POLITECNICO DI TORINO

Master degree course in
Mechatronic Engineering

Master Degree Thesis

Design and validation of a Robotic Patient Positioning System

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"Chi dice che è
impossibile
non dovrebbe disturbare
chi ce la sta facendo..."
[Albert Einstein]
"...piuttosto aiutarlo!"
[Io]

Abstract

Finding new and more efficient techniques in the treatment of cancer diseases is one of the main challenges in which the modern medicine is involved. Radiation therapy represents, in this field, an excellent alternative for inoperable patients, or when the surgery is rejected. Among all the used radiation therapies, proton therapy ensures well known dosimetric advantages in patients, and minimizes possible risks to damage vital organs causing unwanted side effects. Here is presented the "Enhanced Radiotherapy with HAdrons (ERHA)" project intended to design an innovative, compact and cheaper system for proton therapy delivery treatments. As part of this bigger system, a new prototype of "Robotised Patient Positioning System (RPPS)" is studied to provide an alternative solution compared with those commonly used. Thanks to a 7 Degree-of-Freedom (DoF) manipulator carrying a patient lying down on a couch top attached to the robot end effector, the system aligns the tumor target (inside the patient body) with respect to a fixed particle beam entering the room through beam delivery system. The following thesis project will follow all the steps in analysing the RPPS system, starting from the design stage until the validation tests.

Acknowledgements

Questo giorno, che segna un nuovo traguardo nella mia vita personale e professionale, mi rende fiero di me per essere arrivato fin qui. Allo stesso tempo, guardandomi alle spalle, c'è molto di più: questo traguardo è soltanto la punta di un iceberg fatto di successi e insuccessi, delusioni e soddifazioni, pianti e risate, che da solo non sarei mai riuscito ad affrontare. Per questo sento di dover dire il mio grazie a quelle persone speciali che, per mia fortuna, la vita mi ha fatto incontrare.

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Chapter 1

Introduction

Many cancers, in particular when at early stage, are curable but, unfortunately, others have no prognosis at the current state of the art of medicine in this field; so the curability of them needs to be evaluated in each case. Initially, in its development stage, a tumor is generally well localized inside the patient body, and it tends to infect to neighbouring lymph nodes and healthy organs. When the tumor is extremely close to vital structure or it is anyway inaccessible, surgery can not be considered as viable option. In these cases radiation therapy will be a useful approach. However, even if aggressive surgery or high dose of radiation and chemotherapy can destroy the cancer, they can cause unacceptable morbidity for the patient. Therefore must to be found the right balance between tumor cure and risk of possible injuries to normal tissues. Most of new studies and researches in radiation therapy are focused on minimizing the health hazard of the patient, making tumor control probability higher. Moreover radiation therapy is, of course, a less invasive treatment than surgery, and in many cases it represents the healthiest and safest therapy to attend. That is why many company involved in this field are always investigating better solutions to improve technologies available on the market.

At present, techniques based on beam of high-energy X-rays (often denoted as photon beam) are the most commonly used in radiotherapy treatments. Other possible forms of radiation used are: neutrons, electrons beam, radioactive sources, protons, heavier charged ions.

In the last few years, the interest in using ionizing radiations in the treatments of tumor has grown. Innovative techniques are investigated in order to increase the treatments efficiency: one of them is proton therapy. The proton therapy is an innovative technique that uses heavy particles positively charged (protons). The advantages, in accordance with physical phenomena related to this kind of particles, are to be found in the capability of the particle beam to hit the tumor target with extremely high precision and, at the same time, to reduce dangerous effects on the tissues near to the target. These characteristics are particularly interesting in treating different kinds of tumor and, in particular, paediatric tumor since developing tissues are more sensitive to the effects of radiations.

Nowadays about 50 centres worldwide (between USA, Japan and Europe) and many others are in construction in the next ten years. Actually in Italy are present 3 operative centres in this field and the biggest one is in Trento.

This is the context in which Itel Telecomunicazioni srl., a company focused on developing and installing Electromagnetic Shielding for Diagnostic Imaging and located in Ruvo di Puglia (BA), is focused on. Thus, ITEL has started in 2009 a new division, ITELPHARMA, for the production of radiopharmaceuticals and services for Nuclear Medicine, and is involved in an ongoing project to design a compact Proton Accelerator for Hadron Therapy.

The Itel R&D group is carrying on the **ERHA (Enhanced Radioterapy with HAdrons) project**. This is an innovative system for proton therapy treatments developed by Itel and completely made in Italy. The aim of the project is to design and build a linear protons accelerator suitable for clinical purposes, a robotised platform able to place the patient in the treatment position inside the treatment room, and a software to analyse and develop treatment plans. At present, the main part of work is focused on the design of the linear accelerator, an innovative machine which will be able to take the place of much more huge and expansive machines such as cyclotron and synchrotron.

Thanks to Itel company, I had the possibility to know this reality and spend about five months inside Itel Mechatronic Lab working on the prototype of **RPPS (Robotised Patient Positioning System)**. In particular this thesis work was focused on the goal to investigate the possibility to use an anthropomorphic manipulator to hold and move the medical couch on which the patient is lying. This kind of system has been thought in order to find a viable alternative to the ones commonly used; as it will be clear in the following, nowadays are generally used huge, complex and expansive structures able to guarantee all the specifications for a patient positioning system. That is why the innovative idea is to have a compact well designed system starting from the particles accelerator, followed by a cheaper and simpler positioning system. In conclusion, my goal, during this period, was to validate the possibility to use the anthropomorphic manipulators in order to reach the project objectives through simulation and experimental tests.

Chapter 2 summarizes theoretical basics about physics of proton beam; physical phenomena related to their interaction with matter and benefits for patient body coming for their utilization. Subsequently, is presented a brief overview of technologies currently used in facilities, equipped for proton therapy, in order to understand and appreciate the context in which ERHA project would like to introduce innovations.

In Chapter 3 is explained in general terms the ERHA project, presenting what are the goals the R&D group is intended to achieve. Here is briefly described Itel particle accelerator currently under construction and the progresses already done on it. Then the object of this work will be presented: the RPPS system. The attention is focused on the goals on which the project is based on, making it an innovation in radiation therapy field, and requirements which should be attended by the final system.

Chapter 4 presents the work done during the internship in Itel company. In this part, are described, in detail, the design stage of the RPPS, the main results achieved through simulations and experimental tests done on the real set up available in the Mechatronic Lab.

The last part, Chapter 5, provides conclusions and future developments about the RPPS project.

Chapter 2

Basic on ionizing radiations

Subatomic particles (electrons, protons, neutrons, etc.) and electromagnetic waves with energy above a few electron volts (eV) are the so called "ionizing radiation". This means that, when particles or photons passing through tissues, they lose energy and, at the same time, ionize them in atomic or nuclear interaction. These kinds of radiations have enough energy to damage biological molecules such as DNA. The previous physical phenomenon can be used to cure cancer concentrating a high dose of radiation at the cancerous cells. In fact dividing cells are more susceptible to radiation than non-dividing cells and these will kill dividing cancerous cells more effectively than healthy cells. The key of a good and healthy treatment is a controlled amount of radiations directed at the concentrations of cancerous cells in order to cause damages to them rather than to normal cells of patient body.

In the last few years, the interest in using particles therapy for cancer treatments has grown. The reason of this interest has to be found in the pattern of energy disposition in matter, which heavy charged particle beams have, that represents the main advantage in using protons or heavy ions rather than more conventional photons (X-ray) or electrons.

2.1 Proton Therapy: a general overview

2.1.1 Physical concepts

The proton therapy is a medical treatment in which, by using accelerated protons, the objective is to destroy cancerous cells. In 1946, the physic Robert Wilson found that the energy released by protons passing trough whatever material is not uniformly distributed but has a peak at the end of their trajectory. Both protons and heavier ions show an inverse depth dose distribution significantly different from the one produced by electron beams and X-rays as it shown in Figure 2.1.

It is possible to observe that protons, transferring energy to the tissues in an inversely proportional way to their velocity, allow the maximum dose delivering at a well defined depth, which is a function of the starting energy. The region in tissue where the particles release the major part of their energy is called **Bragg peak**.

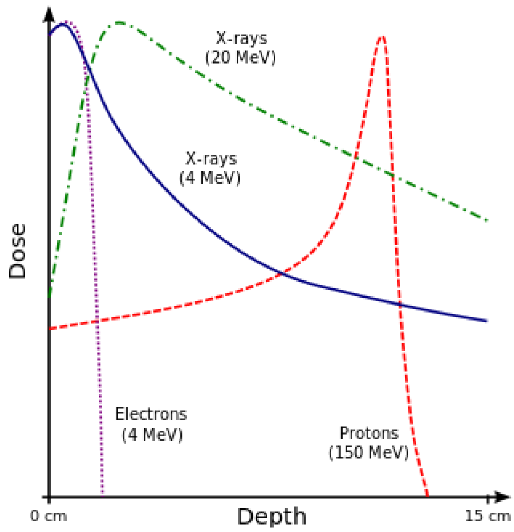


Figure 2.1: Comparison between dose released in tissues by electrons, photons and protons.

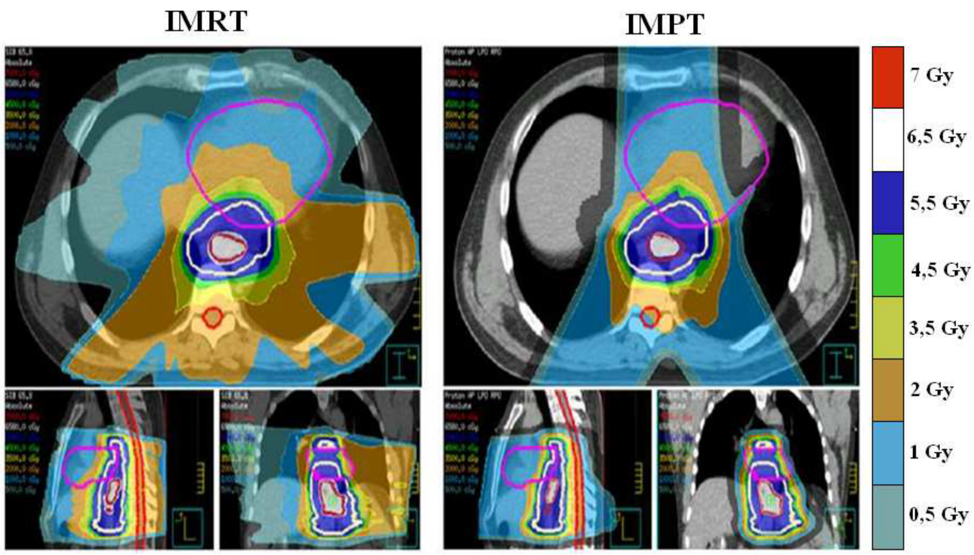


Figure 2.2: Axial, sagittal, and coronal views of an IMRT-SIB plan in which the PTV (planning target volume) is treated to 50.4 Gy while the GTV is boosted to 65.8 Gy [**8**].

In addition, another advantage is that the lateral scattering of proton beams is much smaller than the penumbra of conventional X-ray or electron beams, and it means that proton beams are less injurious for the healthy tissues present around the cancerous cells.

In order to underline the advantages in using proton therapy from the point of view of absorbed dose by tissues around the target, Figure 2.2 is reported. It refers to a study [**8**] comparing the tissues' exposure during IMPT (Intensity Modulated Proton Therapy) and IMRT (Intensity Modulated [Photon] Radiation Therapy), demonstrating that using IMPT allows increased doses to the GTV (gross tumor volume) with decreased toxicity to critical structures.

Ideally, considering a single proton, the Bragg peak will be narrow and fast; while a proton beam will produce a peak of some millimetres due to the stochastic distribution of contributes belonging to each single particle in the beam (straggling effect). In fact particles do not have the same energy and they cause peaks at different depth, which result in a larger Bragg peak than the ones produced singularly. In the real application the therapeutic beam is modulated in order to have different energy layers of proton so that it will cover the whole shape of the target. What is obtained now is the so called **spread-out Bragg peak (SOBP)** (Figure 2.3). Despite the ability of proton to release a homogeneous dose on the target using a single entering direction, in practice are likely used more entering points to optimize dose distribution.

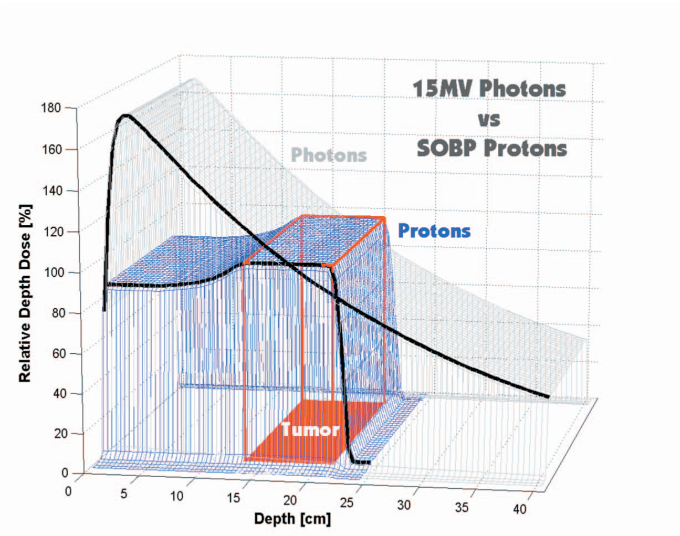


Figure 2.3: Comparison between the depth dose curves for 15 MV photons and a proton spread-out-Bragg peak (SOBP). A target volume is shown in red. Shown also in red lines is an ideal dose distribution for the target volume, which provides uniform, maximum dose to the target volume and zero dose outside the target volume. The proton dose distribution approaches the ideal case to a much greater extent than the photon dose distribution does. Notably, the proton dose stops abruptly distal to the target volume and delivers less dose to the region proximal to the target volume.[**13**]

Compared with photons used in conventional radiotherapy, charged particles offer an improved dose conformation to the target volume due to their characteristic way of interacting with matter. From a microscopic point of view, protons interact with the travelling medium principally in three ways:

a They are decelerated, as a consequence of the collisions they have with electrons of atoms presents in the matter;

b They are deflected due to collisions with atoms present in the matter (scattering);

c Thanks to collisions with nuclei of atoms in the matter, secondary particles are generated.

Particle Stopping Power theory

Heavy charged particles traversing matter lose energy primarily through the ionization and excitation of atoms. They exert electromagnetic forces (due to opposite charge) on atomic electrons and impart energy sufficient to ionize the atoms or to excite them. This kind of particles travels an almost straight path through matter, losing energy continuously in small amounts through collisions with atomic electrons. Note that before stopping and completely loosing their energy, a proton suffers thousands of collisions for centimetres of travelling material.

For a particle of energy E travelling a distance x with speed v, the energy rate loss in medium for ionizations expressed in $\frac{MeV}{cm}$ is mathematically described by the following Bethe-Bloch expression:

$$-\frac{dE}{dx} = \frac{4\pi N_A}{m_e c^2}\frac{z^2}{\beta^2}\frac{Z}{A}\rho \ln \frac{2m_e c^2\beta^2\gamma^2}{I} - relativistic\ terms) \tag{2.1}$$

where:

- c is the speed of light
- β is the ratio between the velocity of particle and the speed of light ($\frac{v}{c}$)
- N_A is the Avogadro number
- z is the particle charge
- m_e is the rest mass of the electron
- Z, A, ρ, I are the atomic number, the mass number, the density and the mean excitation energy of the medium, respectively.

The following equation describes the inverse proportionality between x and energy E. One therefore defines the **mass stopping power** which is positive as:

$$S = -\frac{dE}{dX} \qquad [\frac{MeV}{g/cm^2}] \tag{2.2}$$

The dominant part in the Bethe-Bloch formula is $\frac{1}{v^2}$ and the Z dependence. The $\frac{1}{v^2} \approx \frac{1}{E}$ dependence yields an increase in energy loss with decreasing particle energy. At low energies electrons are collected from the target and Z in the nominator decreases rapidly yielding a distinct maximum of energy loss at low energies. When the energy loss is plotted over the penetration depth, its maximum is located at the end of the track causing the Bragg peak.

Energy loss occurs in discrete interactions and thus has statistical fluctuations. Protons passing through a solid or simply air will lose slightly different amounts of energy. As a consequence, monoenergetic protons will not all stop at exactly the same depth in some material. This effect, called **range straggling**, means that Bragg peak will have some minimum width even if the incident beam has zero energy spread.

Scattering

This phenomenon is caused by the interaction of protons with the nuclei electromagnetic field. According to the Molière theory, a proton deflection caused by a single atomic nucleus is extremely small. So when the proton beam results to be deflected, after travelling in a slice of material, this deflection is the result of more deflections, which summing together give an angular deviation of the proton trajectory.

This kind of interaction of therapeutic particles with air and human tissue is often negligible for carbon ions, but it is of crucial importance for protons, which have a mass 12 times smaller.

