UNIVERSITÀ DEGLI STUDI DI CATANIA

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A 5 DOF manipulator for remote inspection: design, simulation, implementation and trials

Master Thesis

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INTRODUCTION

The term radioactive waste (or shortly radwaste) indicates waste containing radioactive material. It is usually produced as a residue of nuclear processes, such as nuclear fission, even though industrial processes and medical applications may also produce radioactive waste. After the nuclear disasters occurred in Fukushima, for instance, the population sensitivity to the problem of radwaste increased. Contrary to chemical waste dangerousness, radioactivity decreases with time, therefore one could in principle seal and isolate the waste for some time until its radioactivity poses no relevant risk. Unfortunately “some time” can range from a few hours to years for medical and industrial radwaste, and up to tens of thousands of years for high-level waste from nuclear fission reactors and nuclear weapons decommissioning. The only viable solution proposed so far to the problem posed by the radioactive waste produced all over the world is packing it into special drums to be segregated into suitable storage sites, for short and medium term radwaste, or into so called geological burial sites for long-term radwaste.

The DMNR system (Detector Mesh for Nuclear Repositories), developed at INFN-LNS within the framework of the INFN-E strategic project, aims at the remote on-line monitoring of radwaste drums in the short and medium term storage sites, in order to minimize the direct interaction of human operators with radwaste and to provide a real time overview of the activity around each single radwaste drum.

To achieve this goal low cost one-dimensional scintillation sensors were developed, that can be arranged in order to create a 3D map of the activity inside the disposal site. A high-level graphical interface has been implemented which allows the operator a real-time view as well as a complete historical reconstruction of the activity around each single drum.

In this context robotics aims to create solutions and tools that can improve the inspection in the storage sites. Several robotic systems have already been developed during recent years for this purpose, as for example SWAMI, ARIES, ABCD which will be analyzed below. However all of them are typically rather complex and quite expensive.

In this thesis we propose a simple and rather cheap prototype of robotic arm for remote inspection, which interacts with the radwaste environment by means of a radiation sensor and a video camera. It moves vertically thanks to a crane while the other degrees of freedom are satisfied by revolute joints.

The organization of the thesis is the following: the chapter 1 is an introduction to the problem of radioactive waste, to the types of radiation, to the situation of Italian and international management of radwastes and to the various steps to be followed for a correct decommissioning.

In chapter 2 the definition of short and long term waste is presented, followed by a short description of the DMNR project, its main components, electronics and a few experimental results. There I will try to answer to the question “why make an inspection robot”, discussing the integration between the robotic arm and DMNR.

Chapter 3 describes the first practical part of the work, which is composed by an interface for the simulation of the arm (with description of the languages MatLab and VRML), a description of the initial structure that interacted with the robot and the kinematic theory.

Chapter 4 describes the robot from the mechanical, electronic and software point of view, explaining why an arm was chosen and the possible alternatives to it, the choice of engines and several programming tools.

Chapter 5 describes the final interface that will be used for the real-time management of the manipulator by the operator.

CHAPTER I

Radioactive waste

1.1 Introduction

The term radioactive waste (or shortly radwaste) indicates waste containing radioactive material. It is usually produced as a residue of nuclear processes, such as nuclear fission, even though industrial processes and medical applications may also produce radioactive waste.
The main sources of radwaste are typically products of:

- Nuclear fuel cycle, including mining, enrichment, reprocessing, decommissioning.
- Nuclear weapons decommissioning.
- Legacy radwaste
- Medical diagnostics and treatment.
- Industrial applications, like high-energy gamma radiography
- Natural radioactive material, like 40K that is contained in water

Contrary to chemical waste, radioactivity decreases with time, therefore it is possible in principle seal and isolate the waste for some time until its radioactivity poses no relevant risk. Unfortunately "some time" can range from a few hours to years for medical and industrial radwaste, and up to thousand years for high-level waste from nuclear fission and from decommissioning of nuclear weapons.
Radioactive waste can be classified according to various parameters such as the origin, the type of radiation emitted, the half-life of the radionuclides, the radiotoxicity of the radionuclides, the management mode.

International Atomic Energy Agency (IAEA) defines three level of waste:

- high level waste (HLW);
- low and intermediate level waste (LILW);

- waste that can be cleared from nuclear regulatory control.

LILW is further separated into short lived and long lived waste according to the typical decay time of its radioactivity. Operational waste from nuclear power plants typically falls into the category of short lived LILW if it cannot be cleared from nuclear regulatory control.
Spent fuel would be HLW if declared as waste, whereas most of the currently produced radwaste belongs is LILW.

1.2 Types of radiation emitted by the radwaste

Radioactive decay is a spontaneous process in which some species of atomic nuclei (unstable isotopes of chemical elements) are transformed into other (stable or unstable isotopes of the same or of other chemical elements), emitting radiation. In this transformation the atom tends to move into a situation of greater stability.

The emitted particles are distinguished by their penetrating ability:

- Alpha decay, typically occurring in heavy elements, consists in the emission of an 4He nucleus, also called “alpha particle”, with a given kinetic energy. Due to its mass and electric charge it is not penetrating and is typically stopped within few micrometers of matter.
- The beta decay can be positive or negative, depending on the emission of a positron (e+, positive electron) or an electron (e-). In both cases an additional neutral particle is emitted, which shares the available kinetic energy with the beta particle. For this reason the beta energy of a given decaying species is variable from 0 to a maximum value. The beta radiation is typically stopped within few millimeters in matter or few centimeters in air.
- The gamma decay consists in the emission of a high-energy quantum of electromagnetic radiation (also called “gamma photon”) by a nucleus in an excited state. Stopping gamma rays can require from centimeters to meters

of high-density materials. X rays, also produced in radioactive decays, are simply lower-energy gamma rays.

The three particles are called “ionizing radiation”. We can also list the nuclear fission and neutron emission:

- Nuclear fission is the process where a heavy nucleus splits into two fragments. The two fragments are typically radioactive according to one or more of the previous decay modes and are stopped immediately in matter. Conversely, the neutrons have not electric charge and as a consequence they are highly penetrating and do not produce direct ionization. However, in order to lose kinetic energy they have to collide directly with nuclei, hence they will produce indirect ionization even at relevant distance from their production point. In order to stop neutrons one needs special materials and geometries.

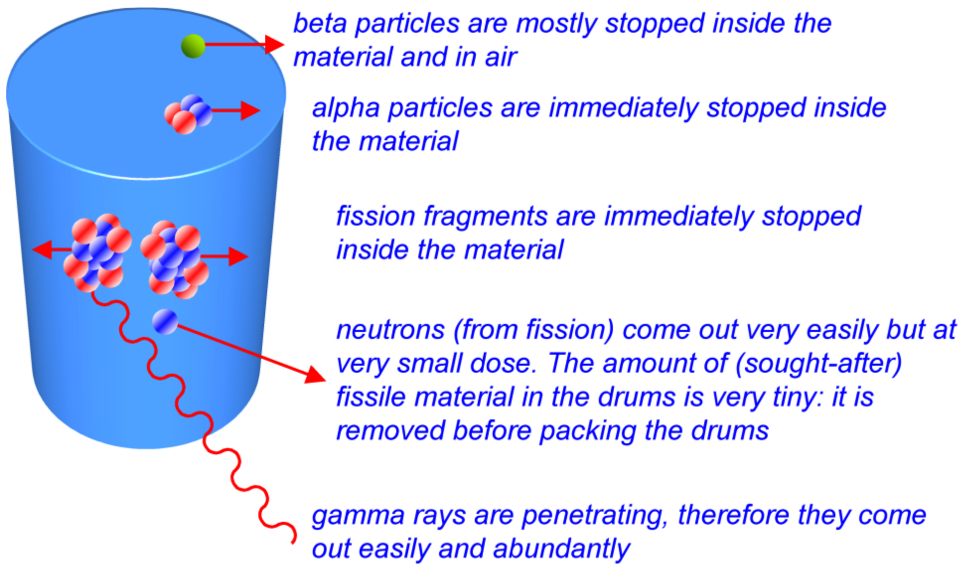

Fig.1 Summary of radiation type, and their penetration level.

All the listed types of radiation are emitted by the radwaste, in absolute and relative amounts that depend on the particular composition. This is why each kind of waste need to be embedded in a suitable matrix, then surrounded by some shielding envelope and finally inserted into a a drum.

1.3 Measure unit

Now it is very important to define the main measure unit for this field, that help us to understand the dangerousness of radiations.

The **Becquerel** (Bq) is the units of the International System and it represents the activity of a radionuclide, or the activity of the source, defined as the number of nuclear disintegrations in a time interval and it is defined as the activity of a radionuclide that has a decay (disintegration) per second. The **Curie** (CI) is an old unit, and corresponds to 3.7 * 1010 disintegrations per second (approximately equal to the activity of 1g of radio).

The units of the absorbed dose, that is the energy deposited by the radiation in a reference mass, is the **Gray** (Gy). It is equal to 1 joule per kg of mass.

The units of effective absorbed dose is **Sievert** (Sv), which is the dose in Gray multiplied by a quality factor from 1 , for X-rays and gamma ray, to 20 for heavy ions (for alpha rays is 10). The Sievert measures the effects and the damage to an organism caused by the radiation.

It is estimated that the exposition to 4/5 Sv causes the death of 50% of subjects exposed during 2 months, the exposition to 50 Sv within 2 weeks, over 5 KSV over two days.

The **Roentgen** (R) is referred only to gamma radiation and it is defined as the amount of radiation that produces in a 1 ml sample of air at 0 ° C and 1 atm, a quantity of ions corresponding to an electrical charge of 1 ues.

1.4 Management of radwaste

The decommissioning management of obsolete nuclear installations and management of radioactive waste, including disposal, are closely interconnected and, for the sensitivity of the issue, and the attention of public opinion, require a comprehensive national strategy, defined by the contribution of technical, scientific, administrative and political.

The deactivation (decommissioning) of a nuclear power plant has the aim to remove some or all radiological regulatory constraints, guaranteeing the long-term safety of the population and of the environment.

This process depends on many factors and involves intermediate stages. It has variable duration in function of different parameters of countries, such as the prospects use of nuclear energy, the availability of qualified personnel, the availability of fund, the availability of disposal sites for radioactive waste, etc...

To identify the different levels of advancement in the activity of decommissioning of a nuclear installation, it is usually referred to a scale proposed by the IAEA, which identifies three levels or stages:

- Stage 1 - **Storage with Surveillance**: minimum of activity necessary for the conservation in safety (in the case of nuclear power plants the irradiated fuel is removed from the site).
- Stage 2 - **Conditional Release**: Dismantling or decontaminate parts less contaminated and conventional parts of the plant. The heart of the plant is put into safe conservation.
- Stage 3 - **Unconditional Release**: the plant is completely dismantles and the site is released without further need of surveillance. The site can be reused to conventional activities or released as "green grass".

Of course, intermediate situations are also possible.

