponding to each of the detectors.

-file_ERs: this vector specifies the names of the energy correction files corresponding to each of the detectors.

-file_sensib_xtal: not used in this version.

-file_sensib_trans: not used in this version.

-file_sensib: sensibility correction file.

[Isotope]

-isotope_name: Isotope's name. It is written with its standard abbreviation and followed by its mass number.

halflife: halflife of the isotope expressed in seconds.

beta_branching: β-branching ratio of the isotope used.

-keV_min: minimum threshold of the energy window.

-keV_max: maximum threshold of the energy window.

[Log]

The first line of this section indicates if the acquisition was finished correctly, if it was aborted by the user of if it was aborted by the program itself due to a low number of counts.

-total: number of events for each ADC card.

-valid rate: events per second in each ADC card.

-overflows: percentage of events that overflows each ADC card.

-total acquired chuncks: total number of chuncks acquired.

-total flood warnings: possible number of chuncks thathave been lost. Number of times that there hasn't been a waiting period because the acquisition buffer was full.

-**total valid events:** total number of valid events.

-total processed events: total number of processed events.

Time: Acquisition time.

Processing rate: total number of processed events.

ACQ_info.log: informs the user about the acquisition state. The values that appear in this file are the following:

1.- Elapsed time (sec)

2.- Coincidences per second

3.- Randoms per second

4.- Singles per second

5.- Coincidences in this frame

6.- Current time frame

7.- Current bed position

8.- Dead time

9.- Flag that will be 0 during the acquisition system, 1 if the acquisition has finished correctly and 2 if it wasn't possible to initiate the motor control box.

INPUT

Alignment file: This file stores the detectors misalignments with respect to its ideal position in the YZ plane according to the detectors own reference system.

The nomenclature used is the following:

offset_tubeN_D

Where N is the tube number and D the dimension at which the displacement is measured (x,y,z).

This file also contains the parameter angle between blocks that shows the angular error that exists between the pair of detectors.

motor_params.txt: file containing all the information needed for the mechanic system configuration

BaseVelocity	Base velocity of each axis in steps per second	-
MaxVelocity	Maximum velocity of each axis in steps per second	-
Acceleration	Acceleration of each axis in steps per square second	-
Homedir*	Direction in which HOME routine starts	**-1**: CCW (counter clock wise)
		1: CW (clock wise)
Resolution	Step resolution of the controller	-
PosTrigger	Decides whether the controller sends or not a confirmation when it reaches the programmed position	**1**: Send confirmation
		0: Do not send confirmation
LinkIO	Indicates if the entries/exits of the motor control box are linked or not with the movement of any of the	**1**: a link exists
		-1: a link doesn't exists

	motors	
VelTrigger	Decides whether the controller sends or not a confirmation when it reaches the programmed velocity	**1:** Send confirmation **0:** Do not send confirmation
ModQuit	Activates or deactivates MODULO_QUIT in each axis	**1:** Activates MODULO_QUIT **0:** Deactivates MODULO_QUIT
AccelProfile	Selects the acceleration profile in each axis	**1:** LINEAR **2:** PARABOLIC **3:** USER
standbyDelay	Shows the time in seconds that the controller waits between the last movement and the STANDBY mode activation.	
JoystickMode	Functioning mode of each axis when they are activated by a joystick	**0:** OFF **1:** LINEAR. Linear relation between acceleration and joystick position **2:** LINEAR_12BAND. The central band (12% of the travel distance) is considered as the center **3:** LINEAR_25BAND. The central band (25% of the travel distance) is considered as the center **4:** LOG. Logarithmic relation between joystick position and acceleration **5:** LOG_12BAND **6:** LOG2. Square logarithmic relation between acceleration and

		joystick position
		7: LOG2_12BAND

Table 7: Motor parameters file

*For the case of the X axis, a CW home direction means that the bed starts at HOME and moves far from the ring.

rPET_params.txt: basic configuration file of the rPET. It contains the physical and running parameters of the rPET.

It is possible to change some aspects of the software's functionality using this file.