For the clinical application, the lateral scattering of the beam is more important than the longitudinal. Because of possible range uncertainties, the treatment planning will avoid a beam directly stopping in front of a critical structure. Therefore, tumour volumes close to critical structures can only be irradiated with the beam passing by. How close the beam can get is consequently determined by the lateral scattering.

In addition, at the same way as for electrons, when a proton interacts with nuclear electric field it will be accelerated, causing the production of photon spectrum (**Bremsstrahlug phenomenon**). In case of proton beam, the photon emission due to this phenomenon has to be considered negligible from a clinical point of view, because the probability to generate a photon emission is directly proportional to the inverse of the particle mass squared, and consequently it results lower for protons than electrons.

The particle scattering is used in proton therapy to spread the pristine pencil beam in order to obtain a larger and homogeneous dose distribution, similar to that used with photons.

Nuclear interactions

In addition to electromagnetic interactions (stopping and multiple scattering), protons and carbon ions experience nuclear interactions.

Three types of nuclear interactions can occur:

- *Elastic*: a reaction in which the incident particle scatters of the target nucleus, with the total kinetic energy being conserved (the initial state both of particle and nucleus remain unchanged);

- *Nonelastic*: in this case the kinetic energy is not conserved. For instance, the target nucleus may be excited into a higher quantum state, or a particle transfer reaction may occur;

- *Inelastic*: a kind of particular nonelastic reaction in which the kinematic energy is not conserved but the final nucleus is the same as the bombarded one.

In particular, considering non elastic nuclear interactions, a proton can react with the bombarded nucleus causing its fragmentation in one or more of its parts. Thus will be created **secondary particles** (protons, neutrons, heavy ions, γ rays), which are different from the primary ones that have suffered only electromagnetic interactions. Secondary particles tend to have a lower energy than the primary ones but, at the same time, greater deflection angles. As a consequence there is a dose disposition in the proximity of the target.

Summarising, nuclear interactions are responsible of the following consequences:

- primary protons number reduction;
- production of secondary protons able to travel for high distances in the matter and (with a lower energy) to create a lateral scattering with a little dose propagation around the target;
- ionizing fragments creation that increase the biological efficiency in the proximity of the target;
- neutrons creation which travel along the patient body without other interactions but producing a dose contribution.

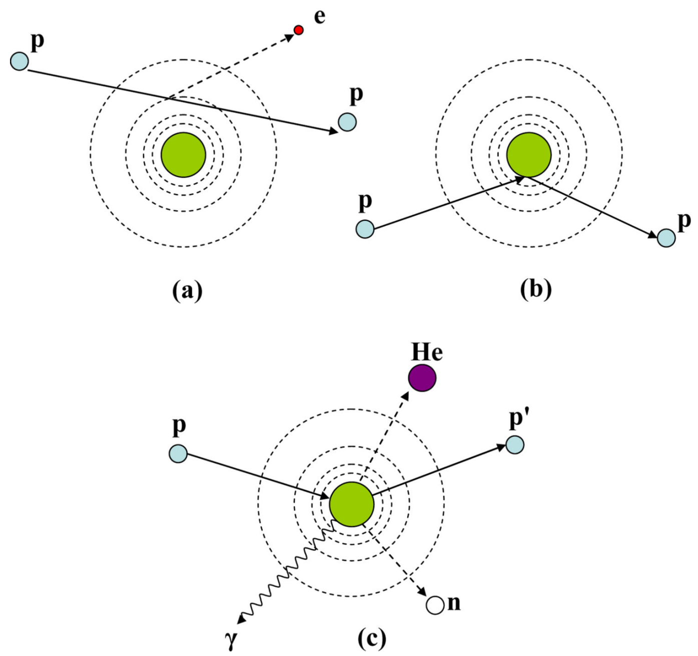


Figure 2.4: Schematic illustration of proton interaction mechanisms: (a) energy loss via Coulombic interactions, (b) deflection of proton trajectory by repulsive Coulomb scattering with nucleus, (c) removal of primary proton and creation of secondary particles via non-elastic nuclear interaction. (p: proton, e: electron, n: neutron, He: Helium, γ: gamma rays)[**9**].

Physical Dose

The physical absorbed dose at some point of interest in a radiation field is the energy absorbed per unit target mass:

$$D \equiv \frac{dE}{dm} \qquad [1Gy \equiv 1\frac{J}{kg}] \tag{2.3}$$

It is important to observe that the energy absorbed by the target material may be less than the energy lost. As said before, protons have nuclear interactions that produce neutrons and others secondary particles. Neutrons (being neutral), instead of depositing their energy in the material, go away and usually stop in the shield walls of the radiation therapy facility. This results in a lost energy about a few percent.

The following equation relates the physical absorbed dose to the fluence and stopping power:

$$D \equiv \Phi S \tag{2.4}$$

where Φ stands for the number of particles passing trough a sphere in the time unit and S is the mass stopping power already defined.

Typical value for stopping power is $5MeV/(g/cm^2)$ and a therapeutic physical dose per fraction is in the order of $1Gy$; on the basis of these values, fluence results to be of the order of 10^9 protons per cm^2.

Charged particles offer several additional advantages compared with photons, not only for their interaction with matter but also for radiobiological properties.

Biological effects are related to the absorbed dose, defined before; however the absorbed dose alone is not sufficient to estimate the biological effects. Physical dose is accepted as standard because it is relatively easy to define and measure.

Biological effectiveness is quantified by using **RBE** (relative biological effectiveness), defined as the ratio of a known absorbed dose of x-radiation during irradiation with a reference field, to the absorbed dose of interested radiation (R) to produce the same amount of biological damage.

$$RBE(R) = \frac{D_x}{D_R} \tag{2.5}$$

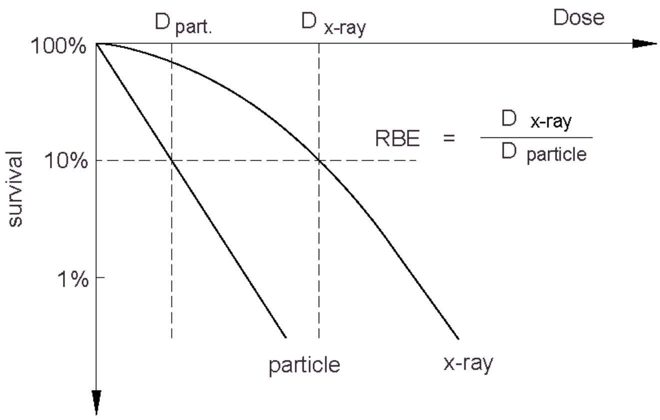


Figure 2.5: Survival patterns for the reference beam (X-ray) and and charged particle one compared at the same amount of biological damage equal to 10% [**11**]

As it is possible to observe in Figure 2.5, the fraction of cells surviving a particular dose of x-irradiation is larger than the fraction of cells surviving the same dose of charged particles.

The RBE of protons is around 1.1, that means their biological effect for a given physical dose is not greatly different from photons. That contrasts with the RBE of other heavier particles, for instance carbon ions (~ 2.5) or neutrons (~ 10 to 20).

The biological effects depend on many factors: the particular form of radiations, LET (Linear Energy Transfer) which represents the amount of energy given by particle to the travelling medium, the amount of dose, the target tissue type, the fraction of an organ exposed, etc.

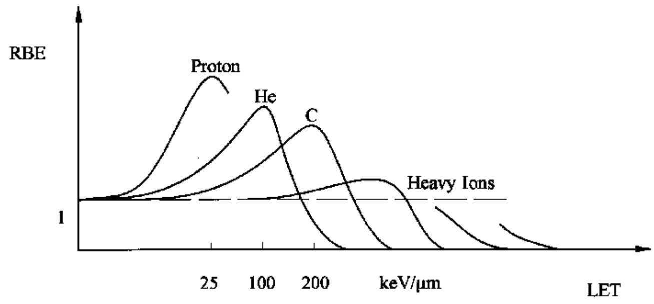


Figure 2.6: RBE measurements performed using different ions and a wide range of LET values.

Figure 2.6 shows the characteristic relation between the change of LET and the RBE of a specific particle beam.

For protons, for example, the biological effect increases throughout the Bragg peak, reaching a maximum, and, as the velocity decreases and LET increases, the killing efficiency per unit dose decreases.

Biologically effective dose has its own units: $Sieverts(Sv)$, which has the same dimensions as the Gray (J/kg), but it measures a different quantity. Thus 1 Gy of carbon ions equals 2.5 Sv. Because of their increased relative biological effectiveness (RBE) ions heavier than protons are called heavy ions in radiobiology, although they are light ions compared to the terminology used in nuclear physics.

Different radiations show different spatial distribution of absorbed energy at the microscopic level: the main reason for a high RBE is the increase in ionization density in the individual tracks of the heavy particles, where DNA damage becomes clustered and therefore more difficult to repair. For example, when Double-strand breaks occur, the damage is very difficult to repair, because both strands in the double helix are severed. This effect is particularly hazardous to the cell, because they can lead to genome rearrangements. The damage, or the density of the produced ionizations and the radius of the track, depends also on the charge and velocity of the particles.

2.2 Hadron therapy equipment components

A hadron therapy facility consists of three main equipment components:

1. a particles accelerator equipped with an energy selection system;

2. a beam transportation system;

3. a beam delivery system, which may include gantry, beam nozzle, volume-tracking and beam-gating device, positioning and immobilization system.

2.2.1 Particles accelerator

The first step in generating a beam, suitable in hadron therapy, is to have a source of protons or other ions, which can be then accelerated to energies sufficient for treatment. For example, this can be done starting from hydrogen atoms and separating their electrons from protons by using an electric field. Once proton have been generated, they must be accelerated in order to reach the distal edge of a tumor.

Particle accelerators use an electrical field to accelerate photons and a magnetic field to steer the charged particles. The physical process of acceleration is described with the **Lorentz force laws**: $F = qE$ and $F = qvxB$. They show that an electric field E increases the energy of a particle with charge q while a magnetic field B defines their trajectory. In order to accelerate charged particles in a compact machine, it is efficient to reuse the electric one. This is the working principle in circular machines, such as cyclotron or synchrotron, in which the same electric field is used to repeatedly steer the particle beam.

In photon therapy linear accelerators are commonly used. For what concerns hadron therapy using a linear accelerator (LINAC) is more complicated, because it does not produce sufficient electric field to build a compact system. Nowadays the most common and diffused are circular and cyclic accelerators like cyclotrons, isochronous cyclotrons, synchrocyclotrons and synchrotrons. The first and the latter are the most widespread in hadron therapy.

Accelerators requirements

The overall goal of an accelerator for therapy with protons and heavier ions is to produce a beam that penetrates 26-38 cm in human tissue. Translated in particle energy, incident protons of 215 MeV are required on the patient surface and the beam emerging from the accelerator must have an energy between 200-250 MeV (depending on the efficiency of the delivery system in use). For carbon ions the beam energy at the accelerator exit must be between 300-400 MeV/u.

In addition the beam must have sufficient intensity to allow therapeutic doses to be delivered within few minutes. Typically beam intensities of between 1.8 x 1011 and 3.6 x 1011 particles per minute are required if doses of 2 Gy min^{-1} are delivered uniformly to target volumes of one litre. Beam intensities too high are not easy to control, and to achieve reasonable dose rates and treat patient safely, the intensity range should be between 10-20 nA.

Cyclotron

In the cyclotron, a high-frequency alternating voltage applied across the gap between the two halves ("dees" electrodes) alternately attracts and repels charged particles. A magnetic dipole field covers both the "dees". The perpendicular magnetic field (passing vertically through the "dees" electrodes), combined with the increasing energy of the particles, forces the particles to travel in a spiral path.

With no change in energy the charged particles in a magnetic field will follow a circular path. In the cyclotron, energy is applied to the particles as they cross the gap between the electrodes. The polarity of the electric field is switched at the exact time when the beam reaches the gap to ensure acceleration of the beam and not deceleration.

Cyclotrons for hadron therapy have relatively few adjustable parameters, and produce continuous wave beams.

The continuous time structure, the intensity stability, the relative simplicity together with the limited dimensions compared with synchrotron are the main advantages of cyclotron. On the other hand the fixed energy together with particle type availability are the main drawbacks.

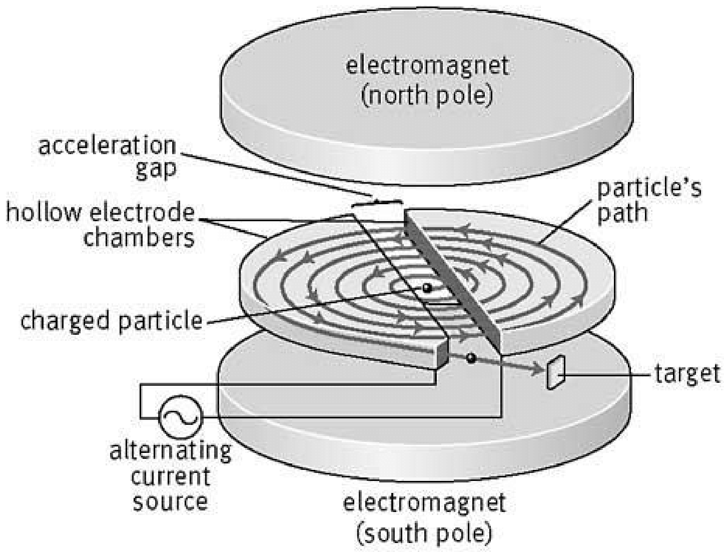


Figure 2.7: Schematic diagram of a cyclotron.[**15**]

Synchrotron

While a cyclotron uses a constant magnetic field and a constant frequency applied electric field, both of these fields are varied in the synchrotron and one is varied in the synchrocyclotron. By increasing these parameters appropriately as the particles gain energy, their path can be held constant as they are accelerated.

The beam is injected from outside the synchrotron by, typically, a LINAC with an energy of 3 to 7 MeV. To achieve acceleration, the magnetic field and the frequency of the accelerating electric field must be increased in synchrony. Because of the finite time required to cycle the magnets, synchrotron produces a pulsed output.

When the beam reaches the desired energy it is extracted and directed to the treatment room through the beam transport system.

Using a synchrotron allows to obtain a range of energies, since the beam extraction operations do not depend of the machine characteristics but on the switching on of a magnet.

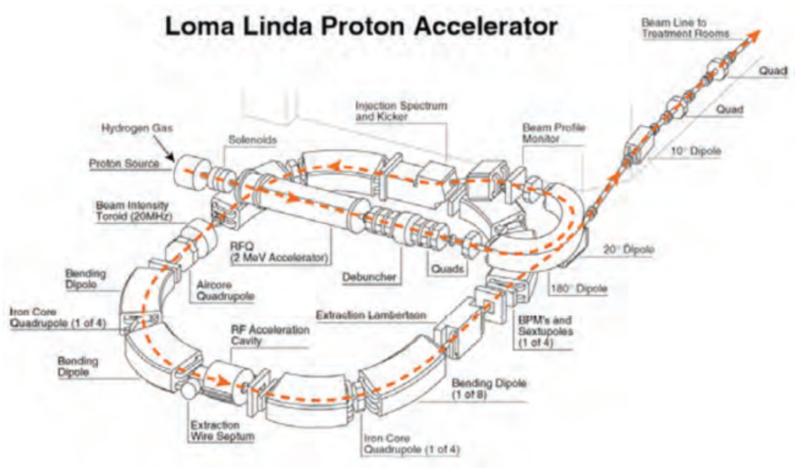


Figure 2.8: Schematic of synchrotron used in Loma Linda (California - USA) centre. [**12**]

Linear accelerator

A linear accelerator is able to produce particles beam travelling on a linear path and accelerated by electromagnetic field, which can be static or variable. Typically it is done using different resonant cavities in sequence powered by radio frequency sources.

Linear accelerators can be of different types, depending on the technologies used for accelerating particles. The technology employed in Itel project involves two kinds of linear accelerator:

- **Side Coupled Tube Linac (SCDTL)**, whose structure is constituted by a number of accelerating structures DTL (Drift Tube Linac), called tanks, with a fixed resonant frequency corresponding to the accelerating radio frequency, coupled each other by cavities (Figure 2.9). Inside these cavities are housed permanent magnets, called PMQ (Permanent Magnets Quadrupole), whose task is to direct the beam. Inside these structures it is necessary to use coolant because the resonance frequency depends on the working temperature, which tends to increase for high beam energy.

- **Side Coupled Linac (SCL)** is a linear accelerating structure using stationary wave radio frequency. The working principle is based on accelerating cells operating in π mode (the electromagnetic field is in phase opposition with neighbours), coupled by not excited cells (Figure 2.10). The beam is directed by grouping these cells in tanks; among them PMQs are used. The energy goes from one tank to the other thanks to a bridge coupler.