According to the IAEA scale, the following general strategies for decommissioning are defined:

- **DECON** (Decontamination) - Proceed immediately after the stop of the plant, to move to Stage 3 as soon as possible.
- **SAFESTOR** (Safe Storage) - After the stop of the plant it proceeds to a stage between 1 and 2. In that stage the system is maintained in safety for a period of ten years, and after radioactivity decay goes to acceptable levels to the dismantling operation, it switches to DECON strategy.
- **ENTOMB** - The radioactive parts of the plant are confined (for ex. embedded in casting of concrete) waiting for decay goes to levels of environment.

1.4.1 International position

For peaceful uses of nuclear energy, from Euratom Treaty, the European Commission issued directives, recommendations, resolutions, regulations or simple technical documents written by expert groups.

However the topic of decommissioning and radioactive waste management has never been central; today the most significant law (legislative) is still associated with the Directive 96/29/Euratom, whose main theme is the importance of protection for health of the population and workers, against ionizing radiation.

Recently (before the enlargement of the Europe to 25), the Commission began to seriously address the problem to a new Community approach, in order to adopt a legally binding rules for the harmonization of criteria for safety of nuclear installations and the management of spent fuel and radwaste.

The new EU approach was first proposed to the European Parliament, with a general document of November 6, 2002, COM (2002) 605 "Communication from the Commission to the European Parliament - Nuclear Security in the European Union. ". The proposed aim (then essentially failed) was to equip the EU, urgently, with a new regulatory framework:

1) A directive regarding safety of working in nuclear installations and under deactivation;

2) A directive regarding the management of radioactive waste and spent fuel.

The proposal was then made with COM (2003) 32 of 30 January 2003, and subsequently with the modified proposal COM (2004) 526 of 8 September 2004, after the discussion in the European Parliament.

The second draft has not been approved by the European Parliament, for the opposition of some member states that have significant difficulties to transform the provisions of directives in national legal provisions.

These conclusions opened to the "Working Party on Atomic Questions" (WPAQ) to activate an "Ad Hoc Working Party on Nuclear Safety" (WPNS) that made consultations of member countries in order to evaluate the harmonization achieved (in terms of safety), with specific reference to:

- The results achieved with the participation of the member states to the "Convention on Nuclear Safety "and the" Joint Convention ";
- The work driven by WENRA (Western European Nuclear Regulators' Association);
- The use by member states of the documents and standard products by the IAEA.

The working group WPNS was organized into three subgroups, SG1 Safety nuclear, SG2 for the management of spent fuel and radioactive waste and SG3 for the financial aspects related to decommissioning. The final reports of the subgroups were regularly delivered in 2006. Thanks to these data, a new consultation process still in progress.

Considerable attention is also paid to the perception of these issues by the public, that is periodically probed with the Eurobarometer. In 2005 a survey was carried out in the EU-25 about the perception of the problems related to the management of radioactive waste, that showed a low level of knowledge from the public, resulting in a misperception of risk. At the same time the public consulted expressed the need to be more involved in decisions. One of the most interesting results of the survey is that almost 60% of the sample considered acceptable the use of nuclear energy only if the problem of radwaste disposal was considered solved, the % go down below 40% if the problem was not solved.

1.4.2 Italian position

Italy, with the referendum on nuclear power in 1987, has banned the use of nuclear power for the testing and production of electricity. On 23 March it was decided for a moratorium of one year for nuclear power. The decision was formalized by the Law n.34/2011. Nuclear power was re-introduced in our country with the Act 99/2009.

The decision to avoid the implementation and construction of new nuclear power plants in Italy has been taken by the government on 19 April, in an amendment of Senate during the examination for the conversion of the Decree Law 34 / 2011.

In the 2011 referendum about nuclear power Italian people have chosen to do not use nuclear energy.

However, the radioactive waste from the ex nuclear power plants are kept in different Italian sites, in condition of maximum safety. In addition, it still remains the open question of “decommissioning”, (dismantling, removal and decontamination) of the ex nuclear power plants of Trino (Vercelli), Caorso (Piacenza), Latina, Garigliano (Caserta). The same approach is applied to fuel cycle plants of Saluggia (Vercelli), Bosco Marengo (Alessandria), in Casaccia (Rome) and Trisaia Rotondella (Matera).

Fig.2 Main Italian nuclear sites

With the enactment of the Law of 24 December 2003, n. 368, there was a first solution that included possible storage sites for radioactive waste in the regions of Sardinia, Tuscany, Puglia and Basilicata, but, as a result of what happened in November 2003 in Scanzano (Basilicata), has been replaced by the idea to create a single Italian site as a dump for radioactive waste.

1.4.3 Rules for management

All nuclear safety regulations want to minimize as much as possible the risks associated to the use of radioactive materials or radiation exposure, taking into account the benefits for the society. The general criteria common to all international rules are:

- optimization of individual and collective doses (according to the ALARA principle);

- the adoption of appropriate rules to reduce the volume of radioactive waste.

Instead, the actual management of radwaste, includes also all the administrative and operational activities like handling, collection, treatment, packaging, transportation, storage and final disposal.

The fundamental rules to follow in this case are:

- manage radwaste in order to ensure an high level of protection of human health and of the environment health;
- manage radwaste to take into account the possible health effects for man and for the environment also outside the nation;
- manage radwaste in order to have a predictable impacts for the health of future generations and in order to do not pass the acceptable levels today;
- managed radwaste according to an adequate national legislation that includes clear attribution of responsibilities;
- the production of radioactive waste must be limited to the minimum possible, taking into account all stages of the generation and management of waste;
- half-life <75 days;
- concentration of radionuclides ≤ 1 Bq / g;
- individual effective dose ≤ 10 mSv / year;
- collective effective dose ≤ 1 mSv x person /year.

1.4.4 Procedures for the management

Waste can be generated from different sources. The most important are: nuclear reactors, fuel cycle, production and use of radioisotopes (medicine, industry, etc.), decontamination, decommissioning nuclear power plants.

In Italy there are about 60,000 cubic meters of radioactive waste of the second and third categories. The Italian nuclear power plants, have produced 55,000 cubic meters of waste in addition to a 2,000 cubic meters of radioactive waste produced by medical sources or created during the research.

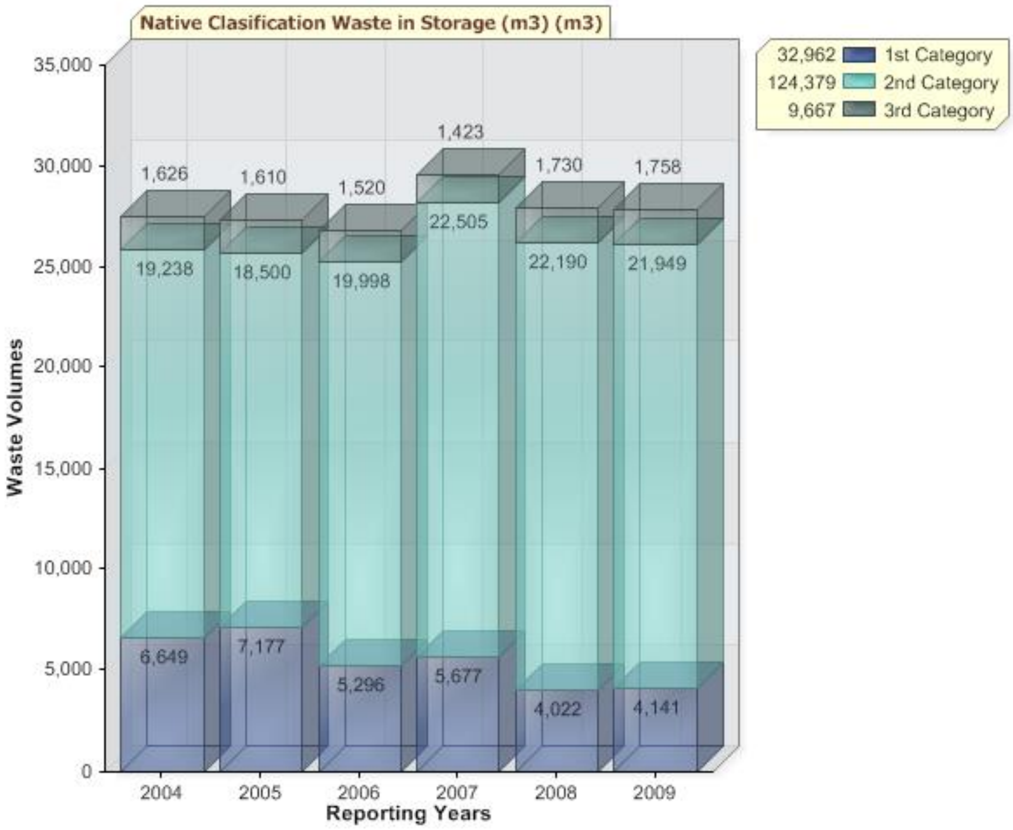

Fig.3 Waste in storage and disposal in Italy (summary graphs for years)

Now it will expose the main procedures for the management of radioactive waste. It will pass by the initial treatment, up to reach the radioactivity level of waste comparable to natural.

1.4.4.1 Treatment

At this stage of management, using appropriate physical (and-or chemical) processes, it tries to reduce the volume and to prepare for the next phase.

1.4.4.2 Conditioning

This phase of the management aims to store, in a suitable container, the radioactive waste, having physical, chemical and mechanical endurance, in order to obtain a final suitable form for final disposal.

The structure must have certain characteristics: physical and chemical compatibility with the waste, insoluble in water, water resistance, mechanical strength, weather resistance, thermal shock resistance, radiation resistance, stability in time.

1.4.4.3 Temporary storage

The main aim of this management phase is to store in safety, for a period of ten years minimum, the conditioned radioactive waste, to allow a final disposal.

1.4.4.4 Final disposal

It is the last phase of the management of radioactive waste.

The most important goals are:

- to place permanently, in appropriate structure, conditioned radioactive waste;
- to protect human health and the environment, until residual radioactivity, due to the decay, does not reach values comparable to the natural ones;
- to do not allow that the annual dose for the population exceeds over the maximum value of annual dose for people defined by law.

The second category of waste, require hundreds of years to reach radioactivity levels comparable to natural background, and so they are disposed in surface deposits or in depth place.

The third category of waste require instead thousands of years to achieve radioactivity levels comparable to natural background and they are disposed in geological deep formations.

CHAPTER II

Inspection and monitoring

2.1 Disposal of Radwaste and Level of Radioactivity

When the conditioned waste are deposited in a final disposal, their isolation from the biosphere must be insured for the entire period of their dangerousness. This isolation is realized through containment barriers placed in series (to prevent the spread of radioactive isotopes outside the deposit).

So, the safety in the short and in the long term, is based on the reliability of these barriers, that depends from the containment and how long must be guaranteed.

2.1.1 Low radioactivity (or short-lived) radwaste

In the case of low activity waste, which constitute about 95% of the entire production, the insulation shall be guaranteed for a maximum of a few centuries.

The efficiency of the barriers and isolation are continuously controlled by systems and by networks of environmental monitoring, and active during the period of institutional control, after which the site is released without restrictions.

There are cases in which the site has such characteristics that not require particularly artificial barriers of containment, like the desert sites, characterized by an almost complete absence of significant precipitation and groundwater.

Final disposal centers for low activity waste, are in activity or planned in all countries that hold radioactive waste of this type. The most modern and advanced are located in France, Spain, Sweden, Japan, UK and USA.