File parameters:

NBLOCKS	Number of ADC blocks that trigger during each event of the DAQ
NADCS	Highest ID number of the connected ADCs
SLOT 1	ID number of the ADC connected to SLOT 1
SLOT 2	ID number of the ADC connected to SLOT 2
SLOT 3	ID number of the ADC connected to SLOT 3
SLOT 4	ID number of the ADC connected to SLOT 4
RANGO DINÁMICO	Highest valid value in a channel of a DAQ
DET_IMAGE_SIDE	Size in pixels of the crystal image of each detector
IMG_TRESH	Percentage of the signal's mean that is used in the algorithm to calculate the center of mass with SNR improvement
NXTALS_Z	Number of crystals used in the axial direction matrices.
NXTALS_Y	Number of crystals used in the radial direction matrices
EN_FACTOR1	Calibrated factor of the energy fotopeak of tube1
EN_FACTOR2	Calibrated factor of the energy fotopeak of tube2
EN_FACTOR3	Calibrated factor of the energy fotopeak of

	tube3
EN_FACTOR4	Calibrated factor of the energy fotopeak of tube4
AUTOCOINC	Study made with a single detector that is in coincidence with itself (values can be '0' if no tube is in autocoincidence or '1' if the detector connected to SLOT1 is in autocoincidence)
STEPS_DEG	Steps per degree of the ring's step motor
STEPS_MM	Steps per degree of the bed's step motor
SLICE_THICKNESS_MM	Width of the axial slices in which the volume is divided
FIXED_SPIN_DURATION	Time in seconds that lasts a whole scan
FIXED_SPIN_ANGLE	Angle that each detector travels per scan
FIXED_STEP_VEL	Ring's step motor velocity in steps per second
INC_ANG_GRAD_MAX	Maximum value in degrees of the angular increment between consecutive synchronism events
INC_TIME_MS_MAX	Maximum value in milliseconds of the temporal increment between consecutive synchronism events
HOME_ABS_POS	Value that should be written in the controller's position register when any of the axis is at home position
BED_STOP_MAX	Location in steps of the bed with respect to the fault indicator that is located the farthest away from the detectors
BED_STOP_MIN	Location in steps of the bed with respect to the fault indicator that is located the closest to the detectors
FIELDLENGTH	Length in millimeters of the axial FOV
JOY_VEL	Bed's velocity when it is being moved by the joystick

ANGLE_INI	Difference in degrees of detector 1 position with respect to the reference 0°
SCOPE_MODE	Determines if scope mode is initiated when the acquisition starts

Table 8: 'rPET_ params' paramenters

ANNEX

I.- CONNECTORS IN THE MOTOR CONTROL BOX

1.- Ring control: Wired to this entry it can be found the 25 pin exit from the Newport. The phases of the step motor and the ring signals used are connected to it.

2.- Bed motor: Contains the phases of the bed step motor.

3.- Clock pulses: This is a 5kHz clock signal used as a reference during the acquisition process.

4.- Joystick: This connector carries the joystick signals moving the bed and the ring.

5.- Ring control: This connector carries a square signal with a number of pulses equivalent to the ring's movement. Specifically, the relation between pulses and angular movement is 250 pulses\degree.

6.- Bed control: This connector contains the bed' fault and home signals. The fault signals determine the bed' moving limits.

7.- Serial port: Communication between the computer and the controller.

8.- Controller power supply: This switch carries the power supply to the motor controller and to the electronics associated to it.