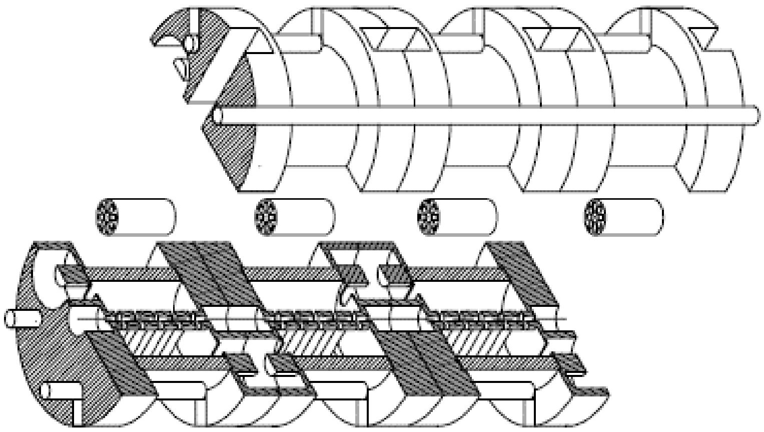


Figure 2.9: Longitudinal section of three cavities of a SCDTL LINAC.[**14**]

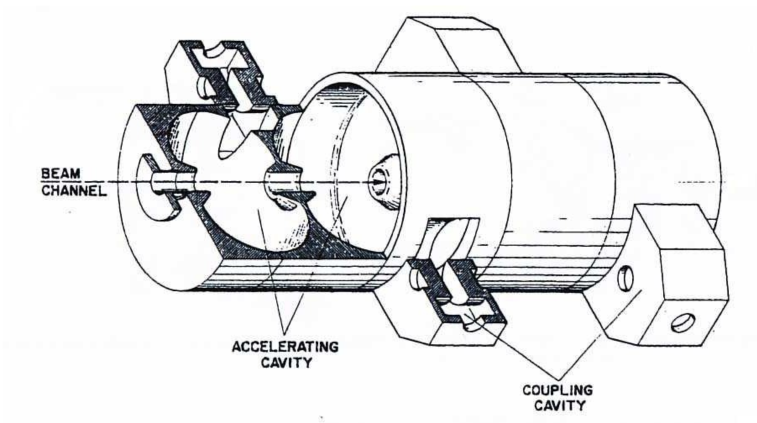


Figure 2.10: Schematic representation of a SCL LINAC.[**14**]

2.2.2 Beam delivery system

The Beam Delivery System (BDS) is the last part of the therapy machine before the patient is transcended by the beam.

Usually the BDS is characterized by:

- A device to shape the pristine accelerator beam to the required clinical treatment beam;

- Monitors to control the beam parameters;

- Instruments to drive the beam.

Some authors include in the BDS also the Treatment Planning System and the Electronic Medical Record, as they are crucial elements in delivery operations.

As said before, BDS may include also gantry, a volume-tracking and beam gating devices, the patient positioning and immobilization system.

2.2.3 Beam delivery techniques

A beam of particles coming from the accelerator is well described by a 2D Gaussian function calculated as a function of the particle type, energy and of the kind and depth of the material crossed from the vacuum exit window.

The starting transversal and longitudinal dimensions are as small as possible to reduce the cost of the beam transport; the typical FWHM (Full Wave Half Maximum) is less than 10 mm and is smaller than typical tumor volume (between 1 cm and 20 cm along x, y and z). The beam coming from the accelerator has a fixed energy and direction and hence, without corrections, it cannot cover any kind of volume. Tumors can have very irregular shapes and can be located from few millimetres to 30 centimetres in depth from the patient skin and close to critical organs, and this is different from one patient to another one.

Therefore it is needed to modulate the beam in order to irradiate uniformly the whole tumor volume. This volume is composed by particular thickness and surface, which are located in parallel and orthogonal planes with respect to the beam direction, respectively. Then the particle beam has to be modulated in energy depending on tumor thickness, and also modulated transversally depending on its shape.

Energy modulation

Modulation in energy can be done through the use of passive or active systems. The first ones are used when the beam has a fixed energy; in this case the beam energy is modulated by using an absorber device composed by multiple carbon block. These elements slow particles until they reach the desired energy. Modifying thickness of carbon blocks it is possible to regulate energy. This kind of modulation has drawbacks:

- The greater the energy variation is the more will be the beam energy spread. In order to avoid a polychromatic beam, two magnetic dipoles curve the beam in order to allow only particles with right energy to follow the imposed trajectory.

- Beam also worsens in traversal direction, because of the lateral scattering phenomenon (already meet in section 1.1 of this chapter).

Modulating beam energy by using active devices allows to avoid the above drawbacks. In this case the energy is modulated directly inside the accelerator varying the power supply of generators. Just before the patient the beam is spread out to cover the overall target volume. The methods used to spread out the beam can be passive or dynamic.

Dose distribution in transversal direction

As said before, it is necessary to enlarge the beam in order to hit the whole tumor volume. Also in this case are available two different methods: passive or active.

Passive systems produce the transversal beam enlargement by using two scattering stages as shown in Figure 2.11; the first one is uniform and produces a Gaussian distribution increasing the beam width and modulating the energy, while this distribution is homogenized by a second scatter. In order to occlude the mid and the outer part of Gaussian distribution, collimator are used to stop unwanted radiations. Since tumor volumes have not regular shapes, it is needed to use a personalized compensator to get a further dose distribution modulation. Also in this case there are drawbacks, as previously discussed.

Active systems allow to avoid problems described for passive ones. The procedure consists in dividing the volume in a number of infinitesimal volumes, called **voxel**, and each of these elements has to be irradiated by a proton pencil beam. Since the pencil beam must reach each voxel, it is modulated in energy and direct to the right position by a couple of magnetic dipoles, which allows beam deflections.

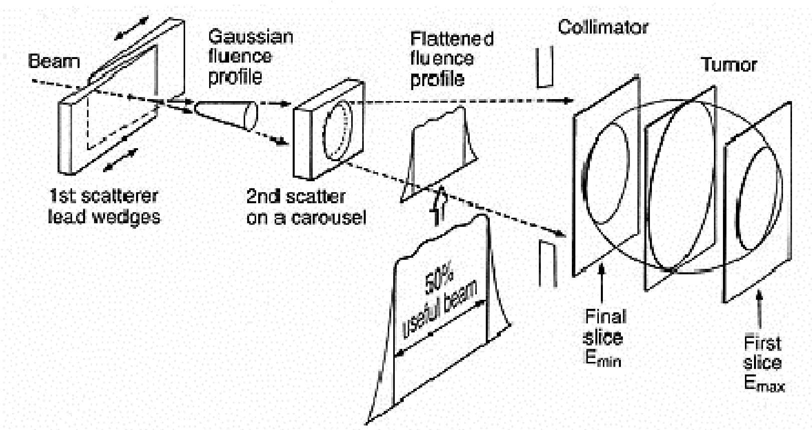


Figure 2.11: Passive beam shaping system to modulate transversally the shape of particle beam.[**16**]

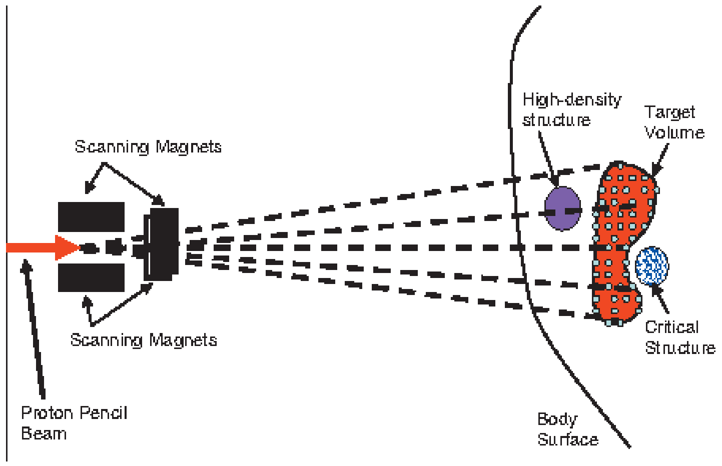


Figure 2.12: Diagram of a typical pencil beam scanning system. Two sets of scanning magnets scan the beam in a 2D pattern: the beam range is adjusted by changing the beam energy entering the nozzle. In the usual case, all spots for the deepest range are scanned, the energy is changed, and all spots with the new range are scanned, etc., until the entire target volume has been scanned.[**17**]

Breathing movements

Another element which has to be taken in account in beam delivery procedure is the following: the target may be close to moving organs as a consequence of patient breathing movements. In this way also the target is not fixed and it should cause a wrong dose delivery.

Three are the possible techniques to overcome this problem:

- Respiratory Gating: beam delivery is synchronized with breathing movements in order to reduce as much as possible the possible errors in dose distribution;
- Tumor is irradiated using different directions for beam entering the body; in this way the movements cause a less overdose of radiations;
- Movements are detected by a device which in real time describes the 3D position of target. These informations are used by delivery system to modulate the energy and direction of particle beam.

Chapter 3

The ERHA Project

The present thesis work is part of the **ERHA Project (Enhanced Radiotherapy with HAdrons)**, which is an innovative project patent by ITEL Telecomunicazioni s.r.l. in the field of proton therapy.

The main idea is to find a new system available for proton therapy treatments, having advantages with respect to the actual systems by using:

- Proton linear accelerator (LINAC);
- Robotised platform for patient positioning;
- A software to analyze and develop treatment plans.

Nowadays all available options for particles acceleration are investigated and used. The acceleration system, whichever it is, integrated with beam transporting lines and treatment rooms form a typical proton therapy centre. Usually a Ion Beam Therapy centre is equipped with a gantry structure, used in order to modify the direction of the beam entering in the patient body (Figure 3.1). What is easily observable is that, apart from the space needed for particle accelerator, also the gantry structure, which is huge and complex in terms of components needed to direct beams, takes up a big space. This is one of the main issues to investigate in other beam delivery techniques, in order to save space and reduce the risk that something goes wrong (mostly inside electrical components used in beam deflection).

Therefore in ERHA project the purpose is to use a modular and compact linear accelerator rather than the most common machines, such as circular accelerators, and a robotised patient positioning system, which works with fixed beam direction inside treatment rooms.

As said before, actually in ITEL Telecomunicazioni s.r.l. the R&D group is working in developing the LINAC (Linear Accelerator) in order to reach the beam intensity requested by proton beam treatments. ERHA accelerator guarantees better performances in terms of beam optical quality and quantity of radiation emitted in the room. Particles, coming from the injector, are accelerated across the line thanks to low and high energy cavities until they reach the energy useful for treatment (Figure 3.2). The structure shall consist of different accelerating stages (see section 2.2.1):

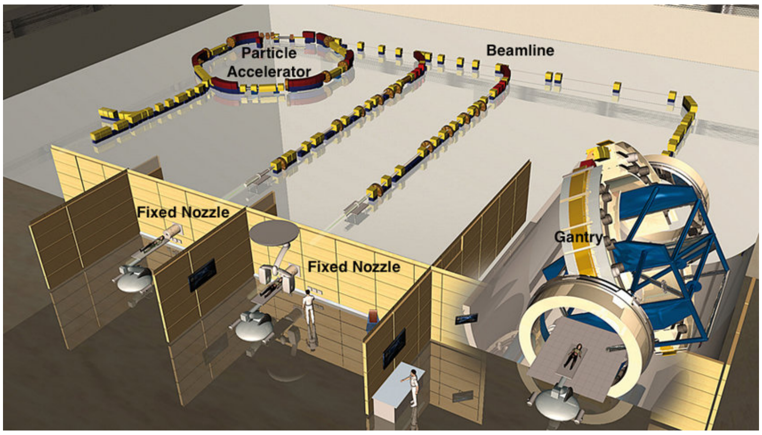


Figure 3.1: Plant of three treatment rooms in the Heidelberg Ion-Beam Therapy Center; the first treatment room, on the right, uses a massive gantry that can rotate and direct the beams to the patient body. (source: www.phys.org)

1. **An injector**, which produces protons and accelerates them until energy of 4 MeV;
2. **4 modules SCDT**, which reach energy until 27 MeV;
3. **16 modules SCL**, which allow to reach energy up to 150 MeV.

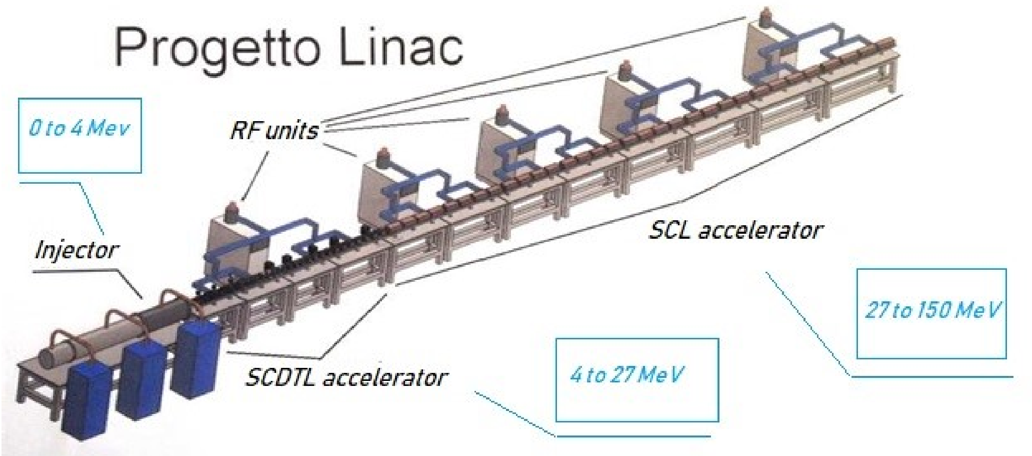


Figure 3.2: ERHA LINAC prototype (source: Itel R&D department)

The whole structure would have to be 24 meters long once completed. Actually the ERHA team is working on a first part of the machine (injector and first stages of acceleration) as it is possible to observe in Figures 3.3 and 3.4. Each LINAC is equipped with RF units in order to use radio frequency waves to accelerate particles inside cavities. Intense and pulsed electromagnetic fields are used inside accelerating cavities whose intensity is around 15-20 MeV/m.

The beam structure and the control systems related to each LINAC allow to quickly modify energy and current of beam so that the machine can be used for **IMPT (Intensity Modulated Proton Therapy)** treatments.

Beam delivery system will be equipped with magnets, which have high dynamic range and allow a 2D scanning on a matrix of $256x256$ points (considering a beam thickness of about 2mm, it is possible to cover a $50cmx50cm$ surface). This system together with the energy modulation implements a high velocity 3D active scanning technique (see Section 2.2.3) in order to minimize radiations on healthy tissues next to target volume.

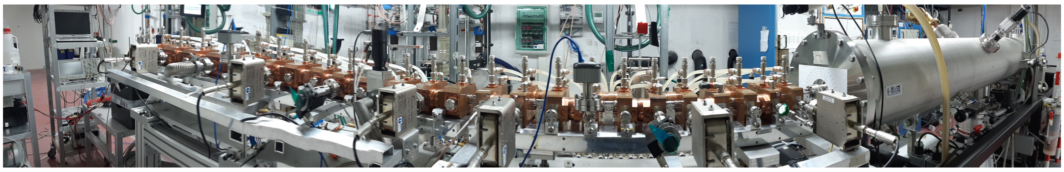


Figure 3.3: Current setup of ERAH LINAC: particles injector coupled with first accelerating modules. Image does not show the whole machine dimensions since it is still in construction. (source: Itel R&D department)

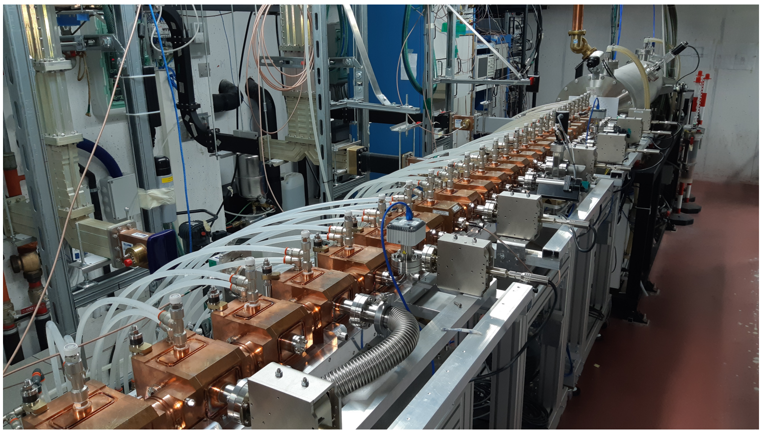


Figure 3.4: Current setup of ERAH LINAC: a view of accelerating cavities excited by radio frequency waves. (source: Itel R&D department)

3.1 Introduction to RPPS project

As it was already discussed in the previous chapter, an important element in hadron therapy facilities consists in patient positioning system.

The aim of this work is to investigate the possibility to have a robot platform able to align the treatment's target with a beam coming from the particle accelerator. In particular the system **4KAOS (For Kinematic Automated Operating System)** is intended for fixed beam treatments and the treatment positions are provided by an external known system: the **Treatment Planning System (TPS)**.