Important projects are in Germany, Switzerland and in some European Eastern countries of Europe. Over 100 stores are operative in the member states of the IAEA and about 50 are designed.

In the world a lot of deposits are made by surfaces (Near surface) characterized by structures simple isolation. Not superficial deposits for low-activity waste are made or provided in artificial cavities (Scandinavian deposits) or disused mines (proposed solution in Germany).

In some countries, are taken into account geological repositories for the low-activity waste.

2.1.2 High radioactivity (or long-lived) radwaste

For the high-level waste, the isolation could be achieved closing the waste in solid matrix of great durability, like vitreous matrix, and depositing it subsequently in geological formations deep (of thousands of meters) that provide isolation of radionuclides from the biosphere for periods of millions of years. For example, saline formations and clay are used for isolation. The case of deep repositories is under study.

Experimental underground laboratories are under construction or in operation in France, Germany, Sweden. The first commercial storage site might be operating in Europe, according to current projections, around 2030. In USA, it works since May 1999, the WIPP (Waste Isolation Pilot Plant), a pilot plant for disposal of long-lived waste(in this case Plutonium).

Waiting the availability of a geological disposal site, long-life radioactive waste are stored in long-conditioned systems, to storage it for a few decades.

The recent problems for the disposition of geological disposals are given by the public consensus. So could gain more credibility, the use of an international geological repository, in order to collect the long-life waste of different countries, and to place radwaste in one of the most remote areas of the planet, in conditions of maximum safety and minimal environmental impact.

It is active, the PANGEA project, funded by International association, which has identified and proposed a site in a remote area of Australia.

2.2 DMNR

Detector Mesh for Nuclear Repositories (DMNR) is a project, currently under development at INFN-LNS in Catania. The goal is the construction a proof-of-principle prototype demonstrator for the monitoring of short-medium term radioactive waste.

The system is based on arrays of scintillating optical fibers read by SiPM photosensors, that is able to detect the tiny light signals emitted.

Front-end electronics and an FPGA-based counter were developed, in order to count data coming from the sensors. It was also developed a graphical user interface and a data storage system. The transmission is done simultaneously on differential cables and on wireless, using powerful low-cost and low-consumption units powered by rechargeable batteries.

In this contest it is necessary the development of a Robotic Arm for remote ad-hoc inspection (visual inspection with a camera and radioactive inspection using high resolution radiation detectors).

2.2.1 The basic sensor unit

The main aim of the system is the measurement of radioactivity around each drum or group of drums. The perfect system would be provide to a continuous detection of radiation with dedicated sensors . This can be done using Geiger-Muller counters, but the problem is the very high cost of these sensors. So it has to choose other solutions, such as periodic inspections made by operators or by robots and appropriate monitoring systems.

The characteristics for the choice of sensor for the specific task are: resistance to radiation, functioning as a counter, high sensitivity, low efficiency, reliability, sensitivity to position, mechanical robustness, redundancy, low cost, easy to maintenance, easy to remove and assembly, sensitivity to specific radiation, ability to measure the total dose, regardless of the historical record of the counts returned.

For this purpose it was created and tested at INFN-LNS, a new sensor that has the previous features. It is low cost scintillation sensor, replicated to form a grid around each drum, in order to count the gamma radiation. The new sensor as said, is constituted by an optical fiber and a SiPM (Silicon PhotoMultipier), (Figure 4).

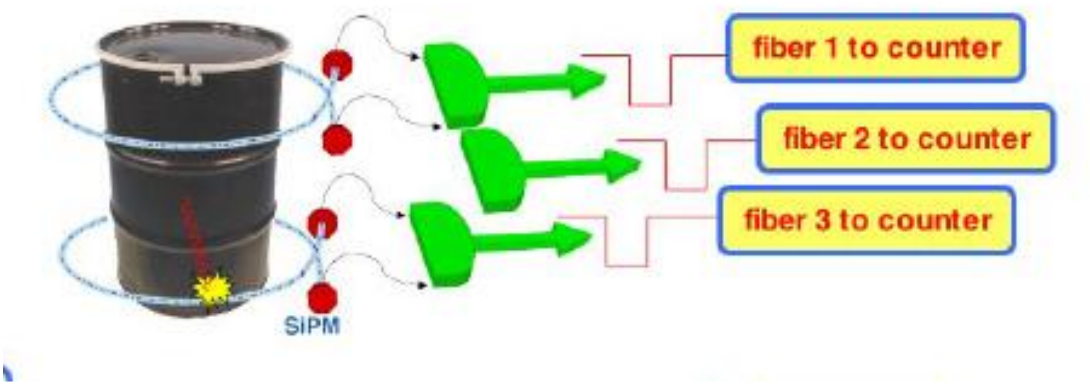

Fig.4 Relation between SiPM and optical fiber

This system is able to acquire information online about the time distribution of counts and about the space inside a storage site.

2.2.2 The Scintillating Fiber

For the system it was decided to use plastic scintillating fibers (Figure 5), because they can be subject to immediate geometric modifications: it is possible cut them at desired length and arrange them around the source.

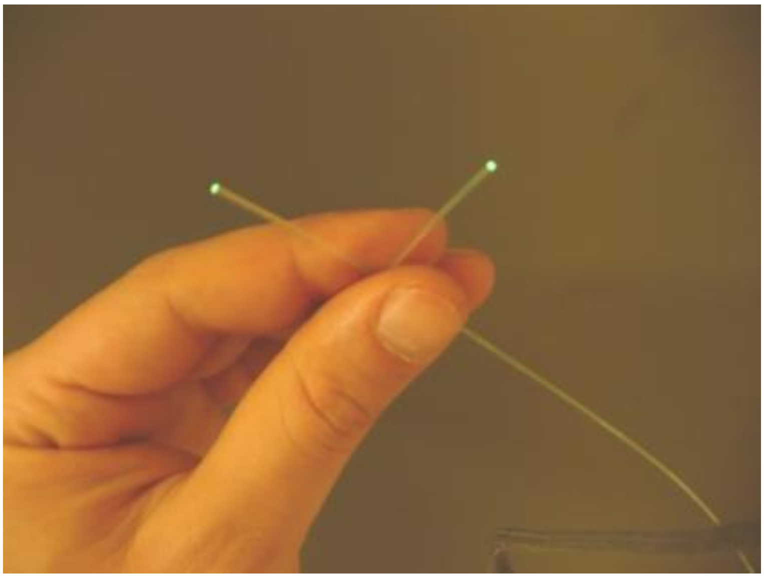

Fig.5 A scintillating fiber

Each detector consists of a scintillating optical fiber, 1-2 m long and 1 mm of diameter, which can be arranged around each drum in longitudinal and/or ring geometry (Figure 6). If both geometries are adopted, the leak position can be determined by combining the increased activity measured by a longitudinal and a ring fiber.

Fig.6 A possible arrangement of the fibers around a radwaste drum

2.2.3 The Silicon Photomultiplier

In order to detect the scintillation photons produced by the fibers, it was used a silicon photomultiplier SiPM.

This device consists of an array of identical photodiode cells, that operated above their breakdown voltage in the geiger avalanche regime, with output terminals connected together. The output signal is the analog sum from many independent identical cells.

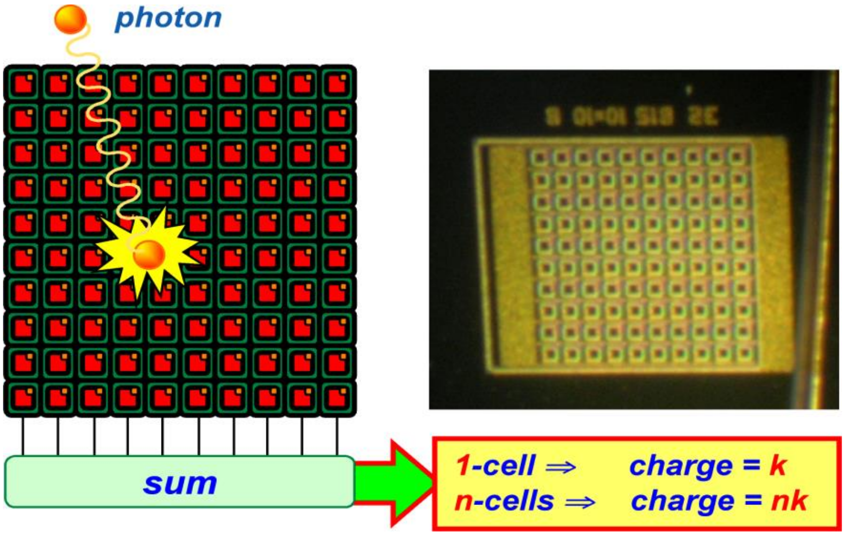

Fig. 7 Sketch of the SiPM operating principle: the output is a charge signal directly proportional to the number of elementary cells fired. The picture on the righthand side represents a close-up view of a prototype SiPM, produced by ST Microelectronics, featuring 10x10 cells on a 0.5mm x 0.5mm area.

It was decided to use two SiPM, operating together and that allow to set a threshold value suitable for each fiber.

The typical shape for the spectrum of a SiPM (tested with a laser source at low intensity) is shown in Figure 8.

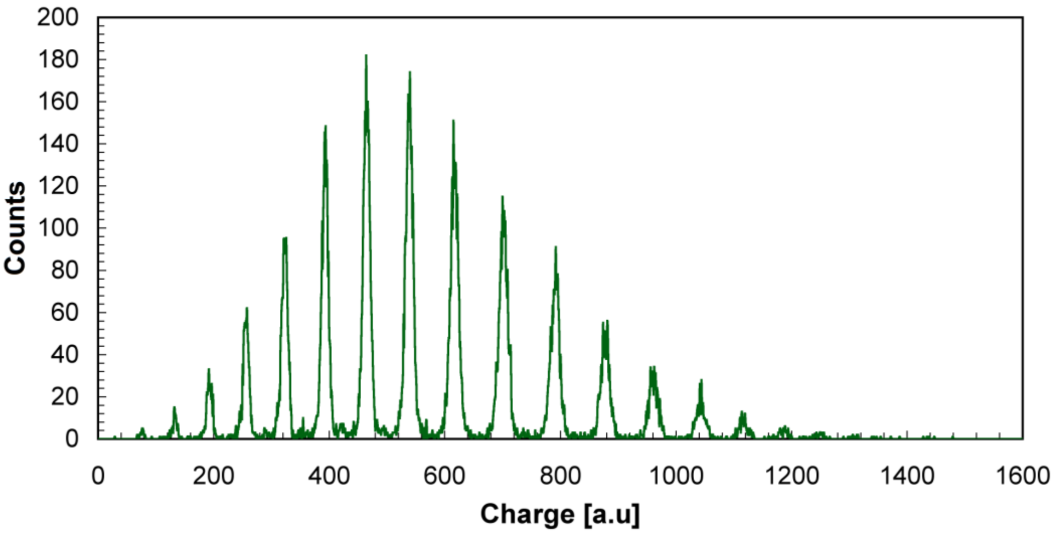

Fig.8 The charge spectrum of a SiPM illuminated with low-intensity light pulses produced by a fast pulsed laser. A linear amplifier developed at LNS was employed

2.2.4 Front-End Electronics

Each fiber provides two light signals which will be converted into electrical signals by the SiPM. Using the coincidence of signals at both ends, the radiation is detected on the fiber and by the determination of the time interval between the two signals, the position of radiation is obtained.