II.-JOYSTICK SPECIFICATIONS

M-series miniature resistive joystick

Distributor: APEM

SPECIFICATIONS

MECHANICAL (FOR X AND Y AXES)		
Break Out Force	–	0.7N (0.16lbf)
Operating Force	–	1.3N (0.29lbf)
Maximum Applied Force	–	100N (22.48lbf)
Mechanical Angle of Movement	–	56°
Expected Life	–	See potentiometer options
Mass/weight	–	Varies
Package Size (mm) (L x W x H) or (Dia x H)	–	Varies
Lever Action (Centering)	–	Spring or Friction

MECHANICAL (FOR Z AXIS)		
Break Out Torque	–	0.022N·m (0.19lbf·in)
Operating Torque	–	0.040N·m (0.35lbf·in)
Maximum Allowable Torque	–	0.049N·m (0.43lbf·in)
Mechanical Angle	–	90°
Handle Action	–	Spring

ENVIRONMENTAL		
Operating Temperature	–	-25°C to 70°C (-13°F to 158°F)
Storage Temperature	–	-40°C to 70°C (-40°F to 158°F)

POTENTIOMETER OPTIONS

Potentiometer	P	M	R
Electrical Element	Conductive Plastic	Conductive Plastic	Conductive Plastic
Track Resistance	5K	5K	5K
Linearity	±1.0%	±5.0%	±1.0%
Track Operating Angle	220°	56°	50°
CRV	±1.5%	±1.5%	±1.0%
Power Dissipation	0.25W @ 40°C	0.5W @ 70°C	1W
Rotational Life	1,000,000	1,000,000	10,000,000

CENTERING OPTIONS

- SPRING CENTERING

The joystick returns to center when the handle is released.

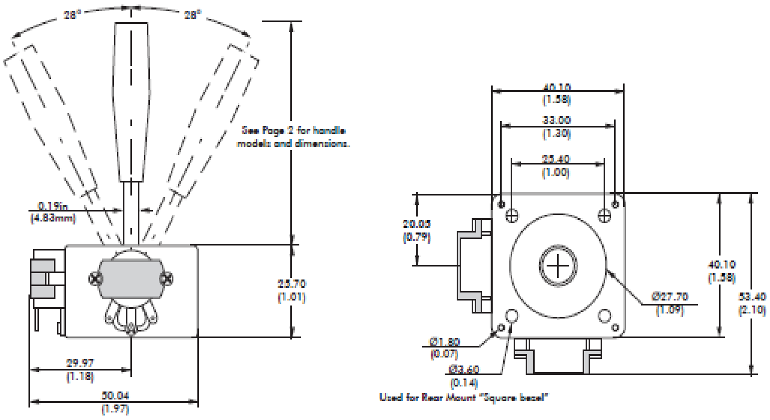
- TORQUE SET

Torque set provides absolute positioning with uniform friction applied to "X" and "Y" axes.

NOTES:

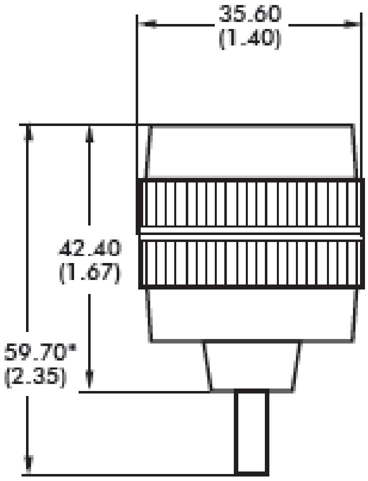
- All values are nominal
- Specifications are subject to the joystick configuration. Contact Technical Support for the performance of your specific configuration
- The M Series is intended for internal applications

2 AXES WITH OPTION A HANDLE

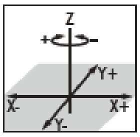


NOTES:

1. Mechanical dimensions represent a joystick with the largest potentiometer option.
2. Potentiometer size will vary according to selected option.



NOTES:

1. Dimensions are in mm/(inch)
2. Pushbuttons are not sealed. Joysticks are intended for internal applications only.
3. Axes orientation: 

4. Wiring information: -Cables are provided for pushbuttons and the Z axis.
   -Cables are not supplied for the potentiometers (axes X and Y).

III.-SYSTEM'S ACQUISITION EVENT FORMAT

The acquisitions system will send to the PCI card by means of the bus the data each time a valid event is detected:

CNT 0 32 bits	CNT 1 32 bits	CNT 2 32 bits	CNT3 32 bits	CNT 4 32 bits	NBLOCKS (ADCs) x 16 (channels /ADC) x 16 (bits/channel)

The variable NBLOCKS indicates the number of ADC blocks that trigger per event (1 or 2). This number is fixed by the connection between the trigger module and the rest of modules by means of the coincidence matrix.