The main idea is to move the treatment couch holding patient with the help of an anthropomorphic robot. Thanks to the robot degrees of freedom it should be possible to align the target to the fixed beam achieving positions useful for proton therapy treatments. This kind of RPPS differs from the commonly used system, such as Gantry, because it uses a fixed proton beam. In fact, systems based on gantry architecture have some disadvantages:

- the cost is high;
- a huge structure is needed because of their dimensions;
- they are not so much flexible;
- there is no possibility to track movements due to breathing.

Taking into account all these aspects, the purpose is to find an alternative solution, able to minimize the previous disadvantages. The first result is obtained not moving the proton beam but moving the treatment couch, thus obtaining a much more compact and less expansive system.

The main performances, expected to be reached, of the presented system are:

1. High precision in positioning the target with respect to the accelerator isocenter (defined as the point 1 meter far from the exiting point of the beam): **typically 1 mm**
2. Repeatability of treatment positions with respect to the isocenter in the order of **0.5 mm**
3. Moving treatment's isocenter (target tumor) in all of the points belonging to a **50 cm diameter sphere**.

Together with these innovations, which could overcome disadvantages found in current applications, the ERHA system also includes a new strength: using a second anthropomorphic manipulator in order to perform a Cone Beam CT in treatment position. This innovation is intended to have a better positioning between the accelerator isocenter and the patient isocenter, and represents a new skill for this kind of system since, nowadays, only few centres are able to provide a CT in treatment position. [**6**] An implemented image software, which allows to compare the patient CT, previously achieved and used for treatment plan definition, and the one made in treatment position, will be used; the comparison of patient CT highlights if there are some changes inside the patient body, and if it is necessary to modify the patient alignment with respect to the particle beam.

In conclusion what is expected is a system in which:

- one seven joints anthropomorphic robot is able to hold a patient couch so that it can translate and rotate with respect to a fixed point (beam source) both to achieve positions requested by the treatment plan and to perform movements to correct the alignment of isocenter or compensate breathing movements;

- a second six joints anthropomorphic robot, which allows to move the cone beam CT technology and to perform it in treatment position, once the first robot has already adjusted the patient couch.

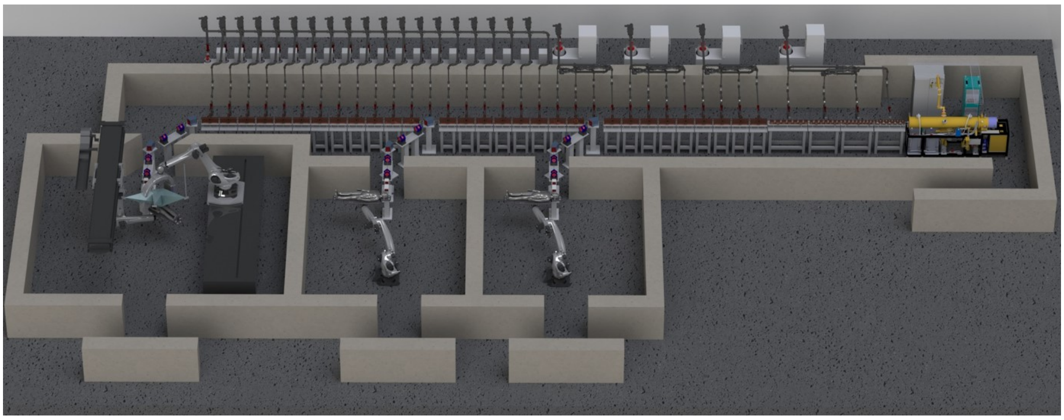


Figure 3.5: Schematic of proposal design of ERHA project. In the last treatment room (left side) is presented the prototype of RPPS described before.

3.2 RPPS project requirements

Since it is a system which has to interact with humans (patient, technical staff in treatment centre, etc.), it is necessary to address some safety requirements.

Calibration

The whole system is constituted by different components (robot, cameras, etc.), each of them having an internal reference frame from which depend the measures and control parameters relative to the particular system. As a consequence, in order to obtain cooperation between all the elements needed in the system, a calibration procedure must be carried out.

The same target could have different coordinates and orientations depending on the reference frame that is considered. It is evident by experimental tests that also small errors in positioning movements during calibration operations result in bigger misalignments between the robot end the effector and desired position. These misalignments affect both robot precision and safety of the performed movements.

Simulation

The configuration which will be taken in account, composed of two robots and linear external units, has its mechanical and geometrical limits. These include not only points that robots can not reach due to hardware limits of their joints, but also elements in the room with which the robot can collide.

In order to prevent unwanted behaviour (such as singularities which result in not predictable robot movements) it was thought to add a simulation software in which, by solving the inverse robot kinematics, the robot trajectory can be reconstructed. From simulations can be predict the robot behaviour, the points it will reach and, eventually, strange movements, such as the ones due to singularities situations that can compromise the safety of whole system.

Naturally simulation software must be able to communicate in real time with the robots and other components in order to provide to the operator all the needed elements for safety operations.

Motion

Once the trajectory has been calculated through simulation in order to reach the desired point without risks for patient or operators or the system itself, the system must elaborate the trajectory and send active command to robots. It is necessary to take into account all the hardware and software limits for each robot, the presence of a linear external unit, the fact that the two robots need to communicate each other to synchronize their motion.

Strictly related to robot motion, is the safety motion requirement. Since the system works with humans, must be taken into account their motion, so that robot movements should not be dangerous for persons present in the room; in this way specific areas are configured as working space or violated one and robot velocity is intentionally kept low.

Vision

In order to ensure high precision in all positioning operations, the positions of the machines and the position of patient on the couch should be measured by an external system. In this way, using a feedback signal coming from this external system, a wrong position could be corrected.

For this reason two different kinds of system are implemented:

1. A **Laser Tracker** is used to control the couch position inside the treatment room. Using some reflectors positioned on the couch it is possible to measure the position of the couch (and consequentially of robots) in the available space
2. **3D stereo cameras system** able to monitor the patient body and relate it to the couch in order to take into account all the possible misalignments and movements due to breathing.

This part of ERHA system will not be analysed in this thesis since it is part of collaboration between ITEL and Politecnico di Bari, which is studying the stereo cameras system.

Chapter 4

RPPS development

On the basis of the purposes and objectives discussed in the previous sections, the following work investigates the project reliability. As will be clarified subsequently, the analysis is based on the results coming from simulation tests and also tests on the real set-up developed in laboratory.

4.1 Specifications analysis

Before starting with the description of the different tests, a brief overview regarding project specifications will be now presented; it contains all the technical information about different components that will take part in the whole set-up. Note that, since the project is just in its initial stage, some components are not physically available but are just designed and simulated by prototypes.

4.1.1 KUKA Robots

ITEL already has a patented robot patient positioning system which should be improved to meet the current needs of proton therapy treatments. In the Mechatronic lab, are currently available two six-joints anthropomorphic KUKA robots (Figure 4.1) able to perform the tasks requested by the project and, at the same time, suitable to be used with particle beams utilized in hadron therapy from the point of view of constructing materials.

In particular, robots belong to the following series:

- KR 210 R3100 C ultra
- KR 210 R3100 ultra.

Both of them are equipped with an additional external linear axis. The only difference is that the first one utilizes a ceiling slide, so it is overturned with respect to the second one. The external additional axis allows to have a greater workspace available for robot movements. As it will be explained better, the linear external unit will be utilized only for

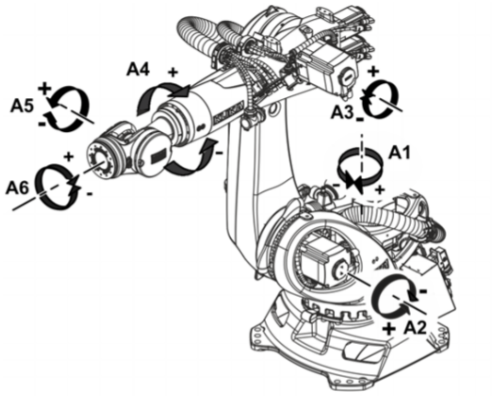


Figure 4.1: KR210 R3100 ultra C direction of rotation of the axes. [**10**]

one of the two robots (the one used for positioning task), while the second one will be kept fixed.

The robots are controlled by using KR C4 controllers via smartPAD. Additional add-on technology packages such as KUKA.RoboTeam 2.0, KUKA.SafeOperation 3.1 and KUKA.EthernetKRL 2.2, are implemented inside the robot controller in order to improve machine's skills and to satisfy all the requirements (Figure 4.2). KUKA.RoboTeam is intended, briefly, to enable communication and synchronization between two or more machines by allowing various complex operations; on the other hand KUKA.SafeOperation is used to configure all the safety parameters, such as software and hardware limits, working space, forbidden spaces, etc. facilitating human-machine interaction; finally KUKA.EthernetKRL through communication protocols allows the data exchange between robots and an external server.

Tables 4.1 and 4.2 report some technical information from KUKA datasheets. Observe that an interesting parameter for this specific project is the robot *Pose repeatability* as will be clarified in the following.

	KR 210 R3100 ultra	KR 210 R3100 ultra C
Maximum reach	3095 mm	3027mm
Rated payload	210 kg	210 kg
Rated supplementary load, rotating column / link arm / arm	0 kg / 0 kg / 50 kg	0 kg / 0 kg / 50 kg
Rated total load	260 kg	260 kg
Pose repeatability (ISO 9283)	**± 0.06 mm**	**± 0.06 mm**
Number of axes	6	6
Mounting position	Floor	Ceiling
Footprint	830 mm x 830 mm	830 mm x 830 mm
Weight	approx. 1154 kg	approx. 1154 kg
Controller	KR C4	KR C4

Table 4.1: Robots technical data. [**10**]

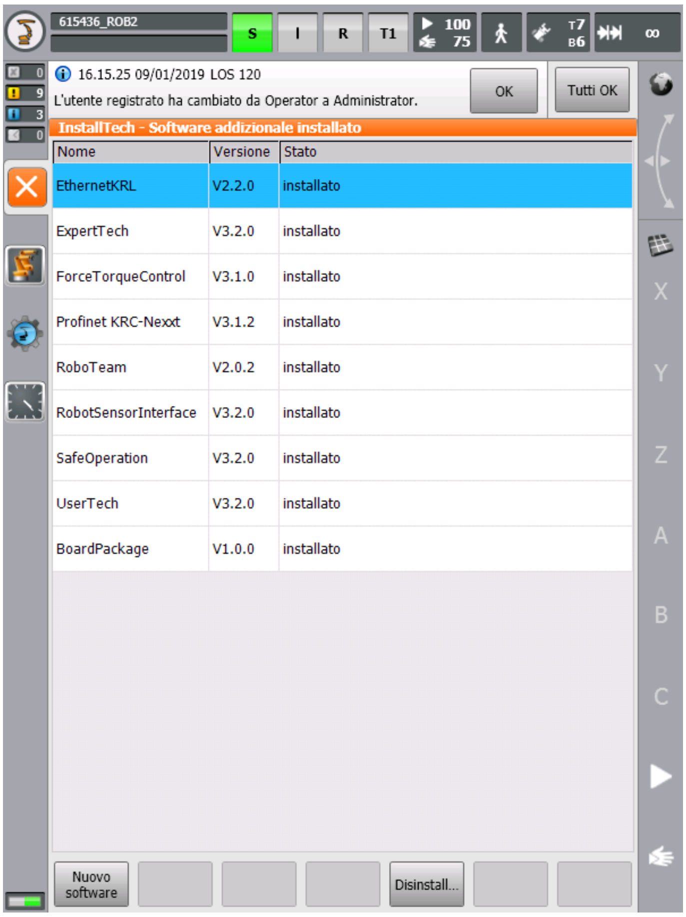


Figure 4.2: Additional packages installed on KR C4 controllers.

ROBO1

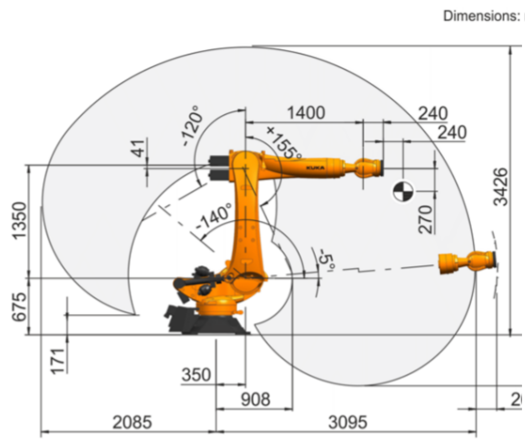
From now on, the robot KR 210 R3100 ultra, the one which will be used to move and operate the c-arm for CBCT, will be denoted as ROBO1. As already said, this robot is fixed on its linear external unit: this is just because, for the project's purposes, is not strictly relevant to move it along the external axis, being able to reach all the desired positions from a pre-defined point. In other words the reference frame attached to the root of the robot (ROBOROOT frame) has a fixed position with respect to the robot world frame.

ROBO2

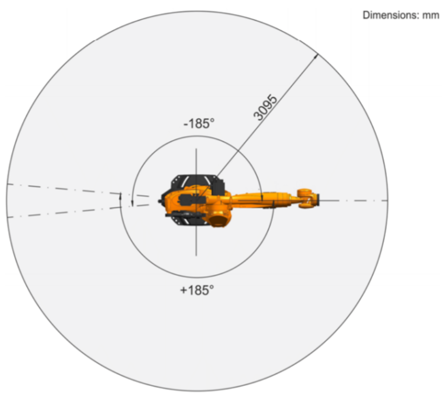
On the other hand, the KR 210 R3100 C ultra robot, used to accomplish positioning tasks, will be denoted as ROBO2. In this case it will be useful to move the robot along its external axis; the reason of that will be explained in the design validation section. Since the robot runs along the linear unit, its ROBOROOT is a moving reference frame with respect to the robot world reference frame, which coincides with the ROBOROOT frame when the displacement

	KR 210 R3100 ultra	KR 210 R3100 ultra C
Motion range		
A1	±185°	±185°
A2	-140 ° / -5 °	-140 ° / -19 °
A3	-120 ° / 155 °	-120 ° / 155 °
A4	±350 °	±350 °
A5	±122.5 °	±122.5 °
A6	±350 °	±350 °
Speed with rated payload		
A1	105 °/s	105 °/s
A2	101 °/s	101 °/s
A3	107 °/s	107 °/s
A4	136 °/s	136 °/s
A5	129 °/s	129 °/s
A6	206 °/s	206 °/s

Table 4.2: Robots axis data. [**10**]



(a) Side view



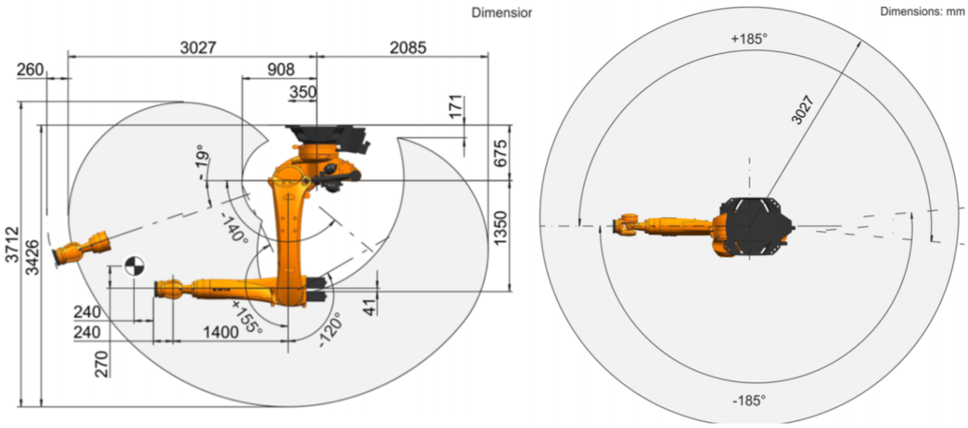
(b) Top view

Figure 4.3: KR 210 R3100 ultra working envelope. [**10**]

along the external unit is equal to zero.

4.1.2 kVue^{TM} One Proton Couch Top

The patient couch is hold by ROBO2 so it needs to use a component designed for this specific application. Itel is in contact with Qfix, a medical device company focused on solutions for radiotherapy patient positioning, which produces kVue^{TM} One Proton Couch Top specifically designed for use with robotic couch useful for our purposes.



(a) Side view

(b) Top view

Figure 4.4: KR 210 R3100 C ultra working envelope. [**10**]

Figure 4.5: $kVue^{TM}$ One Proton Couch Top designed by Qfix with $kVue^{TM}$ standard insert (source Qfix company).