If we consider the gain of a SiPM (number of electrons generated by the avalanche effect of a single cell) is about 10^5-10^6, it is necessary use a linear amplifier. In this application are used linear amplifier with nominal gain of 200 and bandwidth of 4 Ghz, realized for this purpose at INFN-LNS.

So each of the two SiPM outputs from a fiber is fed to an amplifier, whose output goes into a discriminator as said. The outputs of the two discriminators are combined by the coincidence unit in order to produce an output pulse only when a predefined amount of light is detected at both fiber ends.

A single FPGA can handle several fibers at once. Figure 8 shows a sketch of the front-end electronics architecture for one fiber.

The output signal shape and type (analog or digital and polarity) are represented near each component.

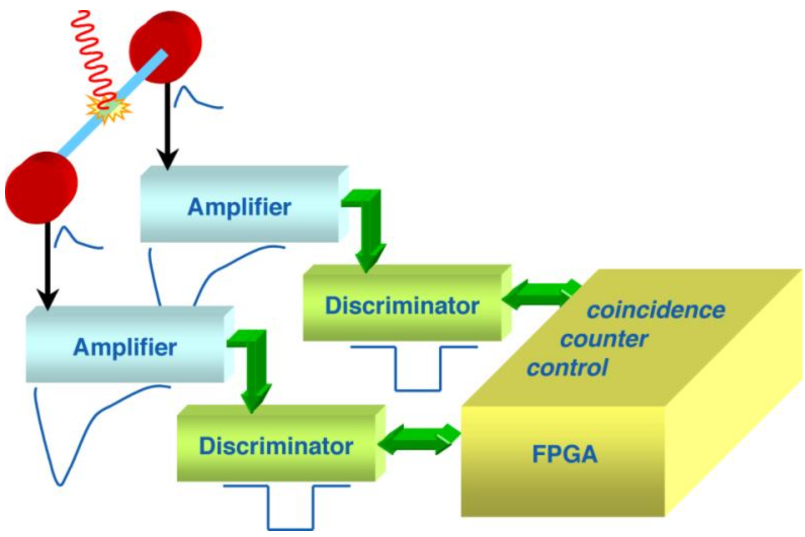

Fig.9 Sketch of the front-end electronics architecture

2.2.5 Counting and readout

An FPGA-based counting unit was developed. It was programmed to implement a set of logic coincidence circuits, with a corresponding set of counters, and to link the data and control communications with the main console. FPGA (Field Programmable Gate Array, Figure 10) is a programmable component that allows to build complex logic circuits by software programming.

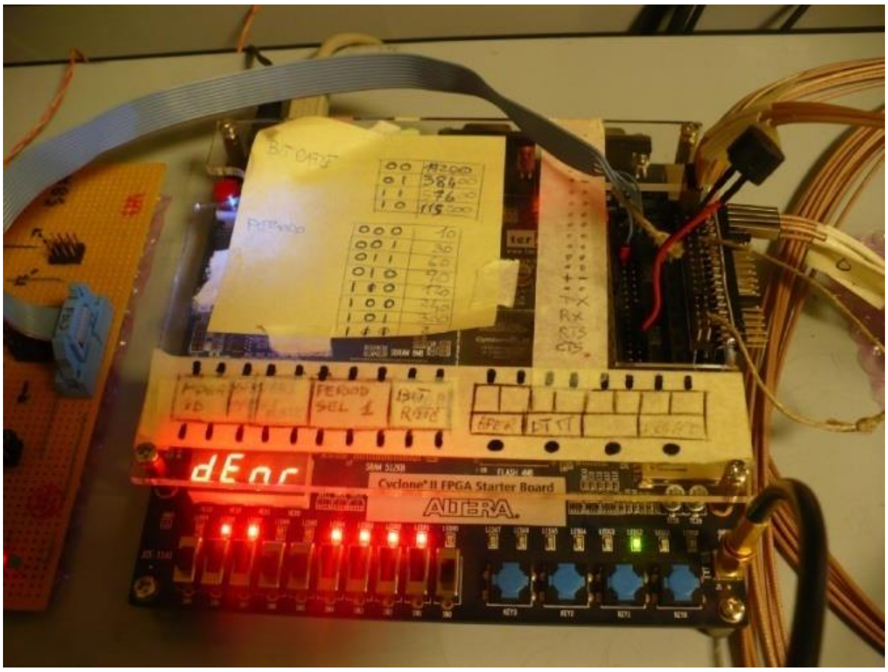

Fig.10 Control unit based on FPGA

The data transmission protocols implemented are UART RS232/RS422 (or RS485 multidrop).

A standard industrial bus (and its protocol) could be used for a real implementation (ProfiBus, ProfiNet, CanBus, Ethernet, etc.). For the wireless transmission the activity is currently focused on the implementation on ZigBee modules.

Once data reach the console, they are passed into a storage process. An online analysis allows to set an interactive synoptic table, useful to the operators. The storage process, will consist in the creation of a double copy of logfile, one local and one remote. The database at the end, will be available via web under properly authorized by subjects and entities.

Figure 11 shows the hierarchical data structure for a repository in the DMNR architecture.

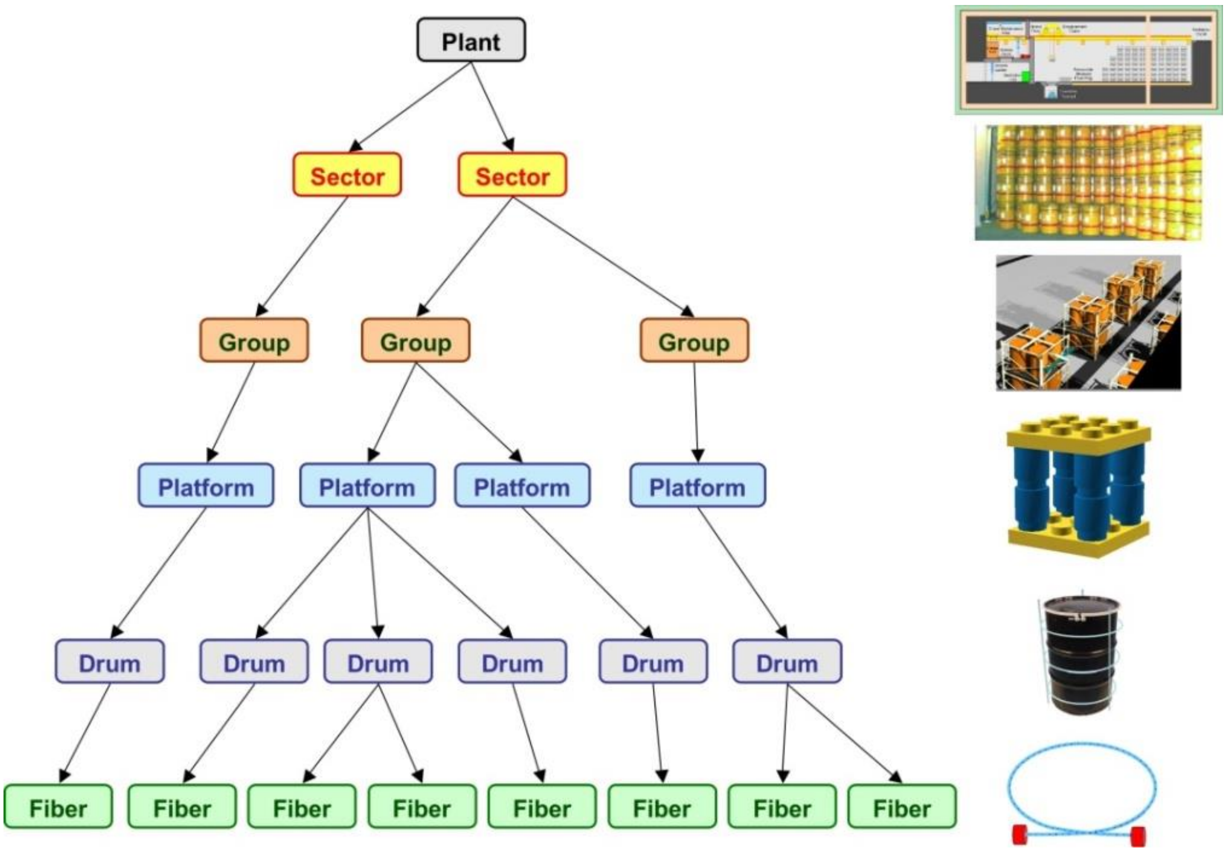

Fig. 11 The hierarchy structure for a repository in the DMNR architecture

The results of reviews could be archived online for a long time, and they could be available also to make statistical analysis.

2.3 Importance of the robotic inspection

The monitoring of waste in the short, medium and long term is one of the main problems in the storage of radioactive waste. We have already said that for the long-term waste disposal plans are provided; waste in the short and medium term instead are packed into drums or transported to dedicated sites.

In any case special care must be devoted to the prompt detection of possible leaks due to structural weakness or accident.

So it is important to make measurements with a certain time rate, to record results and to process them in order to detect anomalies in time series.

In this contest, a system for remote inspection becomes a must-have, like a robotic system for example. A robot could avoid to a human operators, exposition to the radiation, even low, following ALARA principle. An inspection procedure by robot allows a higher degree of automation and repeatability.

It is important so to include a robotic system in a real time monitoring system, to take information from the environment and to confirm the problems detected by sensors.

2.3.1 State-of-art

The inspection of nuclear power plants can be improved implementing an automated robotic system, in order to ensure better working conditions.

In the international area were developed four complete robot prototypes in scale. All of these are composed by a mobile vehicle, equipped with a package of sensors that allow to identify automatically rust and corrosion.

- SWAMI II
- ARIES

- ABCD
- IMSS

SWAMI is an Autonomous Mobile Robot for Inspection of Nuclear Waste Storage Facilities (Fig. 12).

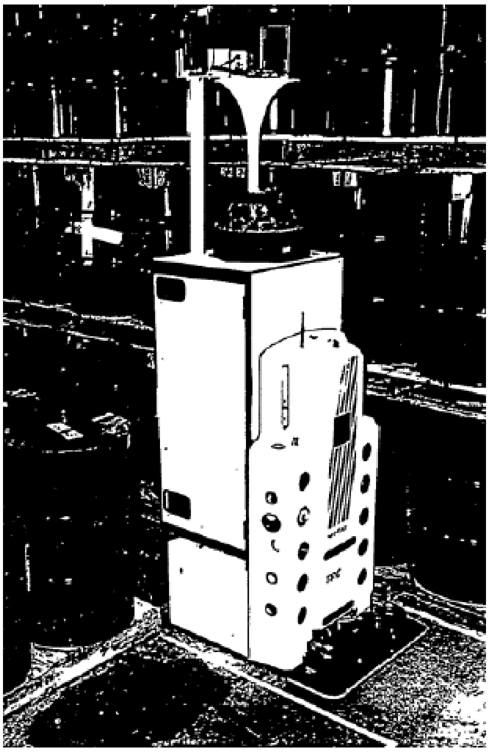

Fig.12 Robot SWAMI

Two prototypes were developed. The last, made in 1995 was called SWAMI II, and it was developed at Fernald's TS-4 .