Apart from the format showed in the previous table, each counter (CNT0…CNT4) as well as the data channels from each ADC arrive with four header bits that allow classifing the events as correct or incorrect. The format for this header is shown in the next table:

Counters:

1000	CNT0	0000	CNT1	0000	CNT2	0000	CNT3	0000	CNT4

ADC

ADC number	Ch0	0000	Ch1	0000	Ch2	…	0000	Ch15

IV.-SCALER'S MODULE TECHNICAL CHATACTERISTICS

Module characteristics	**Vale**
Entry impedance (latch)	100 Ohm
Entry threshold (latch)	+ 0.4 V
Entry impedance (counters)	50 Ohm
Entry threshold (counters)	+ 0.4 V
Maximum instantaneous counting rate (counters)	100 Mhz
Counters size	28 bits
Temporal spacing between	

V.-ADITIONAL FUNCTIONALITIES OF THE TRIGGER MODULE

The trigger module has a commutator with 3 positions:

- **Up**: The system will acquire coincidence events.
- **Center**: All the modules' trigger are disabled.
- **Down**: This mode is used to compute the offsets of the acquisition system. All the modules are "sensitized" each time a pulse from an internal clock signal of 10 kHz arrives. This implies that all the ADCs will dump the data into the bus each time the flag signal arrives.

Computing the offsets of the acquisition systems consist on obtaining the value of the data channels for all the ADCs without a real signal. The values obtained are subtracted from the data obtained during the acquisition process, improving the SNR.

There is also a 10 pin IDC connector (where all the even pins are ground). This connector which is located in the lower part of the trigger module provides the following signals:

- **Pin #1,2**: "True" counter. In this pin the coincidences that cause a data flux in the BUS LVDS can be found. The output signal from this pin corresponds to the integration time of the ADCs.
- **Pin #3,4**: This pin contains all the coincidences detected in the system, even those that didn't produced a data dump into the BUS due to the blockage of the trigger module. The trigger module is blocked while it is waiting to receive the "End of transference" signal. This sigal can be used to compute the dead time.
- **Pin #7,8:** Intermediate signal that allows adjusting the threshold and the temporal retardation. This output provides the OR of the entry pulses that have exceeded the ULD ref value.
- **Pin #9,10:** Intermediate signal that allows adjusting the threshold and the temporal retardation. This output provides the OR of the entry pulses that have exceeded the LLD ref value.

VI.-ADCs GENERAL SPECIFICATIONS

ADC specifications	Value
Analog entry impedance/polarity	50 Ohm/negative
Sensitivity	0.25 pC/ bin (typical value)
Non differential linearity	0.25 LSB(typical value)
Useful integrating time	40 … 3000 nsecs
Time lag between consecutive output words (32 bits)	40nsecs
Digital channel order arriving to the BUS	16,8,14,6,12,4,10,2,15,7,13,5,11,3,9,1
Power supply	+6V -450mA, -6V -280mA, +/- 12V con -230 mA

VII.-STEPS NEEDED TO INSTALL THE PCI INTERFACE AND USER FUNTIONS

STEPS NEEDED TO INSTALL THE PCI INTERFACE

1.- Create the files needed for the communication with the system. The commands needed to create this files are:

mknod-m 0666/dev/pfba c 60 0

mknod-m 0666/dev/pfbb c 61 0

The meaning of the previous parameters is:

- -m 0666: file mode
- /dev/pfba **or** /dev/pfbb: file
- c : This parameter indicates that the former file is a special character file and not a special block file.
- The numbers at the end of the commands (60 0, 61 0) indicate the largest and smallest device.

2.- Copy the driver (pfb.o) in the appropriate path (in this case the path is: /lib/modules/2.4.20-8smp/kernel/drivers/char/).