The kVue Couchtop is a state-of-the-art radiotherapy couchtop optimized for the most recent advances in technology to guide patient from simulation through treatment. The entire cantilevered section of the kVue is radiolucent and meets IEC and FDA requirements for attenuation. The design provides excellent quality images for kilovoltage imaging using standard x-ray and cone beam CT, as well as portal imaging using MV energies; it is designed to minimize the dose to the patient's skin and maximize the dose directed to the tumor through the use of easily interchangeable, low attenuating $kVue^{TM}$ Inserts.

The producer has provided product's specifications and CAD files which will be used in the simulation environment to have a realistic representation of how the set-up would be. The product is not currently available to Itel, so that in the demo prototype will be used a couch with dimensions similar to the real ones.

4.1.3 CBCT C-arc

A crucial point for the designed system is the possibility to use volumetric image guidance, thanks to a Cone Beam CT system in order to improve precision and efficiency of beam delivery system. In CBCT technology, imaging is accomplished by rotating x-ray source and detector around a fixed fulcrum, which is usually the centre of region of interest. During rotations, sequential planar projection images of the field of view (FOV) are acquired and then overlapped in order to obtain a 3D representation.[**4**] Usually the acquisition process requires a complete rotation of the machine but, according to recent studies [**2**], a rotation of 180° plus the beam angle it would be sufficient for reconstruction of a full FOV. As a partner in ERHA project, a research group of Politecnico di Bari is developing the algorithm for 3D image reconstruction, which shall include also the case of non complete x-ray source rotation during 2D images acquisition.

Analysing the state of the art of CBCT systems [**6**] and according to purposes and requirements of the project, a robotic C-Arm plus a concentric rotating C-ring was designed (Figure 4.7). Initially it was considered a single C-Arm mounting CBCT technology, which should rotate thanks to the robot movements. In order to simplify the movements in the room and avoid possible limitations due to mechanical limits, the new idea is to use the robot movements only to place the C-Arm in imaging position and then perform the rotation rotating only the C-ring mounting x-ray source and image detector.

Considering projection images (on patient body) of $260x260mm^2$ that would be enough in order to detect all of the possible kinds of tumor, the FOV on panel detector results fixed to $420x420mm^2$. To be sure that this data are consistent with products present on the market, has been contacted a Imaging Components producer field, which proposed a panel detector for CBCT suitable whit previous requirements. Knowing FOV dimension and fixing the Source to Imager Distance (SID) to 1200mm (enough to allow C-Arm positioning over couch), by mathematical computations are defined (Figure 4.6):

- Focal Spot $\approx 20°$
- Source to Object Distance (SOD) = $764{,}7mm$
- Object to Detector Distance (ODD) = $435{,}3mm$.

Itel R&D group is still in contact with the imaging components producer regarding an x-ray source consistent with our design requirements.

Unfortunately during this work it was not possible to produce the component, since it was designed for our specific application and it is not a commercial product. In order to perform validation tests, has been realized a prototype of C-Arm (without rotating C-ring), which has SID and panel detector dimensions equal to the ones previous described. Rotating movements will be tested and, moving robot joints, analysed in order to demonstrate the reliability of the real set-up.

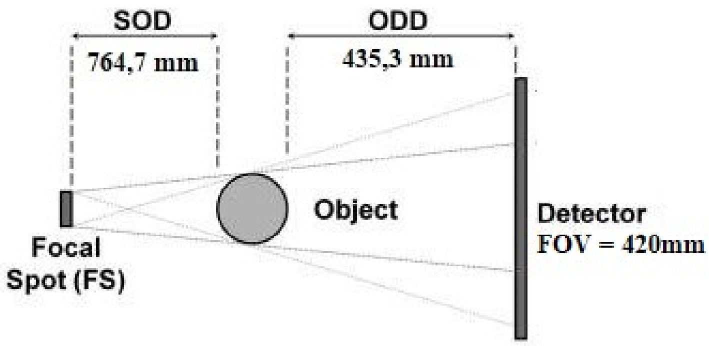
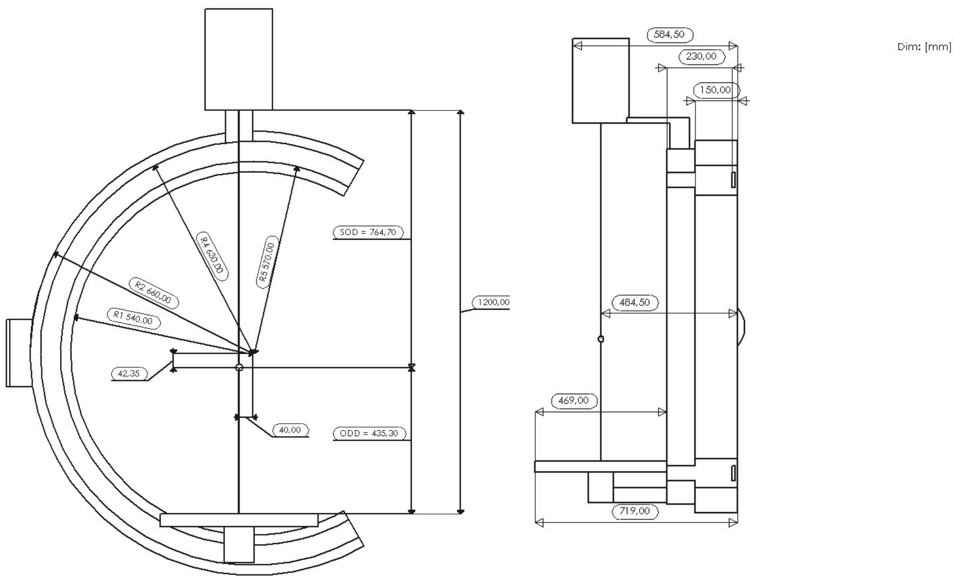


Figure 4.6: KR210 R3100 ultra C direction of rotation of the axes. [2]



(a) Front view

(b) Side view

Figure 4.7: Design of robot C-Arm mounting CBCT equipments.

4.2 Preliminary design and validation

First of all it was important to determine a treatment room possible configuration in which RPPS has to be employed. For the purpose to realize a system able to be employed in reality, a number of possible couch positions with respect to accelerator isocenter have to be assured. In addition the intended system, which consists of many mechanical components, needs to be well designed from the point of view of space occupation. Therefore the simulation environment KUKA SimPro, provided by KUKA, was used in the first stage.

The initial idea was to have a treatment room configuration like that in Figure 3.5, in which the beam nozzle is positioned in the back of the room. The first analysis of this proposed configuration showed that it was not valid in terms of space occupancy. For this analysis and for the following ones, the system capability to reach at least three specific treatment positions has been evaluated:

- **LOCATION A**: the couch orientation is parallel to the exiting direction of the particle beam (aligned with the base reference system x axis);
- **LOCATION B**: the couch is orthogonal to the exiting beam rotating in positive direction around the base z axis (rotation of +90° starting from Position A);
- **LOCATION C**: the couch is orthogonal to the exiting beam rotating in negative direction around the base z axis (rotation of −90° starting from Position A);

For all the three situations is set a **tratment distance of 65 cm** (distance of the target from proton beam exiting point); this value has been determined by ERHA team on the basis of accelerator characteristics. Of course points A, B and C are just a first requirement requested to the positioning platform, which must guarantee much more treatment points. Note that these locations have been selected on the basis of the fact that in proton therapy are commonly treated brain tumours, head and neck cancers, pelvis and abdomen sites.

As result of first simulation, the configuration initially proposed showed some problem mainly in robot positioning tasks; the available space was not enough to make possible robot cooperation and synchronous movements.

So as a consequence of these results, a new configuration was found (Figure 4.8). This time the beam nozzle is in front of the positioning robot so to make easier couch positioning. In order to perform all the robot movements, reference frames are defined for each moving

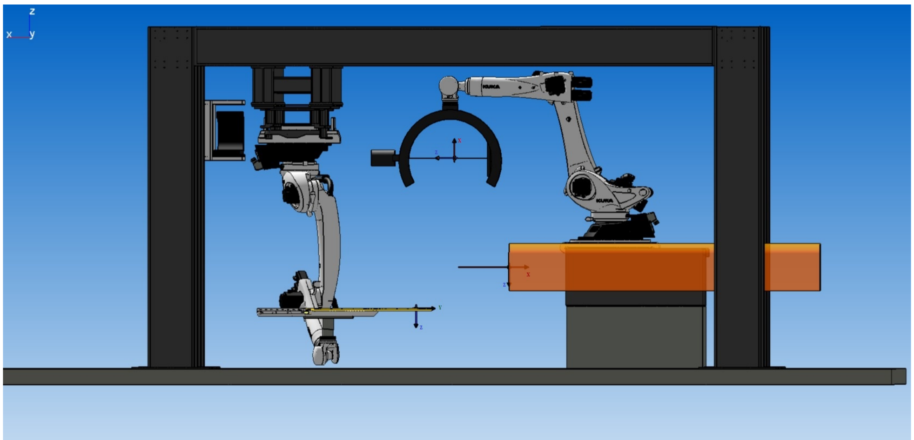


Figure 4.8: Load position of new configuration proposed for the treatment room in which RPPS platform is employed. In orange the nozzle from which the particles beam enters the room and in red a simulated proton pencil beam.

components, as shown in Figure 4.9. The reference frame (RF) attached to the beam nozzle has its origin in the point from which the beam comes out, the x axis is in the same direction of the exiting beam but in opposite verse, the y axis is horizontal and orthogonal to the beam direction, the z axis is set according to the hand-right rule. From a programming point of view, the reference frame attached to the beam nozzle is also considered as a new *BASE REFERENCE SYSTEM* for the robots, so that the TCP reference frames (located on the couch surface and imaging point of CBCT, respectively, for ROBO1 and ROBO2) are identified in the space trough translations and rotations with respect to base RF.

Here there is one of main advantages in using computed tomography in treatment positions, i.e., to have volumetric image guidance technique. As said in Section 3.1, nowadays only few centres can perform imaging of target in treatment positions. Usually this is done out of the position in which the target will be aligned to the particle beam, and external components (such as portable O-Arm) are used. Of course in using components external to the system the main difficulty is to relate reference frames of each components with the others, with the risk of having some misalignments. Our application is intended to make this process easier, since the robot TCP is always related to the beam reference frame and, as it will be demonstrated in the following, imaging acquisition in most of treatment positions is possible.

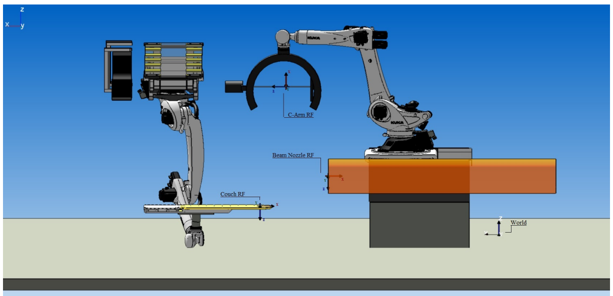
The simulation environment has been well designed (Figure 4.10) in order to be as close as possible to the real suite available in the laboratory. The only differences are:

- The beam nozzle is not present in the real set-up, since the particle accelerator is still in progress, so the beam exiting point will be simulated through a laser source;
- Because linear external unit for ROBO1 will not be used, and the robot will have a fixed position for its base (as already discussed), in the simulation environment the external axis is not present.

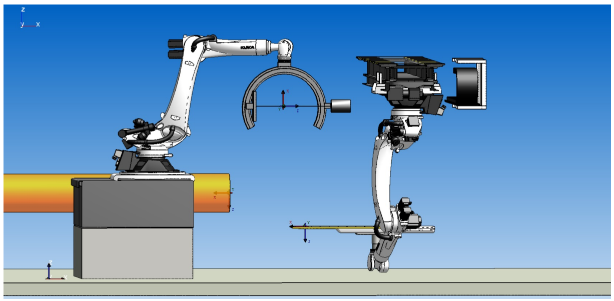
This new configuration allows to reach positions A, B and C with less and simpler movements of the positioning robot. Furthermore, once ROBO2 reaches the treatment position, the remaining space inside the room can be used by ROBO1 in order to perform imaging tasks without collide with other components (couch, ROBO2, beam nozzle). Imaging positions are mainly two; this is due to the fact that the C-Arm position is the same both for Position B and C. Observe that, during C-ring rotation, the C-Arm and the robotic arm are kept fix in order to increase high position accuracy for the X-ray tube and imager, except for small adjustments to compensate the flexibility of the structure. Position A is the easiest situation for the system, since the C-ring can perform a complete 360° rotation (Figure 4.11). For what concerns positions B and C there are limitations in the C-ring rotation due to the presence of the beam nozzle; that's why was estimated for the x-ray source a possible rotation of $\pm 140°$ around the y axis of the C-ring RF from the starting position, avoiding that it hits the beam nozzle. Theoretically this rotation would be sufficient in order to reconstruct a 3D computed tomography in accordance with the considerations discussed in Section 4.1.3.

4.3 Demo prototype

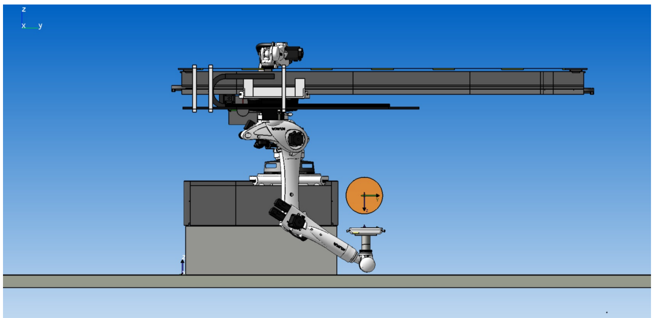
Once simulation gave satisfactory results, the attention has been focused on the real environment. As said before, this is only a demo prototype so the same elements (couch, C shaped



(a) Front view



(b) Rear view

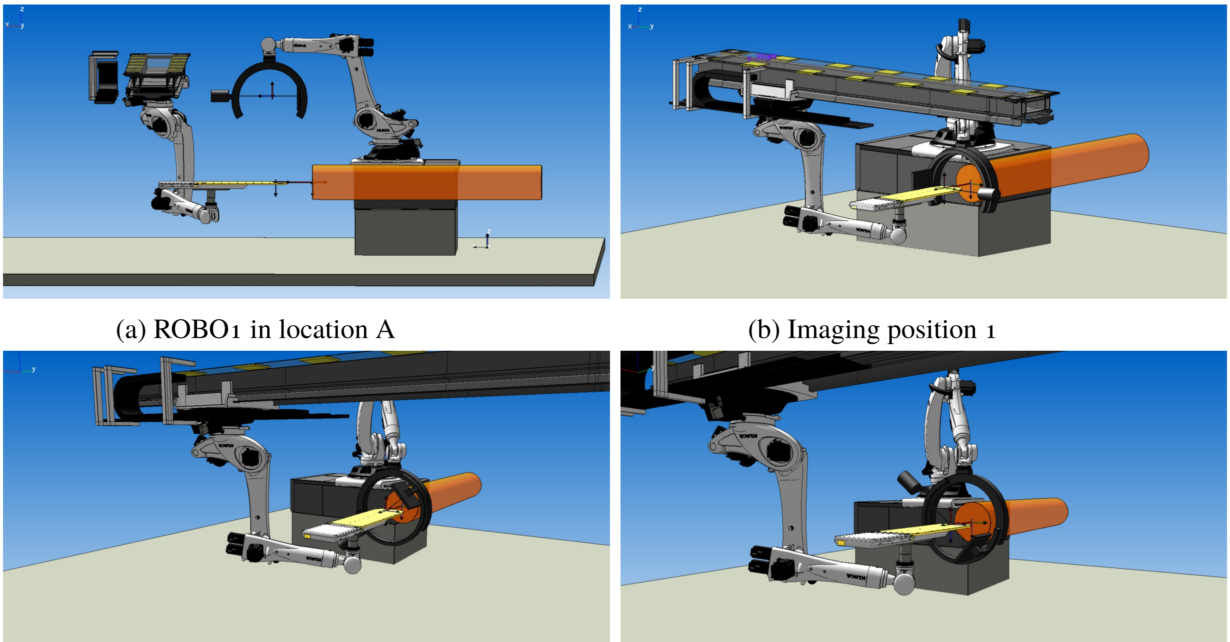


(c) Side view

Figure 4.9: Load position in simulating environment with highlighted reference frames for each component.

Figure 4.10: Load position of real suite in the ITEL Mechatronic laboratory.

arm, beam nozzle) are as well as possible simulated. The main objective is to demonstrate whether the designed configuration is a viable option in reality.



(a) ROBO1 in location A

(b) Imaging position 1

(c) CBCT in treatment position: x-ray source rotation of 140°

(d) CBCT in treatment position: x-ray source rotation of −140°

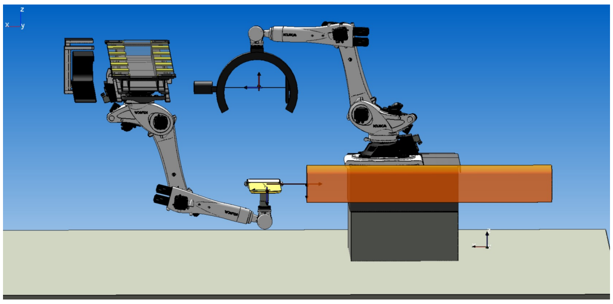
Figure 4.11: Treatment in point A. Target is ideally located on the couch surface where theoretically would be the head of patient.