SWAMI II has the ability to perform a comprehensive inspection and to reduce the operator workload. It uses a structured light system to detect drums

It has two problems that occur in drums: damage and corrosion.

The last one is difficult to detect visually, so this robot can make a geometric inspection in order to detect blisters and to identify an imminent containment failure.

The system uses also laser line generators and CCD cameras to obtain range-to-surface data. To obtain an adequate signal from the projected laser line on the drum surface, the orientation of the sensor must be calibrated continuously as the vehicle passes each drum. Each sensor module will be mounted on an arm with a pan unit, to maintain the required sensor-drum geometry. Data from the geometric inspection will be transmitted to the computer for operator analysis.

The light system requires lasers and cameras to be accurate and to find the relative center of the drum. A drum localization subsystem uses ultrasound sensors to locate each drum during the inspection.

ARIES is a Robotic Inspection Experimental System (1995). It is designed to navigate into rows of drums while it performs an automated visual inspection with cameras positioned in order to inspect the drums. While leaks or damage are detected, the information is maintained in a database that can be used by operators.

Fig.13 ARIES

The mobile robot system is designed to conduct routine inspection of stored waste drums, with intelligence and navigation capabilities.

The system is divided in various subsystems:

- a base vehicle that have onboard ultrasonic system, navigation and collision avoidance and radio communications systems;
- an autocharging station with dock capability;
- work packages for the manipulation of cameras and instruments;
- onboard and offboard computing systems for mission planning, management, and reporting.

ABCD is the acronym of Automated Baseline Change Detection System (1999).

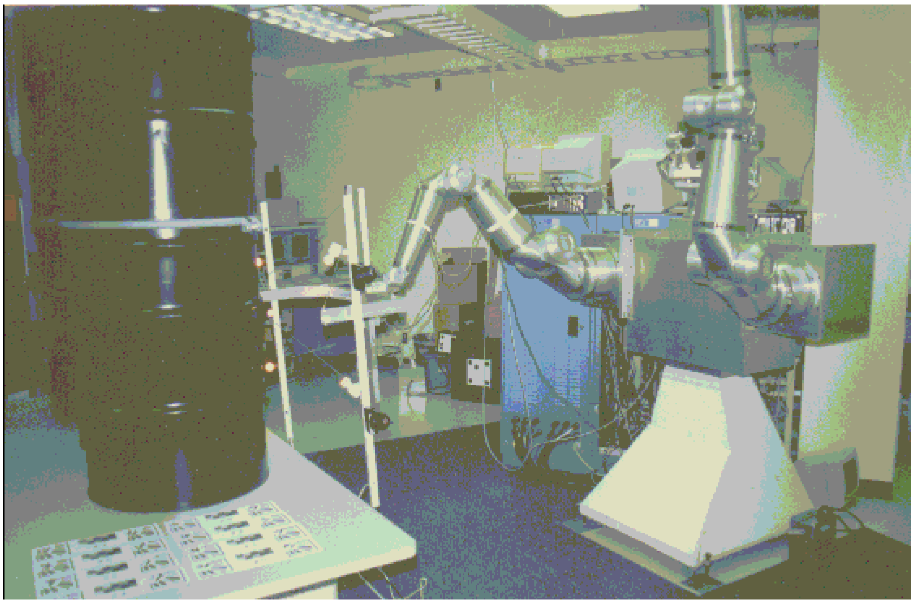

Fig. 14 ABCD

Lockheed Martin's ABCD sensor system integrates robot control and image processing to acquire and identifies targets, to compute sensor poses and to reposition the sensors.

The ABCD project embodies two technical strategies:

- Real-time determination and identification of drums with full 3-D pose (position and orientation) ;
- Registration of image in order to change the pose of the robot through analysis of stored images.

The main components of the ABCD system are shown in the figure 14. In routine operations, the base platform moves the sensor and stops when the sensor is centered respect a label. The sensor helps system to place the camera in the same pose that was used for a reference image. A new image so is compared to the reference image. The image comparison is based on image subtraction.

May be performed also spectral analysis, image analysis and additional images can be saved for subsequent inspections (for example, image analysis may be used to reduce false positive).

If image comparison ends positively, the unit passes inspection. If it do not passes, other actions (like human intervention) could be taken. With this procedure, there is very low risk of failure and human intervention is limited.

The Intelligent Mobile Sensor System **IMSS** is able to operate in narrow aisles.

Fig.15 IMSS

It uses integrated sensors for detection of leaks, and it uses a website interface for inspection planning, correlation of data and generation of report. The robot would be able to solve assigned mission, to collect required data and to report data when the mission was completed.

The most important subsystems of IMSS are the inspection sensors, the autonomous navigation system and the integrated database system.

The sensor systems include commercial components, the same designed to survey the Martian surface .

This robot can solve the following tasks: to locate the drums, to detect surface dents, to measure drum tilt, to plot in a three dimensional space the surface of the drums. In order to build a map of the environment was used structured light or laser. The reasons are:

- the drum surface is smooth;
- stereo vision algorithms have computational problems than structured light or laser .

2.3.2 Robotic Arm and DMNR

It can easily understand how a cart or even a walking robot is not an advisable solution for remote inspection, essentially for space constraints due to two reasons:

- The free space inside a storage site is limited;
- The disposal do not allow the inspection of internal drums.

A possible solution can be a robotic arm carried by a crane, which can be positioned over the destination platform. The navigation would be based on 3D site map generated by CAD files. An arm can be made in a simple way, it would be reasonably cheap and can be easily integrated into preexisting structures. It must be slim but extensible and it should be able to carry a video camera and a lightweight radiation detector.

CHAPTER III

Simulation of a manipulator

3.1 Introduction

The reason for the development of a robotic system, as already mentioned, is the reduction of human-radiation interaction. The possibility to use a manipulator decreases the inspection time and increases the inspected areas.

The first part of the work is aimed to the simulation of a robotic arm. The simulation involves the problems of leakage of radioactive material and the creation of an interface for the control of the robot.

Fig. 16 Example of non-automatic inspection

3.2 VRLM and MATLAB

To simulate a real situation MatLab and VRML have been used.

MATLAB (matrix laboratory) is a numerical computing environment programming language. Developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran.

It is used by millions of people in industry and universities for its tools, in support of the most varied fields of study, and runs on multiple operating systems, including Windows, Mac OS, GNU / Linux and Unix.

Thanks to Robotics Toolbox, widely used in the field of Industrial Automation, it was possible to create a model of manipulator, which will be described later. The results of the toolbox analysis, have been saved in the MatLab workspace and sent to **Simulink**, an additional package, that adds graphical multi-domain simulation and Model-Based Design for dynamic and embedded systems.

To make the simulation more realistic, was used the VRML programming language.

VRML (Virtual Reality Modeling Language) is a programming language that allows to simulate objects in a three-dimensional virtual world. Using the VRML it is possible describe virtual environments containing objects, light sources, images, sounds, movies. These worlds also can be animated and they can also have complex interactivity.

A .wrl file, is a simple text file that uses ASCII characters (as HTML, for example) that contains all the necessary commands to describe a three-dimensional scene. The VRML does not go over what the other modeling programs already do. In fact the results reached by a rendering program, are higher in terms of quality and speed.

But there is another aspect favorable to VRML. The file published on the Internet can be accessed from any machine and from any platform, in the same way of HTML documents.

3.3 Description of the structure with drums (pallet)

Before talking about the manipulator, it is necessary to talk about the structure that interacts with the arm.

The pallet is composed by an iron structure. Inside the pallet there are drums, at the same distance. This structure is composed by a base, where the drums are placed and pillars that close the structure in a cubic shape.

The manipulator will be carried through a crane, located on the storage site and then engaged to the structure.

The support and the prototype drums have been realized physically at INFN-LNS, under the supervision of an mechanical technician. The following images show design drawings and the real implementation.

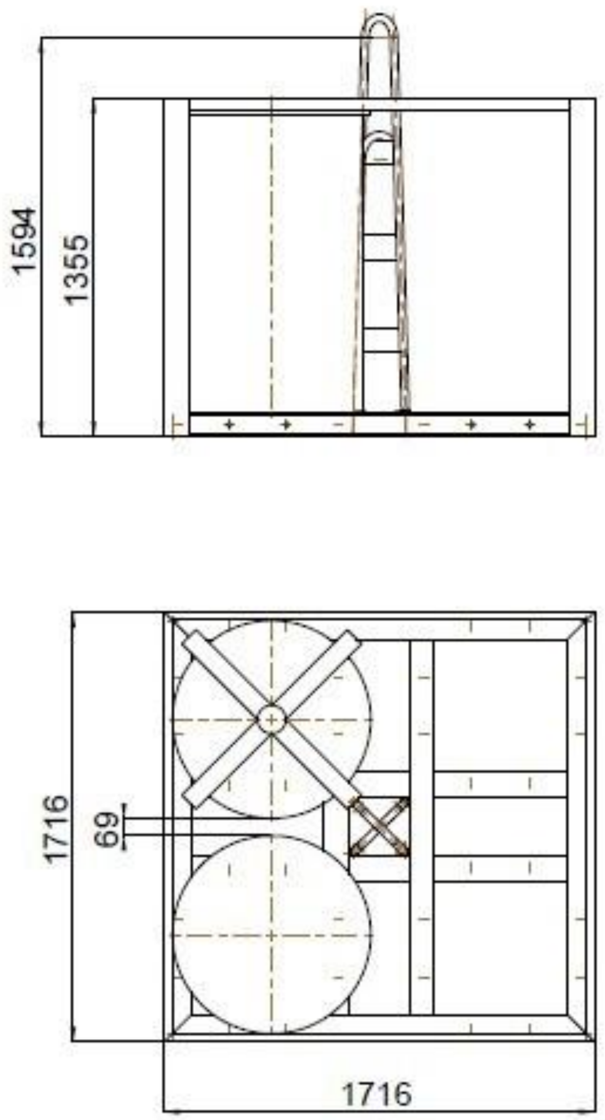

Fig. 17 Iron structure

The dimension of the structure are:

- side: 1,716 m
- distance between two drums: 6.9 cm
- distance frame-structure: 20 cm

Fig.18 Structure built at the INFN-LNS

The drum is composed by supercompact plates (220 liters) which contain the radioactive material mixed with cement. The plates are inserted inside the structure.

Below a figure that show the pallet of drums (empty).

Fig.19 Pallet of drums (empty)

Here instead the 3D simulation of the pallet in VRML.