3.- Add the line */sbin/insmod pfb* to the script */etc/rc.d/rc.local*. This last step allows loading the module each time the system is initialized.

USER FUNCTIONS

These functions manage the data that goes into the PCI card.

Function definition	**Functionlity**
Void pfb_init_dma();	1.- Opens the PCI as a common file 2.-Checks that the PCI is connected to the BUS (PCI_FIND_DEVICE)

	3.-Reads the content of the 4th first fields in the heading as well as the memory block's address saved by the module when it connects to the kernel
Void pfb_launch_dma();	This function writes in the PCI card the following: Byte 120: memory block's address saved by the module when it connects to the kernel. This is the address where the data of the acquisition system will be saved. Byte 72: Size of the block that is going to be moved to the previousaddress.
Int pfb_wait_dma_finished();	This function shows the field from the byte 72 which will decrease as the transference proceeds. When it reaches 0, the transference is finished. This function returns to 1 if everything has proceeded as expected.
Int pfb_check_fifo_counter();	This function shows the field from the byte 68 which will increase as the data from the acquisition system arrive to the intermediate storage element (FIFO) When the counter indicates that the that the FIFO content is greater or equal to the buffer's size, it can be moved.
Int*pfb_copy_dma_buffer();	This function copies the transferred buffer to the appropriate variable. After this action is completed, the memory position of the variable will be returned.
Int pfb_acq_buffer(int**buf,int timeout);	1.- Check if there is any data inside the FIFO. If any data is found, the DMA is launched. If after waiting the period of time determined by timeout there is no data, a message indicating a low count rate is shown to the user. 2.- If the DMA has been launched, the address of the acquired buffer is shown when the transference is completed. The message "buffer OK" is also shown to the user. 3.- If the DMA transference doesn't finish in the required time, an error message is shown to the user.

VIII.-EXECUTION PARAMETERS OF daq PROGRAM

OPTION	FUNCTIONALITY	DEFFECT VALUE
-v	Shows the program version in the screen and terminates the execution	-
-mK	Defines the acquisition time in K minutes	0.0minutes
-f frames	Number of frames in the study	1
-zX	Number of bed positions in the study	1
-dZ	Frame duration for dynamic studies	0.0 minutes
-icode	Isotope code used in the acquisition	F-18
-kcode	Defines the energy correction files	100-700keV
-bnombre	Base name of the LIST and ACQ files in the study	Unknown_Patient
-osolape	Number of overlapped slices in consecutive bed positions. This parameter is used in multi-bed studies	8 slices of 0.8 mm
-pX	Defines if the acquisition performed is a volumetric acquisition (-p0) or a projections acquisition (-p1)	0

ISOTOPE CODES:

Isotope	11C	13N	15O	18F	22Na	64Cu	68Ge	76Br	94m Tc	124I
Code	11	13	15	18	22	64	68	76	85	124

ENERGY CORRECTION CODES:

Energy window	100-700 keV	250-650 keV	400-700 keV
Code	1	2	3

IX.-ADJUSTMENT OF PHOTOMULTIPLIERS' POWER SUPPLY

A crystal map is needed to adjust the photomultipliers supply. In order to avoid the use of radioactive samples, detectors can be configured in auto-coincidence mode.

The photomultipliers' supply can be considered correct if:

- The power supply should be in the range [-700 V, -1100 V] and the level of counts per second obtained after running the program should be in the range [6000-7000 counts/s]
- The trigger signal's amplitude should be of 750 mV approximately.
- The data signal's amplitude should be of 1.5 mV approximately.

ACRONYMS

CPU	Central Processing Unit
CT	Computed Tomography
DAQ	Data Acquisition
EOR	End of Range
LED	Light Emitting Diode
LVDS	Low Voltage Differential Signal
MRI	Magnetic Resonance Imaging
PCI	Peripheral Component Interconnect
PET	Positron Emission Tomography
PS-PMT	Position Sensitive Photomultiplier
rPET	Rotating Positron Emission Tomography
US	United States

LIST OF TABLES AND FIGURES

LIST OF TABLES

LIST OF FIGURES