Mechanical performances of the positioning system are measured according to what has done in the simulation stage. In particular has been measured the capability of reaching points A, B and C without critical movements for the patient, the repeatability of robotic arm movements, the synchronization between the two robots positioning, and the collision detection.

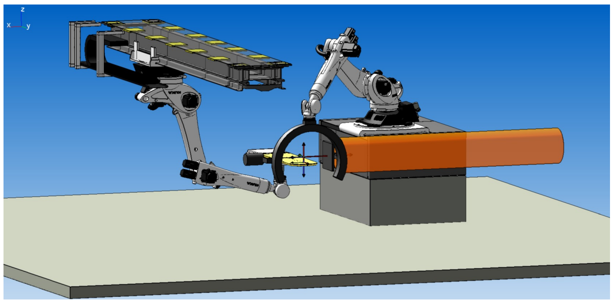
Treatment positions

Like for the simulation environment, also for the real case reference frames have been defined for each moving component. In particular for each robot a new tool has been defined (couch, C-Arm) thanks to the tool calibration method inserting CAD data of the two components. The base calibration is done fixing numerically, in the space, a base reference frame equal for both robots in the exiting beam point derived from the simulation software. From now on, it will be possible to control the robots referring their flange or tools translation and rotation directly to this base reference frame.

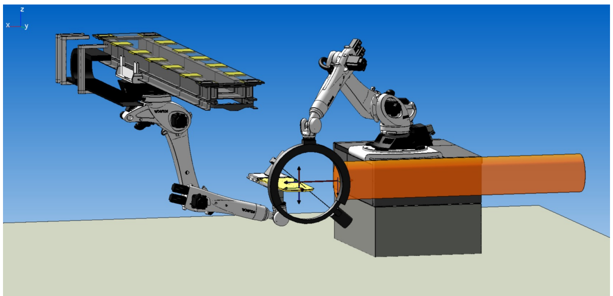
Positioning tests are performed by writing a simple program on two controllers in which each robot (Appendix A), according to its task, reaches predefined points (Figure 4.14). Notwithstanding the assumption that the target is located at a treatment distance of 650 mm, the following three points are selected as reference for locations A, B and C (all values are



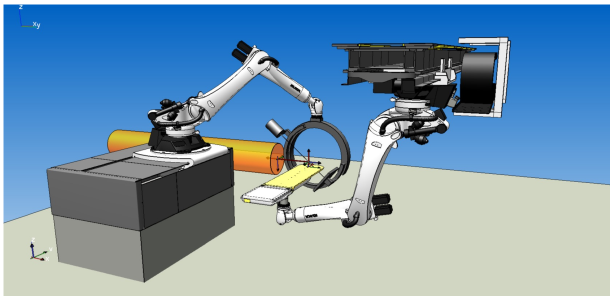
(a) ROBO1 in location B



(b) Imaging position 2



(c) CBCT in treatment position: x-ray source rotation of 140°



(d) CBCT in treatment position: x-ray source rotation of $-140°$ (rear view)

Figure 4.12: Treatment in point B. Target is ideally located 10 cm over the couch surface where theoretically would be the head of patient.

relative to the position of Tool RF located on couch surface respect to base RF):

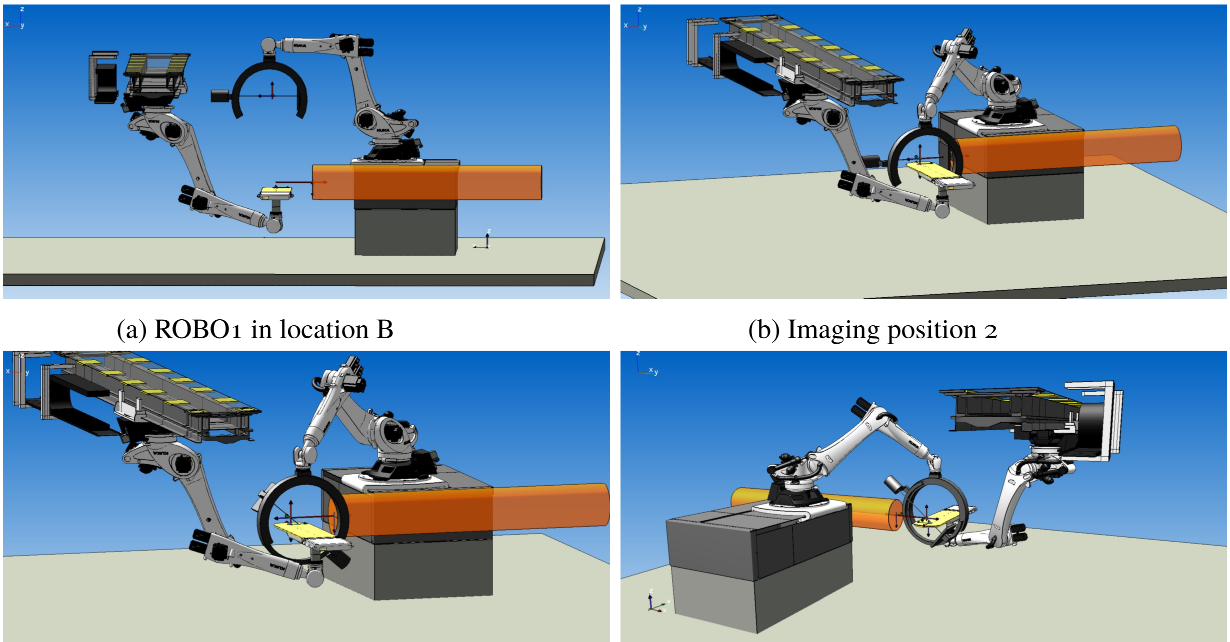
1. LOCATION A: $P1 = (X = -650, Y = 0, Z = 0, A = 0, B = 0, C = 0, E1 = 600)$;
2. LOCATION B: $P2 = (X = -700, Y = 275, Z = 15, A = 90, B = 0, C = 0, E1 = 1000)$;
3. LOCATION C: $P3 = (X = -700, Y = -45, Z = 90, A = -90, B = 0, C = 0, E1 = 2500)$.

Whereas as imaging positions the following points have been fixed (Figure 4.15):

1. Imaging Position 1: $P1 = (X = -650, Y = 0, Z = 0, A = 0, B = 0, C = 0, E1 = 600)$;
2. Imaging Position 2: $P2 = (X = -700, Y = 275, Z = 15, A = 90, B = 0, C = 0, E1 = 600)$.

Note that each of these points is uniquely defined by a six dimensions array composed by:

1. x,y and z values which indicate the translation of each point respectively along the Base RF axis; in this way the origin of Tool RF is positioned in a specific point in the space;
2. A, B and C values which stand respectively for rotations around z, y and x axis of Base RF; by these values it is possible to know the orientation in the space of Tool RF in terms of rigid rotations around the Base RF axis, which are fixed;



(a) ROBO1 in location B

(b) Imaging position 2

(c) CBCT in treatment position: x-ray source rotation of 140°

(d) CBCT in treatment position: x-ray source rotation of −140° (rear view)

Figure 4.13: Treatment in point B. Target is ideally located 10 cm over the couch surface where theoretically would be the head of patient.

3. E1 value, which indicates the current position of ROBOROOT RF in terms of displacement on the external linear unit.

The test carried out validate the results of the simulation stage, since all the positions, considered as requirements for the system, were reached by the robots: in terms of space available for mechanical movements, the current sut-up is a valid configuration. Note that in the robot program used in this stage was tested also the cooperating mode using the package KUKA.RoboTeam. In particular, in our set up the two robots are configured in order to work in a master-slave configuration; ROBO2 is the master and consequentially ROBO1 is the slave. On the basis of these settings, the package provided by KUKA allows to use different kinds of cooperation modes between two or more robots taking part in a team. The configuration we are interested in is the **Process-dependent mode**, in which one robot (or more) processes the workpiece while it is being transferred by point A to point B by the other robot. Through the inline form "PROGSYNC", each of the two controllers can communicate to the other the end of its motion and give to it the possibility to move inside the workspace. In this way the communication is established between the two controllers.

At this stage the aim was to test also a first configuration of safety parameters thanks to the package KUKA.SafeOperation. Firstly, general parameters have been defined, such as the maximum velocity that should be not overcome inside the workspace, and software limits of each robot axis. Secondarily, a first configuration of workspaces for each robot is tested. By using Kuka arrangements, a set of three spheres is configured for the couch; in this way what is obtained is a so called "safe tool" (Figure 4.16) which can not overcome the workspace fixed for the robot and at the same time dangerous clashes between robot axis and the tool are avoided. Each time the spheres come near to the workspace limits, the robot enters its "safe mode", decreasing its velocity and stopping its axis when a point inside the spherical volume hits boundaries. To make visible these configurations, in the simulation environment are plotted (Figure 4.17) both spheres (in red) and the workspace available for robot movements (in green). The dimensions for the workspace have been calculated by simple geometrical computations observing robot positioning movements inside the room. The same procedure is used for ROBO1, but this time what is configured is a "violated space", which cannot be accessed by the safe tool (Figure 4.18). This is done to prevent the possibility that the C-Arm hits the couch during its movements.

Positioning accuracy

The positioning accuracy of the robotic arm in positioning couch with respect to the beam nozzle reference frame, has been measured through the use of Leica Absolute Tracker AT401. Thanks to it, it is possible to measure the spatial position of a point related to its own reference frame or another one previously connected to it. The emitting light is reflected by some spheres with radius of 6.35mm (Figure 4.19) positioned in points to be measured and thanks to them positions are measured with $\pm 10\mu m$ accuracy.

In order to appreciate the capability of the system to align whatever point on couch surface (which stands for possible tumor locations inside patient body) with the proton pencil beam, measures by using laser tracker are carried out. Spherical reflectors were positioned in different positions and at different heights on couch surface and their positions inside the room with respect to beam exiting point are calculated. So that in the first three columns of Table 4.3, are shown the x,y and z coordinates, referred to the base reference frame, of each point in which a reflector is located. After that ROBO2 was programmed so to reach these points and reflectors positions were measured trough laser tracker. Of course the laser tracker is set so that its reference frame is attached with our Base RF already described and, in this way, the results given by the laser tracker (in the last three columns of table) represents the reflectors positions measured with respect to the beam exiting point.

As it is possible to observe the deviation of the measured values from the ideal ones is $0.03 \div 0.04mm$ ($\pm 0.01mm$ which is the laser tracker uncertainty in worst case). This value is in accordance with what it is specified in the system requirements.

At this point it is necessary to do a clarification. Even though the found results satisfy the requirements, also thanks to the high precision of the robot used, the implementation of a CBCT in treatment position is intended to minimize as much as possible the positioning error. Thanks to the data provided by the computed tomography about the target position in patient body should be possible to correct errors committed by positioning robot. In this way the beam delivery can operate in the best conditions, ensuring that the beam will be exactly directed on tumor tissue avoiding healthy tissues.

Desired Positions			Measured Positions		
x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]
-1200	0	540	-1200,029	-0,039014	540,025
-750	46	86	-749,988	46,053	86,047
-650	1055	75	-650,026	1054,966	74,989
-1025	28	83	-1025,015	28,021	82,991

Table 4.3: Measures performed by using Laser Tracker.

Movements repeatability

Always considering the same set-up used before, an external server is used in order to evaluate movements repeatability. A LabVIEW control panel (Figure 4.20) was developed that allows communication between positioning robot and external PC through data exchange via EthernetKRL interface (Appendix B). Thanks to it, it is possible to send the desired position to the robot controller and, at the same time, receive from it the current position of the robot TCP, by compiling an XML file from which the useful data are extracted. In sending data to the robot it is possible to choose between treatment positions 0,1 and 2 which, respectively, correspond to location A, B and C, the number of times the robot must repeat the positioning movement, the position and orientation of the point to be achieved, the value on the external linear unit, which implies a displacement of robot base.

For each of points P1, P2 and P3 defined in the previous section, the position and orientation of the TCP has been measured 20 times in order to appreciate the system repeatability. Therefore in the three following Tables 4.4, 4.5 and 4.6 are reported the achieved results measuring for 20 times the position of the TCP with respect to the Base RF. In particular the first three columns show translations along x, y and z axis of Base RF; the columns A, B and C refer to orientation of the TCP considering, respectively, rotations around z, y and x axis of Base RF; the last one shows the position of ROBOROOT RF in terms of displacement on the external linear unit on which the robot is mounted.

On the basis of the results listed in Tables 4.4, 4.5 and 4.6, the **repeatability error** E_r has been estimated for each of three points:

- P1: $E_r = 0.004mm$

- P2: $E_r = 0.007mm$

- P3: $E_r = 0{,}016mm$

It is then possible to observe that the error made by the positioning robot during repetitive movements is equal to or less than **0.016 mm** and is consistent with robot specifications and project requirements.

X [mm]	Y [mm]	Z [mm]	A [deg]	B [deg]	C [deg]	E1 [mm]
-650,01	-0,021903	0,030382	-0,00047	-0,000636	0,000357	600
-650,01	-0,020114	0,031014	-0,000407	-0,000646	0,000373	600
-650,01	-0,020508	0,029118	-0,000438	-0,000612	0,000332	600
-650,01	-0,019784	0,029678	-0,000386	-0,000624	0,000337	600
-650,01	-0,020202	0,029363	-0,000405	-0,00061	0,000341	600
-650,01	-0,019228	0,029874	-0,000379	-0,000623	0,000362	600
-650,01	-0,019018	0,030337	-0,00037	-0,000632	0,000363	600
-650,01	-0,020364	0,032042	-0,00038	-0,000669	0,000423	600
-650,01	-0,020308	0,032289	-0,000407	-0,000645	0,000385	600
-650,011	-0,020641	0,031733	-0,0004	-0,000653	0,00041	600
-650,01	-0,021282	0,03276	-0,000421	-0,000679	0,000453	600
-650,01	-0,020768	0,032173	-0,0004	-0,000655	0,000414	600
-650,01	-0,021378	0,032936	-0,000401	-0,000672	0,000429	600
-650,011	-0,020002	0,031832	-0,000364	-0,000658	0,000406	600
-650,011	-0,020359	0,033513	-0,000402	-0,00068	0,000428	600
-650,01	-0,021027	0,031477	-0,000427	-0,000647	0,000388	600
-650,01	-0,019612	0,032109	-0,000375	-0,000658	0,000407	600
-650,01	-0,020144	0,030763	-0,000401	-0,000642	0,000381	600
-650,01	-0,019457	0,031866	-0,000375	-0,000659	0,000408	600
-650,011	-0,019718	0,031041	-0,000364	-0,000659	0,000407	600

Table 4.4: ROBO2 TCP position and orientation in point P1.

4.4 Performances evaluation

On the basis of the results found and discussed in the previous section, the system is considered to be able to satisfy the project requests. As a consequence of this, a series of specifications are provided regarding the positioning robot movements (Table 4.7). In particular these values indicate the set of points in the space in which the manipulator is able to place its TCP. Of course, all the positions are defined as translations and rotations starting from the origin of the Base RF (defined and fixed as in Figure 4.9). In particular Table 4.7 shows minimum and maximum values both for translations along x,y and z axis of Base RF and rotations around z, y and x axis of Base RF respectively; in this way, for each of the three treatment Locations defined before we have all the possible displacements that the robot TCP can perform. Observe that (see Section 4.2) the system is intended to treat brain cancers, head and neck ones or abdomen and pelvis tumours; so that the beam should target only the upper part of patient body. Therefore, considering the set of points in the table, the following observations hold:

- In Location A, head tumours can be treated with the possibility to have a target rotation on z axis of ±45 degrees respect to the beam direction. Small rotations around x and y axis increase the possibility to enter the patient body by different angles.