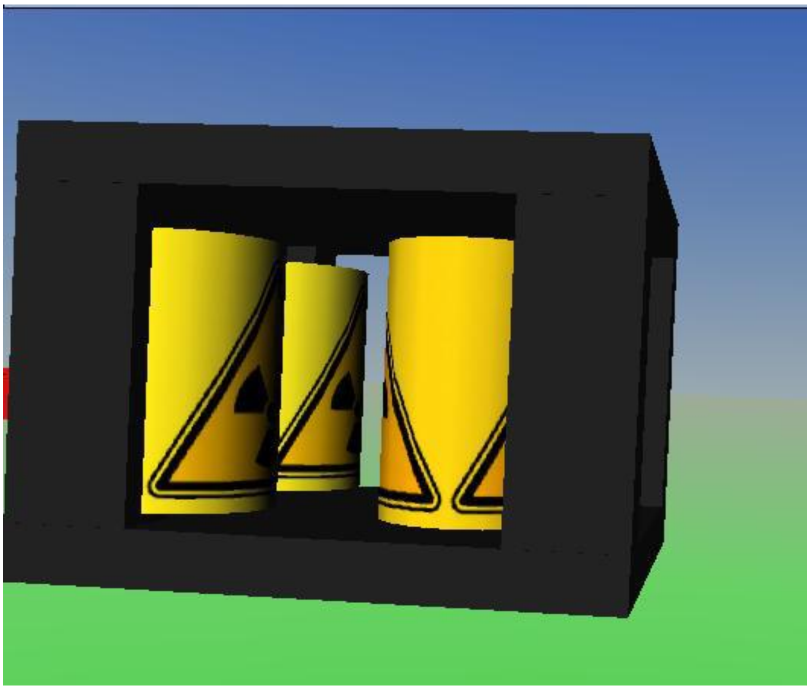

Fig. 20 Pallet simulation on VRML

3.4 Manipulator design

It will now study the robotic arm. It is presented as a manipulator composed by four link, a prismatic joint, two revolute joint and a rotating end-effector. The manipulator has five degrees of freedom. The prism in the upper part of the link is the electromagnet, in order to dock the manipulator to the pallet.

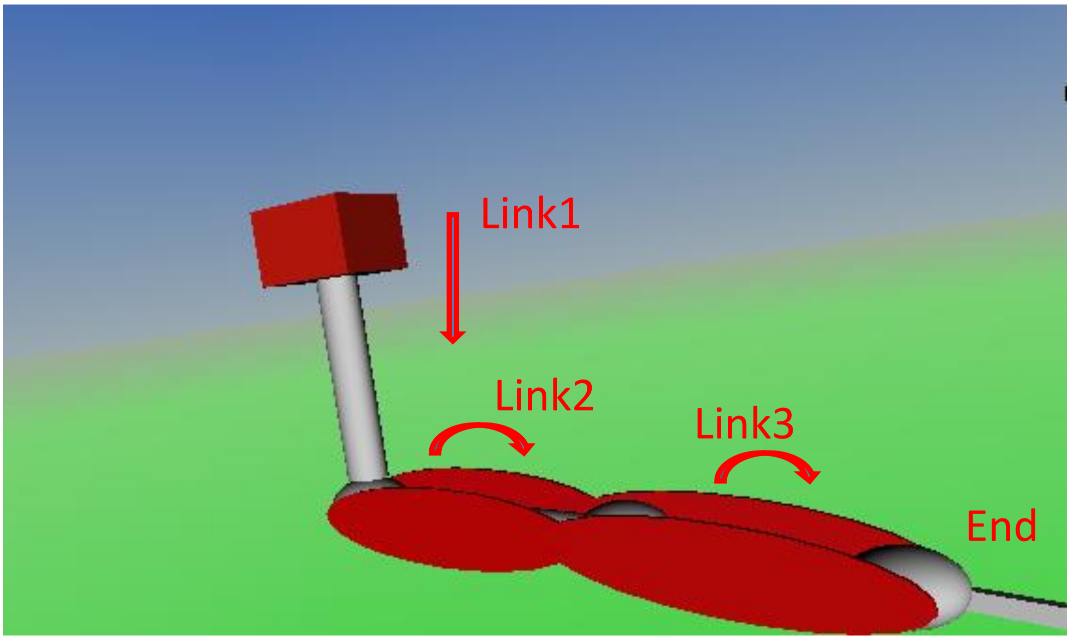

Fig.21 VRML model of manipulator

3.4.1 Frames of reference

It wants to represent the final position of the end-effector respects a fixed base reference. It must to fix a reference system for each joint according to the Denavit-Hartenberg convention.

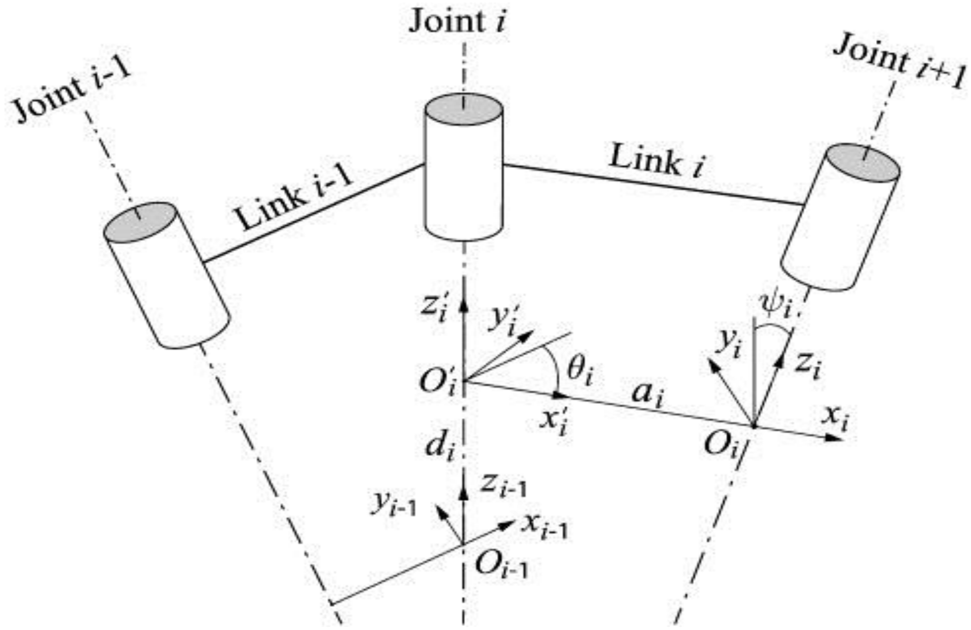

Fig.22 D-H reference for each joint

In MatLab Robotic Toolbox to find the position of end effector were used the following D-H parameters:

- ai, distance between zi-1 and zi (constant = "length" of the arm);
- αi, twist angle between zi-1 and zi around xi (constant);
- di, distance between xi-1 and xi measured in the direction of zi-1 (variable parameter in a prismatic joint);
- θi, the angle between the axis xi-1 and xi around zi-1 (parameter variable in a revolute joint).

In Tab.1 are shown the Denavit-Hartemberg parameters used in the simulation:

Link	a1	αi	di	θi
0	0	pi/2	q1	0
1	1	0	0	q2
2	0.8	0	0	q3
3	0.2	0	0	q4
4	0.2	pi/2	0	q5

Tab.1 D-H parameters used in simulation

3.5 Kinematics theory

The goal of the **direct kinematics** is to find the position of the end-effector starting from the configurations of the joints.

The determination of the frame of reference of a joint, according to the D-H convention, gives us the possibility to find the transformation matrix, which represents the transition from the frame of reference i to the i+1. So it is possible to determine the position of the end-effector simply considering rotation matrix, which is expressed as a succession of partial rotations. Each rotation is defined respect to the previous (rotation in current tern).

The composition of successive rotations respect to the current triad is obtained multiplying from left to the right the individual rotation matrices, in the order of rotation.

The **inverse kinematics** problem allows to determine the value of the joint variables from the position and orientation of the end-effector.

The direct kinematics admits always a solution, the inverse kinematic problem could have multiple solutions, so there are multiple ways to place a link.

It is possible to have infinite solutions at the inverse kinematic problem, in this case it speaks about "redundant manipulator" (number of link greater than the DOF).

To avoid this problem, it did not use the inverse kinematics function of the MatLab robotic toolbox, but it was defined a new function, following geometric considerations.

So the study of the inverse kinematics was made fixing the prismatic joint. This particular case is called **two-link planar manipulator**.

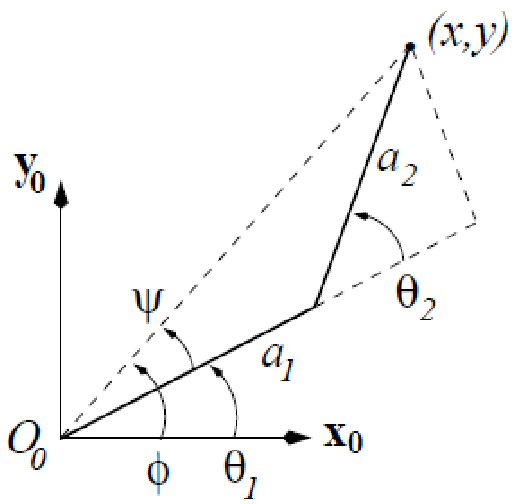

Fig. 23 Two-link planar manipulator problem

The equation implemented in Matlab to find the angle for the link2 is:

$$\theta_2 = \pm 2 \tan^{-1} \sqrt{\frac{(a_1 + a_2)^2 - (x^2 + y^2)}{(x^2 + y^2) - (a_1 - a_2)^2}}$$

while for the first link have been used the following equations:

$$\begin{aligned}\phi &= \text{atan2}(y, x)\\ \psi &= \text{atan2}(a_2 \sin\theta_2, a_1 + a_2\cos\theta_2)\end{aligned}$$

$$\theta_1 = \phi - \psi$$

The approximation to consider the problem planar is acceptable, because in our case the manipulator moves along the axes Z and X, maintaining Y axis equal to 0 in every situation.

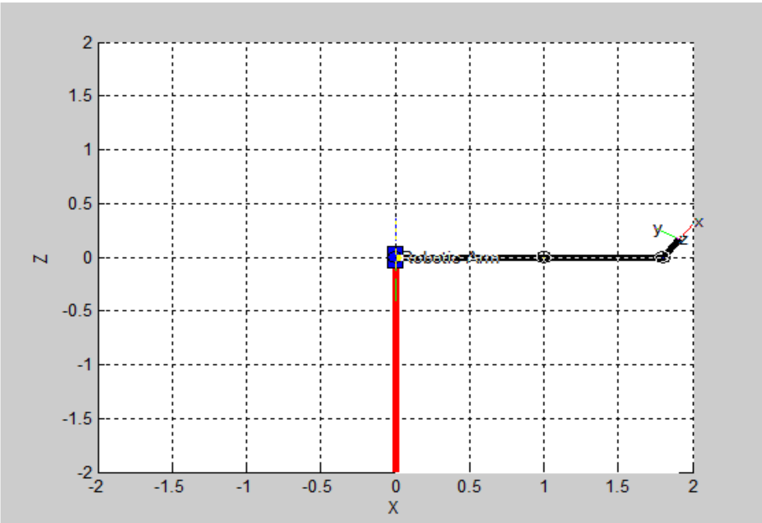

Fig. 24 Model of the manipulator in MatLab, using Robotic Toolbox

3.6 *MatLab users interface*

To make realistic the simulation has been designed an user interface (GUI). It is possible to activate different manipulator functions .