- In Location B and C it is possible to align each point on left and right side of patient

X [mm]	Y [mm]	Z [mm]	A [deg]	B [deg]	C [deg]	E1 [mm]
-700,047	275,002	15,0601	90,0006	-0,00051	-0,001483	1000
-700,047	275,003	15,0599	90,0006	-0,000497	-0,00149	1000
-700,046	275,004	15,0597	90,0005	-0,000496	-0,001479	1000
-700,048	275,002	15,0601	90,0006	-0,000492	-0,001502	1000
-700,043	275,001	15,0625	90,0004	-0,000512	-0,001553	1000
-700,047	275,001	15,0597	90,0006	-0,000506	-0,00145	1000
-700,046	275,003	15,0599	90,0005	-0,000509	-0,001472	1000
-700,046	275,003	15,0608	90,0005	-0,000498	-0,001499	1000
-700,047	275,002	15,0597	90,0006	-0,000508	-0,001466	1000
-700,047	275,002	15,0613	90,0006	-0,000512	-0,001497	1000
-700,047	275,003	15,0601	90,0005	-0,000509	-0,001475	1000
-700,042	275,002	15,0606	90,0004	-0,000505	-0,00144	1000
-700,044	275,003	15,0605	90,0004	-0,000506	-0,001449	1000
-700,046	275,002	15,0604	90,0005	-0,00051	-0,001486	1000
-700,044	275,003	15,0622	90,0004	-0,000527	-0,001511	1000
-700,042	275,002	15,0597	90,0003	-0,000522	-0,001465	1000
-700,047	275,002	15,0593	90,0005	-0,000506	-0,001449	1000
-700,043	275,001	15,0605	90,0004	-0,000509	-0,001478	1000
-700,041	275,001	15,0608	90,0003	-0,000505	-0,001498	1000
-700,044	275,003	15,0605	90,0004	-0,000506	-0,001449	1000

Table 4.5: ROBO2 TCP position and orientation in point P2.

body, respectively, starting from the head until pelvis site. Also in these cases a rotation on z axis of ±20 degrees is allowed and small rotations around x and y axis.

- With this configuration it is not possible to enter the patient body perpendicularly to the thorax plane, considering that it implies to have the patient couch in non safe positions; since this treatment position is much interesting in proton therapy treatments, a possible solution can be implemented to overcome this limit. In particular, the idea is to use a sitting couch in order to locate the patient in front of the beam delivery system. This solution will not be investigated in this work and is left to the project future developments.

4.5 Treatment Plan Software (TPS)

As last part of ERHA project, a brief overview of TPS on which Itel R&D is working on is now proposed. The software allows to translate and access DICOM (Digital Imaging and COmmunications in Medicine) files, which are a kind of medical files useful for treatment definition and delivery. Cancer specialists, by using images acquired of patient body, determine the area to be treated and dose distribution minimizing possible damages on healthy tissues and individuating parameters on the basis of machine used in treatment room. This information forms the treatment plan, which is memorized in files following DICOM standard. Initially

X [mm]	Y [mm]	Z [mm]	A [deg]	B [deg]	C [deg]	E1 [mm]
-700,016	-45,0032	90,0176	-89,9999	0,000174	0,000724	2500
-700,024	-45,0099	90,0309	-89,9999	0,00036	0,001234	2500
-700,025	-45,0056	90,0319	-89,9998	0,000386	0,001291	2500
-700,025	-45,0068	90,032	-89,9998	0,000383	0,001282	2500
-700,024	-45,0057	90,0324	-89,9998	0,000393	0,001291	2500
-700,025	-45,0062	90,0327	-89,9998	0,000381	0,001317	2500
-700,024	-45,0069	90,0318	-89,9998	0,000376	0,00126	2500
-700,024	-45,006	90,0315	-89,9998	0,00037	0,001286	2500
-700,025	-45,006	90,0321	-89,9998	0,000379	0,00129	2500
-700,026	-45,005	90,0321	-89,9998	0,000373	0,001272	2500
-700,024	-45,0061	90,0322	-89,9998	0,000372	0,001313	2500
-700,026	-45,0068	90,0322	-89,9998	0,000382	0,001301	2500
-700,026	-45,008	90,0328	-89,9998	0,000375	0,001301	2500
-700,025	-45,0074	90,0321	-89,9998	0,000368	0,001279	2500
-700,024	-45,0061	90,0318	-89,9998	0,000358	0,00125	2500
-700,025	-45,0082	90,0323	-89,9998	0,000365	0,001271	2500
-700,025	-45,0062	90,0323	-89,9998	0,000364	0,001267	2500
-700,026	-45,0079	90,0325	-89,9998	0,00038	0,001293	2500
-700,025	-45,0078	90,0335	-89,9998	0,000395	0,00134	2500
-700,025	-45,0072	90,0325	-89,9998	0,00037	0,001305	2500

Table 4.6: ROBO2 TCP position and orientation in point P3.

	Location A	Location B	Location C
TRANSLATION			
X [mm]	$0 \div -1500$	$0 \div -1500$	$0 \div -1500$
Y [mm]	$-250 \div 250$	$0 \div 1000$	$0 \div 1000$
Z [mm]	$0 \div 300$	$0 \div 300$	$0 \div 300$
ROTATION			
A [deg]	$-45 \div 45$	$70 \div 110$	$-70 \div -110$
B [deg]	$-5 \div 5$	$-5 \div 5$	$-5 \div 5$
C [deg]	$-5 \div 5$	$-5 \div 5$	$-5 \div 5$

Table 4.7: Summarising the specifications found for the robotic platform in each of three locations.

these files contain information regarding images acquired during CT and areas to be treated. Once these areas have been selected and highlighted through a contouring technique, a DICOM file of RT Struct type is generated. Finally, starting from this file, a treatment simulation is performed and, when it is satisfactory, the achieved results are stored in a DICOM file of type Ion Beam, which includes information regarding the treatment set-up.

The software realized by using LabVIEW has a tab structure in which all treatment plan definition phases are available. Firstly, the different files forming the DICOM one must be loaded inside the software(Figure 4.21). The subsequent tab contains informations both for DICOM of type CT and the one of type RT Struct (Figure 4.22). On the left side it is possible to visualize different CT images, which have been acquired at same time, while on the right side the 3D file of RT Struct is visualized. Here it is possible to observe the tumor volume highlighted by prefixed colour and other organs inside the area of interest. The navigation between the CT files and in 3D view are allowed by central panel. The last tab (Figure 4.23) reports all the treatment plan parameters: the point that must be hit by particles beam, the used algorithm, the number of slices in which the tumour was divided. In the right side are showed all the points in tumour volume and their coordinates useful to direct the beam correctly.

This software must communicate with the robot control system so to uniquely define the position of tumour inside patient body. It should be also used to receive CT files coming from CBCT performed before treatment delivery, in order to validate and, eventually, correct the treatment plan information.

Figure 4.14: Tests for ROBO1 positioning.

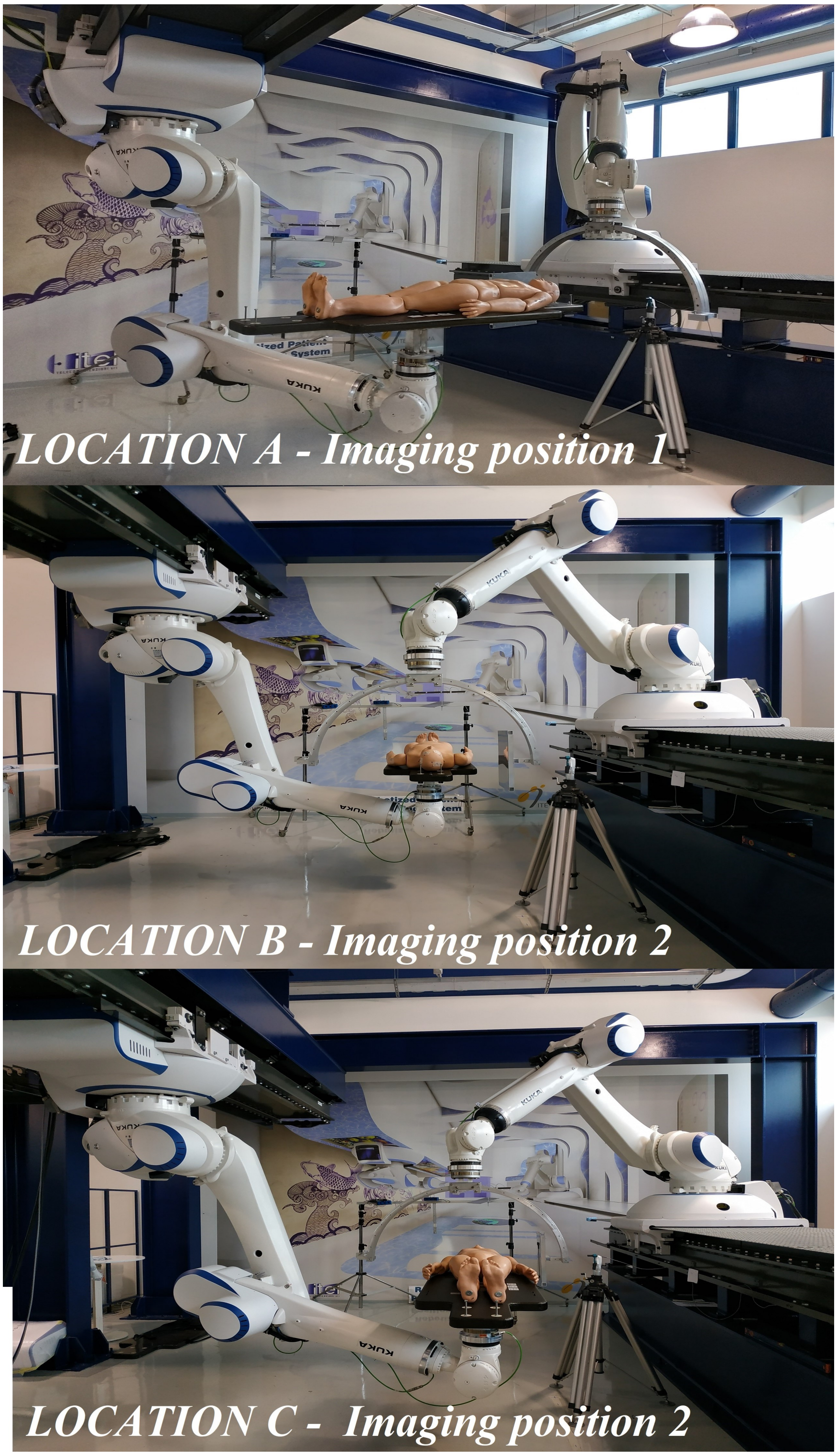
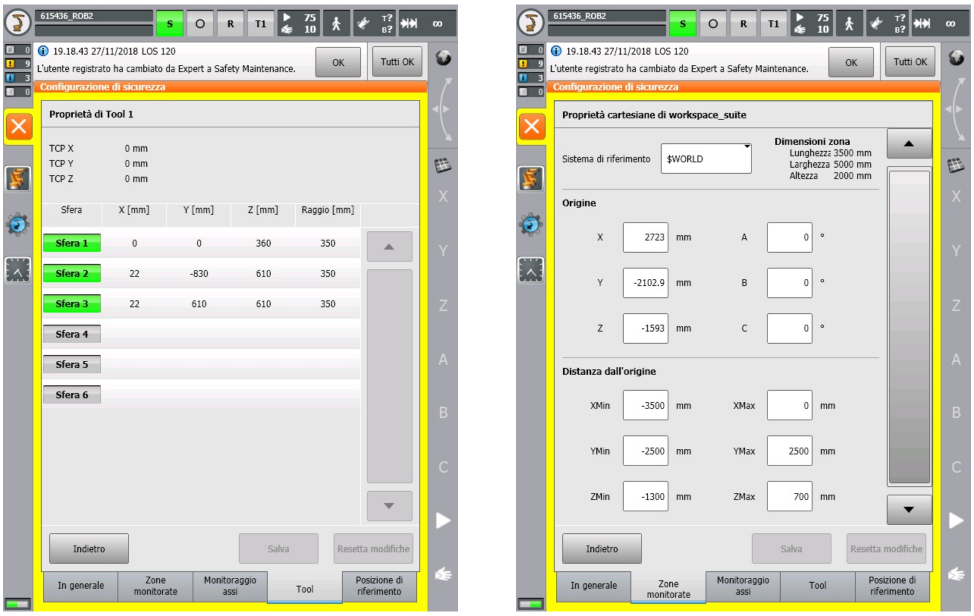
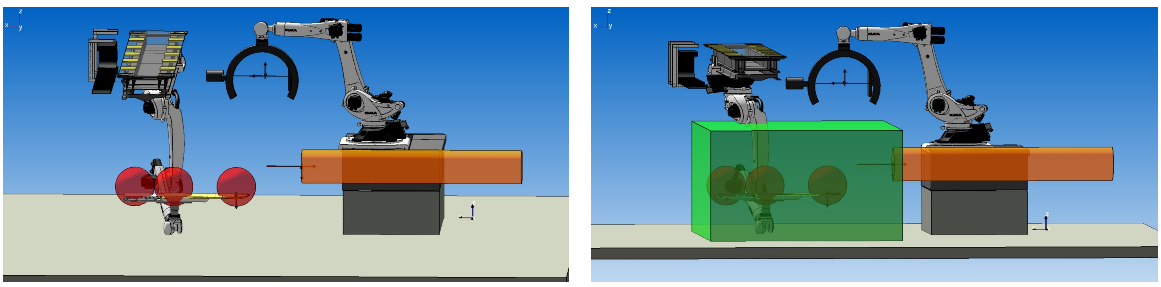


Figure 4.15: Tests for ROBO1 and ROBO2 positioning movements.



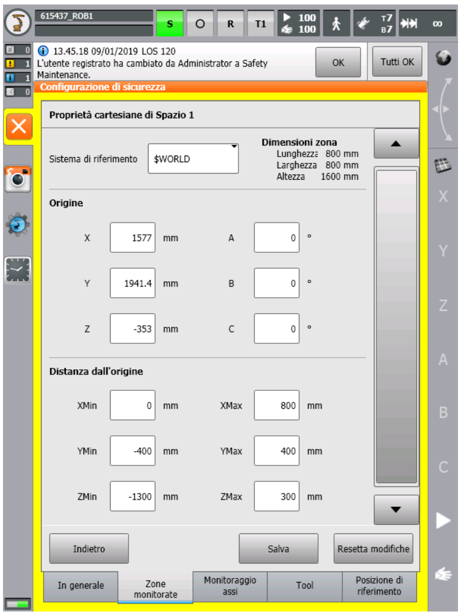
(a) Spheres on robot tool (b) Available workspace

Figure 4.16: Safe tool procedure definition for ROBO2.

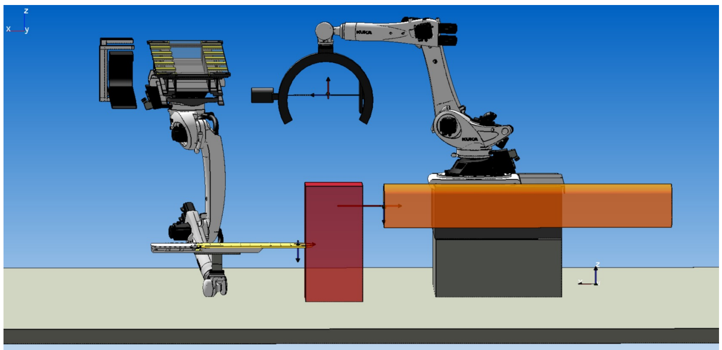


(a) Spheres on robot tool (b) Available workspace

Figure 4.17: Workspace representation.



(a) Violated space definition



(b) Violated space representation

Figure 4.18: Safe tool procedure definition for ROBO2.

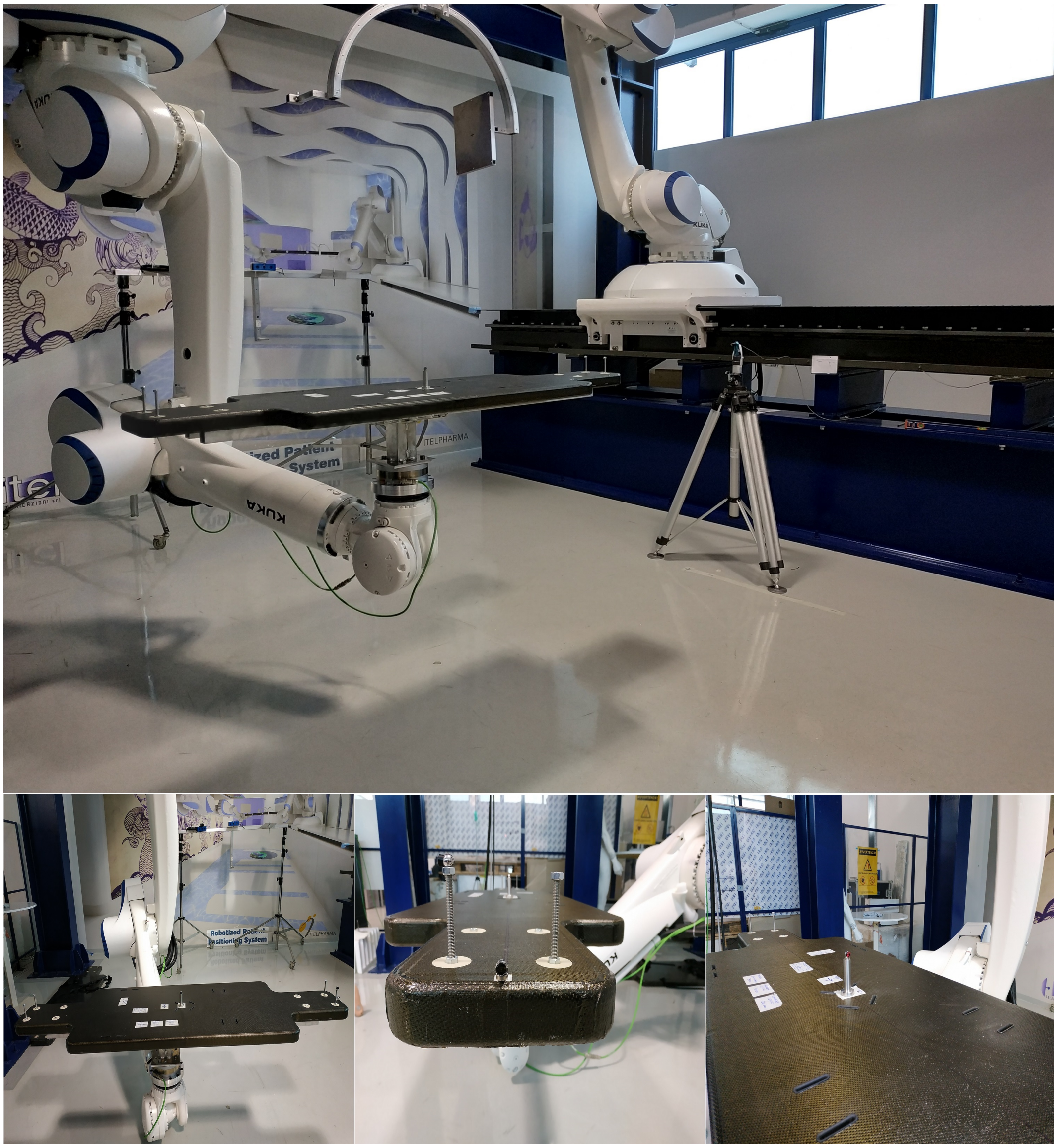


Figure 4.19: Positioning accuracy measurements through Leica Laser Tracker and light reflectors on the couch surface.

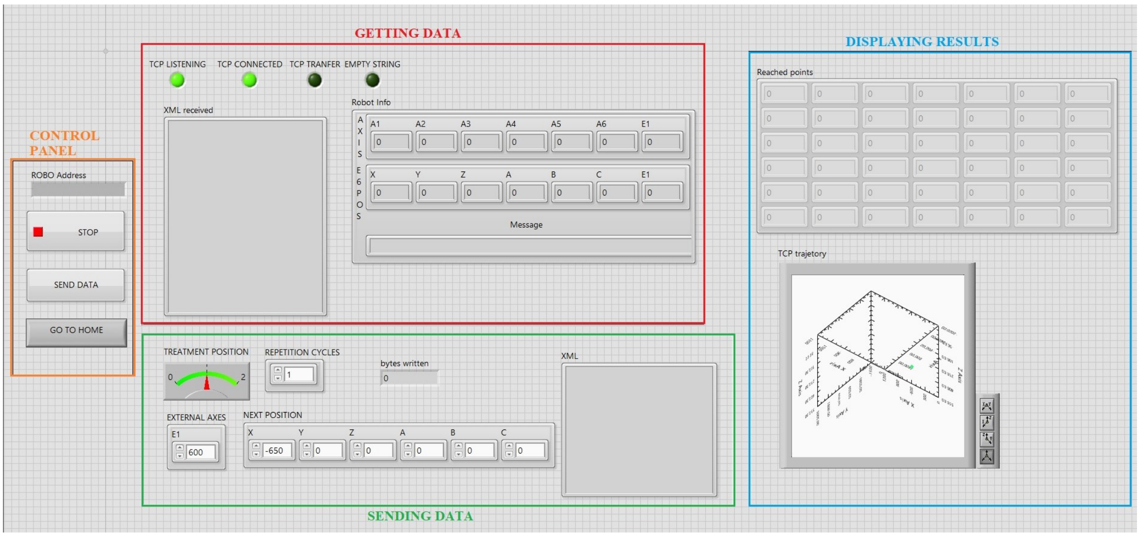


Figure 4.20: LabVIEW control panel to send and get data from ROBO2 controller.

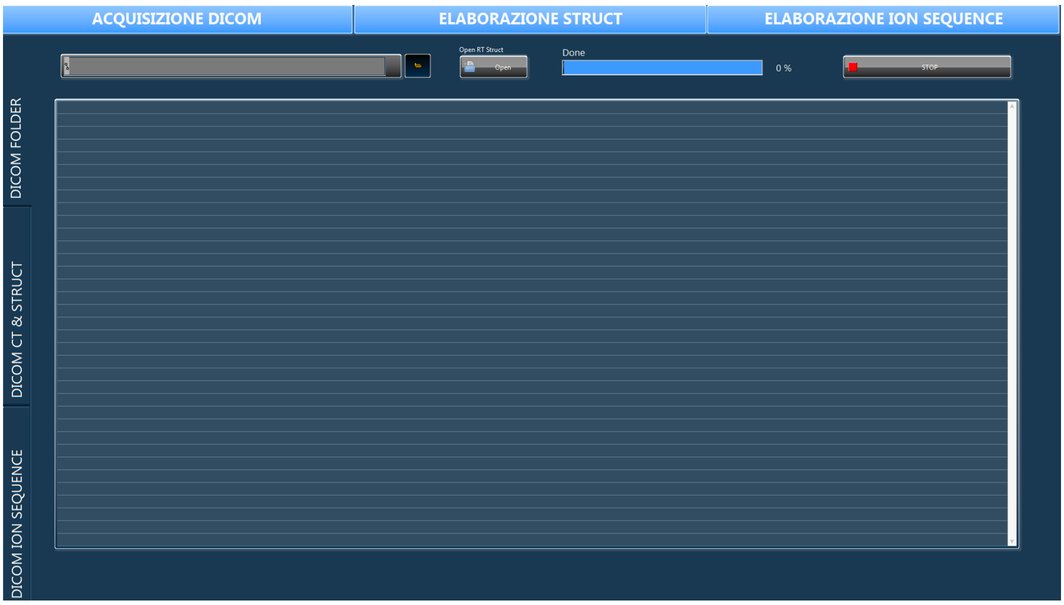


Figure 4.21: TPS: load tab

Figure 4.22: TPS: DICOM CT tab

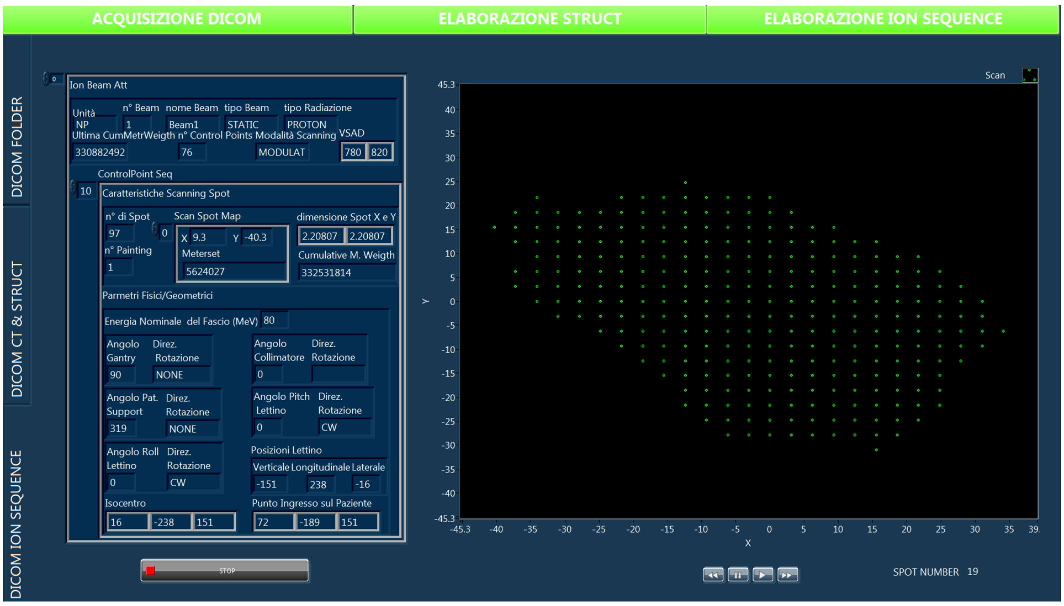


Figure 4.23: TPS: DICOM ION SEQUENCE tab

Chapter 5

Conclusions

On the basis of the initial considerations, the main goal of this project was to investigate the possibility to have a robotised platform performing patient positioning tasks in proton therapy delivery treatments. Taking into account this main goal, Chapter 4 has firstly proposed a possible set up we have designed for that kind of application with all the needed components and specifications. Note that the proposed solution is just one of all the possible viable options. It was found considering what was the real simulating prototype available in Itel Lab, on which has been allowed performing experimental tests.

Results, coming from simulations, show that the proposed solution satisfies requirements in terms of space occupancy, and that the manipulator is able to reach the considered treatment positions. As proof of this, specifications about available positioning points, provided in Table 4.7, are in accordance with tasks for which the system is designed to. Remember that the system has intended for treatments focused on head and neck cancers or on abdomen and pelvis ones; that is why the points reported in the previous table were tested and used as specifications for the whole system. Of course, not all of the points and angles on the patient body are achievable with this system, since the beam direction is fixed and the patient couch can not be rotated in any direction preventing possible risks for the person. So that, it was though to equip the positioning system also with a sitting couch, thanks to which the patient can be aligned in many other different ways with the beam. However, it was not possible to test also this configuration, so it will remain as a possible future development to improve the RPPS efficiency.

Moreover these tests have demonstrated that the idea to use a second manipulator to perform a computed tomography in treatment position is a realistic possibility. In fact, considering the proposed set up, the simulations described in Section 4.3 show how it is possible to perform positioning tasks and imaging tasks in the same room with two different robots cooperating each other.

Another crucial point in the validation of the system was to appreciate the precision it is possible to achieve with our configuration. As already said, proton therapy and, in general, all radiation therapies have many advantages on patient health, but they must have a high precision degree in beam delivery. Also from this side, as shown in Section 4.3, experimental tests were performed achieving satisfying results:

- the position is more accurate than in the expected worst case and, in addition, this parameter has to be still well appreciated, since it could be minimized by introducing imaging guidance operations;
- the movements repeatability, also thanks to the characteristics of the employed manipulator, satisfies the project requirements and ensures high precision in repetitive movements.

Summarising, the proposed design for RPPS system is a good solution in terms of requested performances. The work done during this period has demonstrated that it is possible to use the two anthropomorphic arms in order to produce a more compact and cheaper system. Of course, the system needs to be improved and tested again. As future developments the real system for the computed tomography should be implemented and its benefits in imaging guidance verified in order to improve the ability of the system to align tumor target with the particles beam. Moreover, the TPS software should be integrated with the robot controller in order to test a real treatment plan on the robot platform.

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Appendix A

Robot synchronization programs

```
&ACCESS RVP
&REL 33
&PARAM EDITMASK = *
&PARAM TEMPLATE = C:\KRC\Roboter\Template\vorgabe
&PARAM DISKPATH = KRC:\R1\Program\RPPS_demo
DEF test_coop( )
INI
USER INI

PTP HOME  Vel= 100 % DEFAULT                                            ;ROBO2 in starting position

PROGSYNC SYN1 -> R1_R2 WAIT                                             ;waiting ROBO1 finishes is movement
PTP P1 Vel=100 % PDAT1 Tool[7]:lettino Base[6]:from_simpro              ;point to point movement in point P1
PROGSYNC SYN2 -> R1_R2 WAIT                                             ;waiting ROBO1 finishes is movement
PROGSYNC SYN3 -> R1_R2 WAIT
PTP HOME Vel=100 % DEFAULT
PTP P3 Vel=100 % PDAT18 Tool[7]:lettino Base[6]:proton_BEAM
PTP P4 Vel=100 % PDAT19 Tool[7]:lettino Base[6]:proton_BEAM
PTP P2 Vel=100 % PDAT20 Tool[7]:lettino Base[6]:proton_BEAM
PROGSYNC SYN4 -> R1_R2 WAIT
PROGSYNC SYN5 -> R1_R2 WAIT
PTP HOME Vel=100 % DEFAULT
PTP P6 Vel=100 % PDAT21 Tool[7]:lettino Base[6]:from_simpro
LIN P3 Vel=2 m/s CPDAT3 Tool[7]:lettino Base[6]:from_simpro             ;linear movement in point P1
PROGSYNC SYN6 -> R1_R2 WAIT
PROGSYNC SYN7 -> R1_R2 WAIT
PTP HOME Vel=100 % DEFAULT

END
```

Figure A.1: ROBO2 moving program.

```
&ACCESS RVP
&REL 104
&PARAM EDITMASK = *
&PARAM TEMPLATE = C:\KRC\Roboter\Template\vorgabe
&PARAM DISKPATH = KRC:\R1\Program\RPPS_demo
DEF test_coop( )
INI
USER INI

PTP HOME Vel=100 % DEFAULT

PROGSYNC SYN1 -> R1_R2 WAIT
PROGSYNC SYN2 -> R1_R2 WAIT
PTP PM Vel=100 % PDAT19 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P1 Vel=100 % PDAT20 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P2 Vel=100 % PDAT15 Tool[7]:centroCBCT Base[7]:proton_BEAM
WAIT Time=3 sec
PTP P13 Vel=100 % PDAT22 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP HOME Vel=100 % DEFAULT
PROGSYNC SYN3 -> R1_R2 WAIT
PROGSYNC SYN4 -> R1_R2 WAIT
LIN PM Vel=2 m/s CPDAT0 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P14 Vel=100 % PDAT24 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P3 Vel=100 % PDAT16 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P16 Vel=100 % PDAT26 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP HOME Vel=100 % DEFAULT
PROGSYNC SYN5 -> R1_R2 WAIT
PROGSYNC SYN6 -> R1_R2 WAIT
PTP PM Vel=100 % PDAT23 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P15 Vel=100 % PDAT25 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P4 Vel=100 % PDAT18 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP P17 Vel=100 % PDAT27 Tool[7]:centroCBCT Base[7]:proton_BEAM
PTP HOME Vel=100 % DEFAULT
PROGSYNC SYN7 -> R1_R2 WAIT

END
```

Figure A.2: ROBO1 moving program.

Appendix B

EthernetKRL configuration

```
<ETHERNETKRL>
        <CONFIGURATION>
                <EXTERNAL>
                        <IP>172.31.1.150</IP>                   /*External server IP address*/
                        <PORT>59152</PORT>
                </EXTERNAL>
        </CONFIGURATION>

        <RECEIVE>
                <XML>                                           /*Format of XML send to robot*/
                        <ELEMENT Tag="Sensor/Message" Type="STRING"/>
                        <ELEMENT Tag="Sensor/Positions/Current/@X" Type="REAL"/>
                        <ELEMENT Tag="Sensor/Positions/Before/X" Type="REAL"/>
                        <ELEMENT Tag="Sensor/Scelta" Type="INT"/>
                        <ELEMENT Tag="Sensor/Rep" Type="INT"/>
                        <ELEMENT Tag="Sensor/Ext" Type="REAL"/>
                        <ELEMENT Tag="Sensor/Status/IsActive" Type="BOOL"/>
                        <ELEMENT Tag="Sensor/Read/xyzabc" Type="FRAME"/>
                        <ELEMENT Tag="Sensor/Show/@error" Type="BOOL"/>
                        <ELEMENT Tag="Sensor/Show/@temp" Type="INT"/>
                        <ELEMENT Tag="Sensor/Show" Type="STRING"/>
                        <ELEMENT Tag="Sensor/Free" Type="INT" Set_Out="998"/>
                        <ELEMENT Tag="Sensor" Set_Flag="998"/>
                </XML>
        </RECEIVE>

        <SEND>
                <XML>                                           /*Format of XML received by robot*/
                        <ELEMENT Tag="Robot/Data/AxisPos/@A1"/>
                        <ELEMENT Tag="Robot/Data/AxisPos/@A2"/>
                        <ELEMENT Tag="Robot/Data/AxisPos/@A3"/>
                        <ELEMENT Tag="Robot/Data/AxisPos/@A4"/>
                        <ELEMENT Tag="Robot/Data/AxisPos/@A5"/>
                        <ELEMENT Tag="Robot/Data/AxisPos/@A6"/>
                        <ELEMENT Tag="Robot/Data/AxisPos/@E1"/>
                        <ELEMENT Tag="Robot/Data/ActPos/@X"/>
                        <ELEMENT Tag="Robot/Data/ActPos/@Y"/>
                        <ELEMENT Tag="Robot/Data/ActPos/@Z"/>
                        <ELEMENT Tag="Robot/Data/ActPos/@A"/>
                        <ELEMENT Tag="Robot/Data/ActPos/@B"/>
                        <ELEMENT Tag="Robot/Data/ActPos/@C"/>
         <ELEMENT Tag="Robot/Message"/>
                </XML>
        </SEND>
</ETHERNETKRL>
```

Figure B.1: File loaded in robot controller in order to allow Ethernet data exchange with external system.