The interface is divided in two panels:

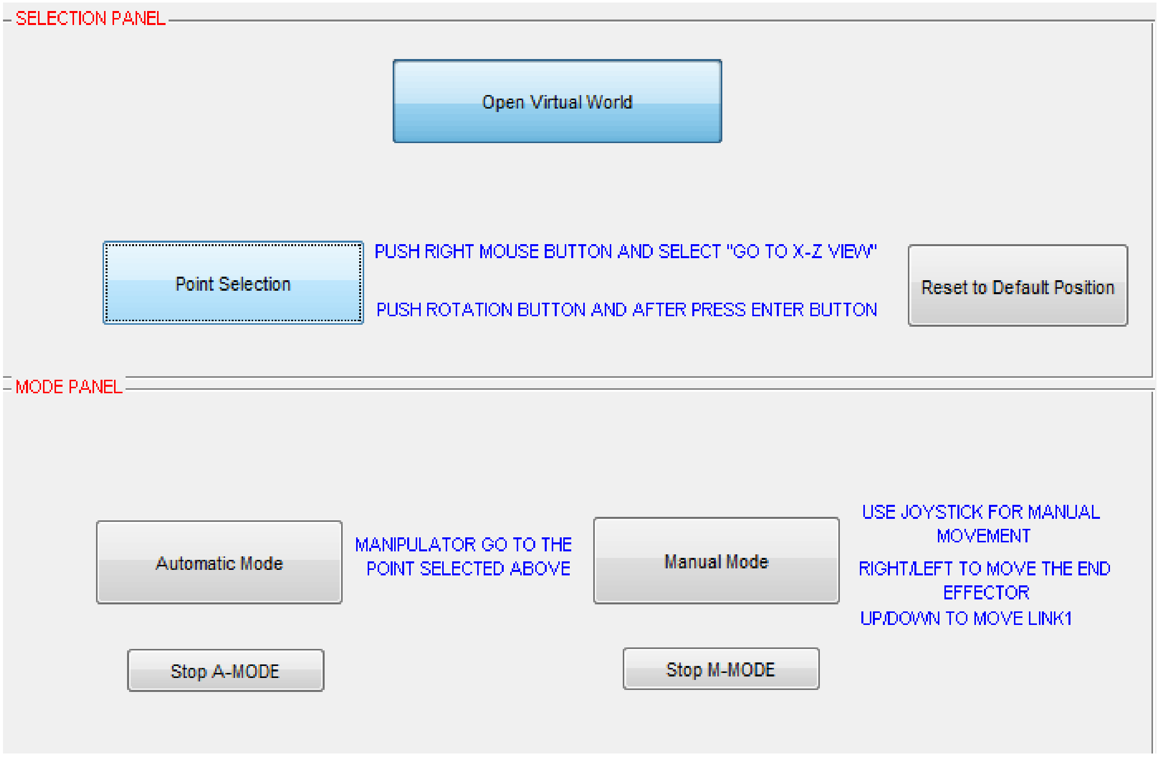

Fig.25 MatLab Interface

The first is said SELECTION PANEL. Using this panel it is possible to open the virtual world (Fig. 27), to choose the point to be tested in space (Fig. 26), and to return to a default position of the manipulator (Fig.28);

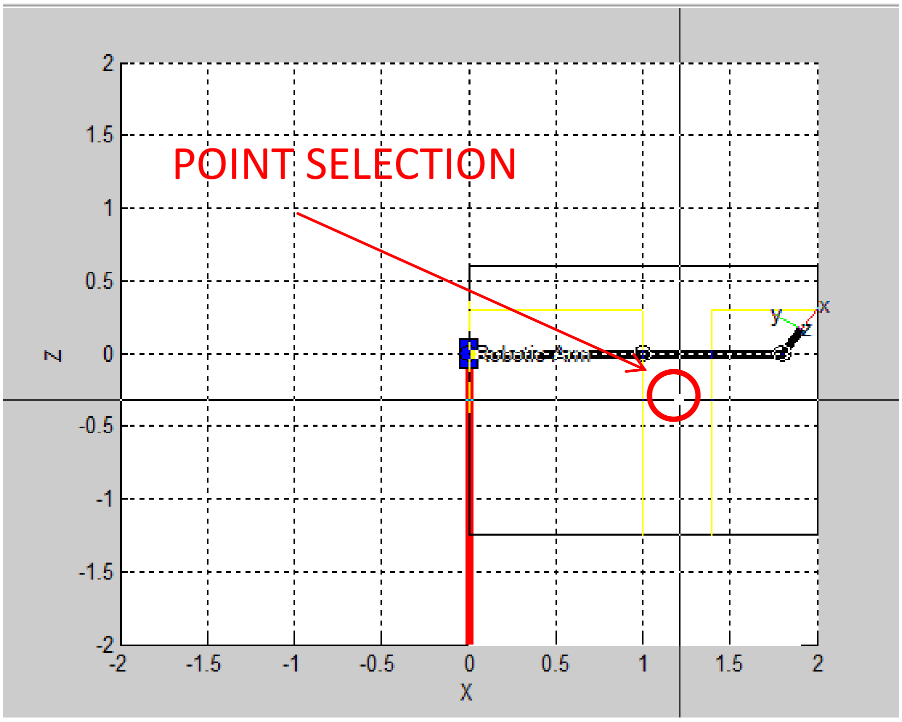

Fig.26 Detail of point selectioned to be inspected

You can choose with this option, the point to be inspected in relation to the layout of the drums (yellow lines). Automatically will be calculate the inverse kinematics.

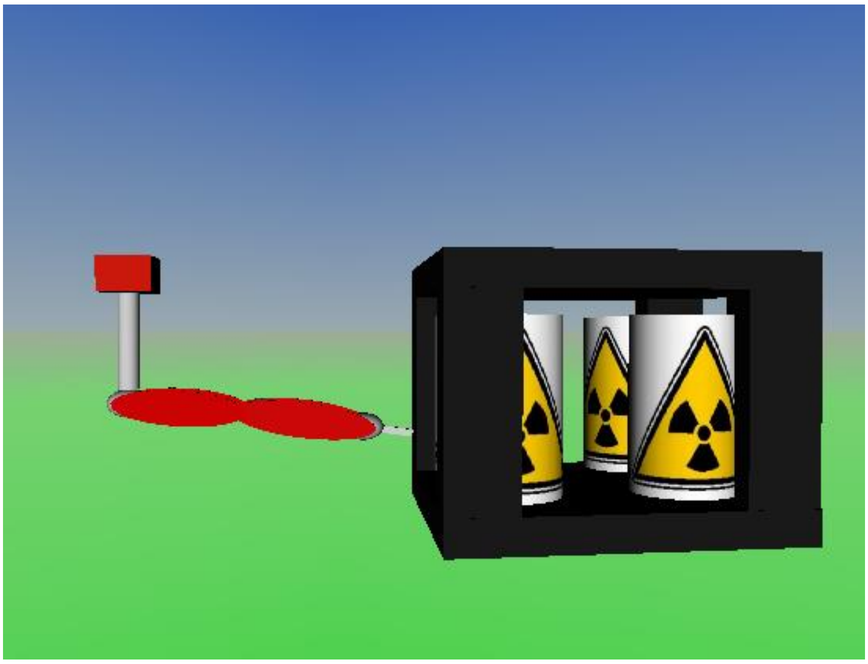

Fig.27 Virtual world made by VRML

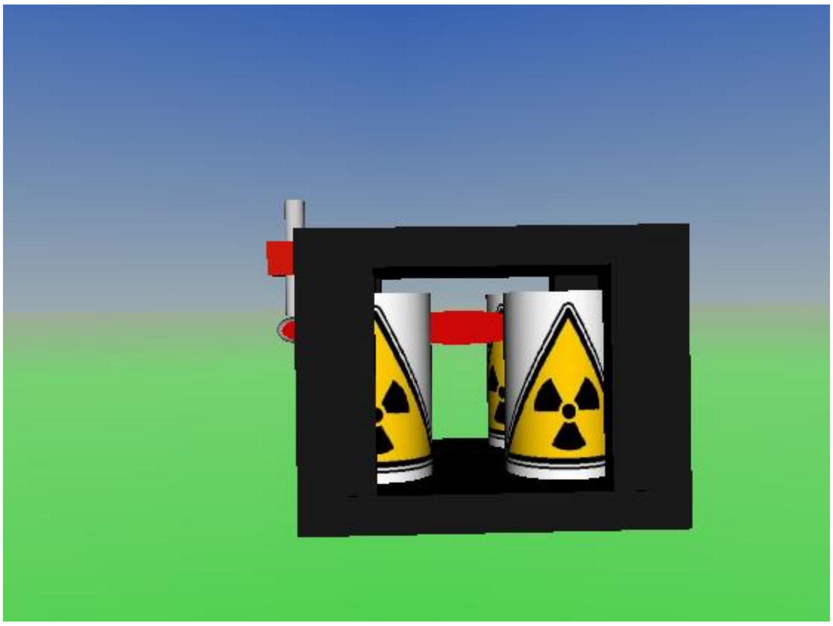

Fig.28 Default position chosen

The second part of the GUI is the MODE PANEL, that allows to choose Auto or Manual mode.

In the **Automatic Mode** the manipulator reaches the desired point through inverse kinematics previously discussed.

After the calculation of the angles of the various joints, it is possible, through the MatLab function jtraj, to create a trajectory that brings the manipulator to a selected point. Subsequently a Simulink block, characterized by a proportional-integral control in feedback, ensure the stability of the system.

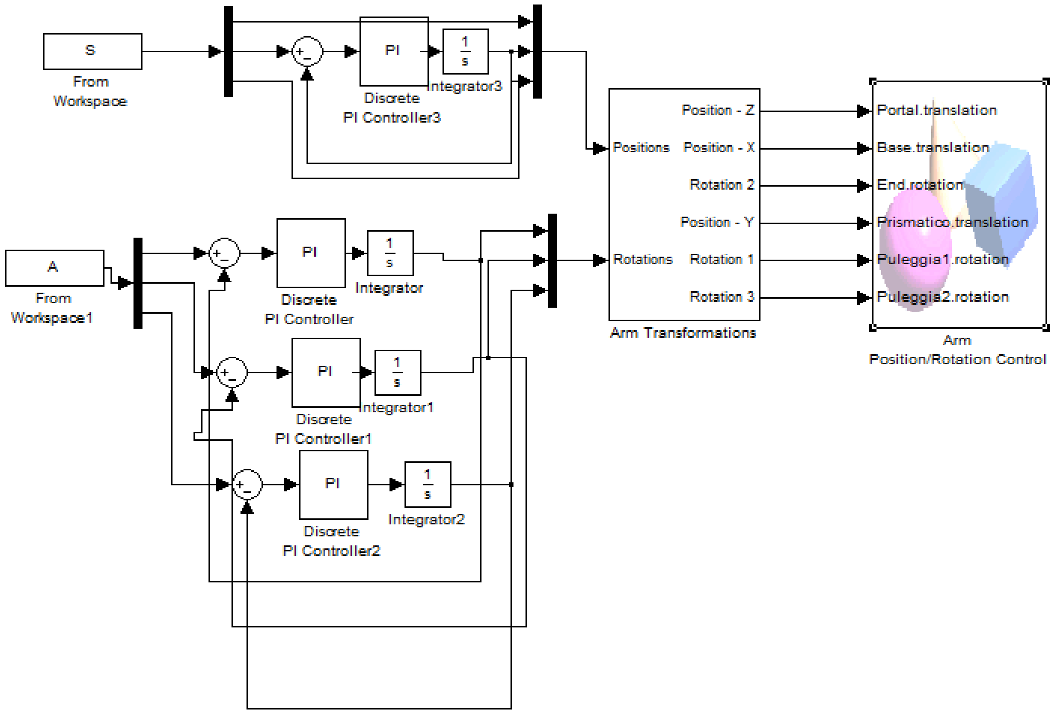

Fig.29 Simulink model of the Automatic Mode button

If the manipulator reaches the desired point, the **Manual Mode** can be activate.

It consists in the possibility to move the end-effector and the various link with a joypad, in order to be able to explore the peripheral areas of the drums, also with the help of a camera-view (Fig.31), applied to the end-effector, which simulates a real camera.

This second part was made by another Simulink model (Fig. 30). In this model was used the Pilot Joystick block. The outputs of this block are roll, pitch and yaw (rotation variables of the joystick). It were also used a gain block to change the sensitivity of the joypad and an integrator, in order to have appropriate values for the input of manipulator.

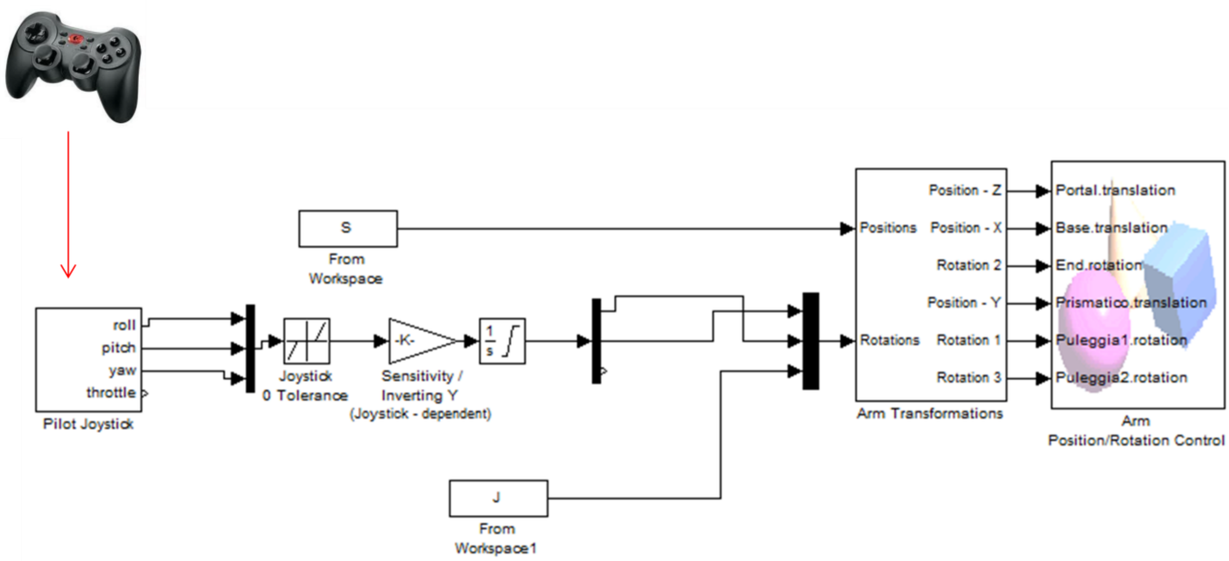

Fig. 30 Simulink model of the Manual Mode button

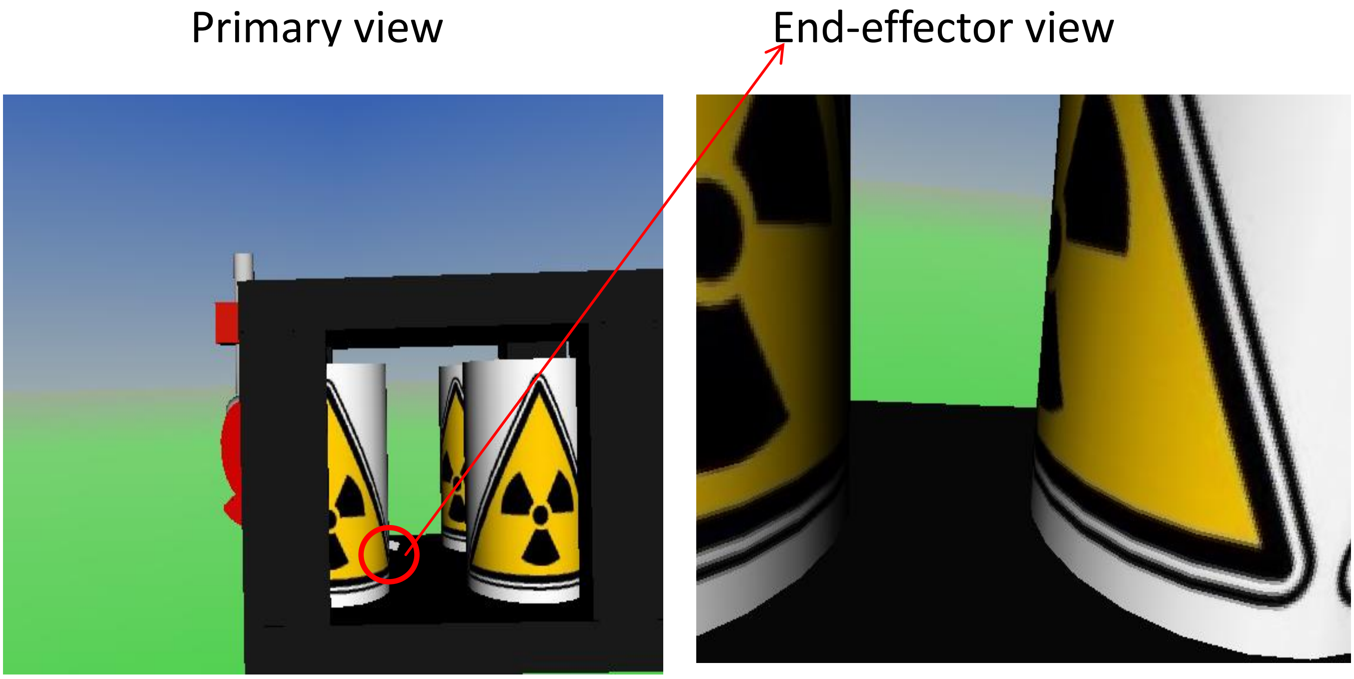

Fig.31 The two view of the arm in simulation

CHAPTER IV

RadIBot: Radiation Inspection Robot

4.1 Introduction at the prototype

After the simulation it was implemented the real manipulator.

The first ideas on the implementation was focused on a robot with belts, that was not the best solution, for problems of consumption of materials.

Fig.32 Robotic Arm with belts

So it was tried a solution that was more robust, more versatile, but especially that responded to the characteristics of weight and dimensions suitable to the task of monitoring.

In this context has been realized RadIBot, a robotic arm with 4 degrees of freedom, to be able to film, to take pictures of damaged drums and to reveal leaks through a radiation sensor.

4.2 Design and mechanical realization

For the reasons indicated it was thought at an aluminum structure, thin and light, that interacts with the engines.

4.2.1 Realization of links

The robot has 3 links and an end-effector. The **first link** was initially designed as a prismatic joint, but the possibility to use crane for vertical movement suggested to implement it as static link.

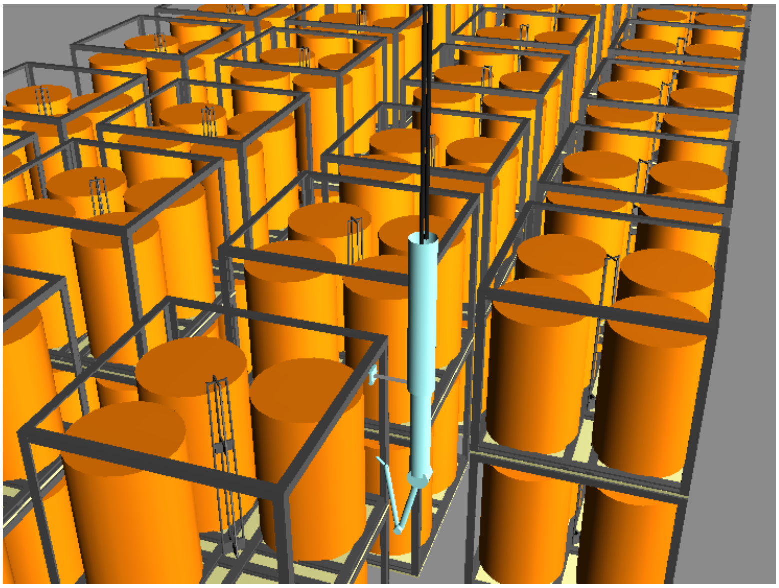

Fig. 33 Simulation of the crane-arm interaction

The **second** and the **third link** are made in order to obtain two revolute joints. They must mechanically support all the structure. They have the size of 25 cm of length, 6 cm of width and the weight of 80 g per link. The shape of the link is rectangular, and it is empty to save weight.

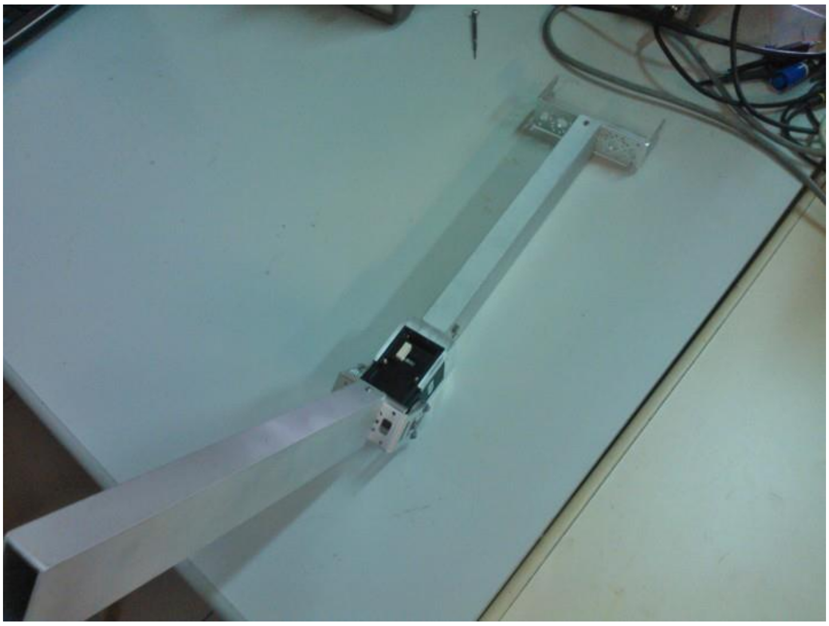

Fig.34 Detail of the third-fourth link

The following image shows the drawings made at INFN-LNS, on which is based the realization of the second and the third link.

It is possible to observe the two views and link measures.

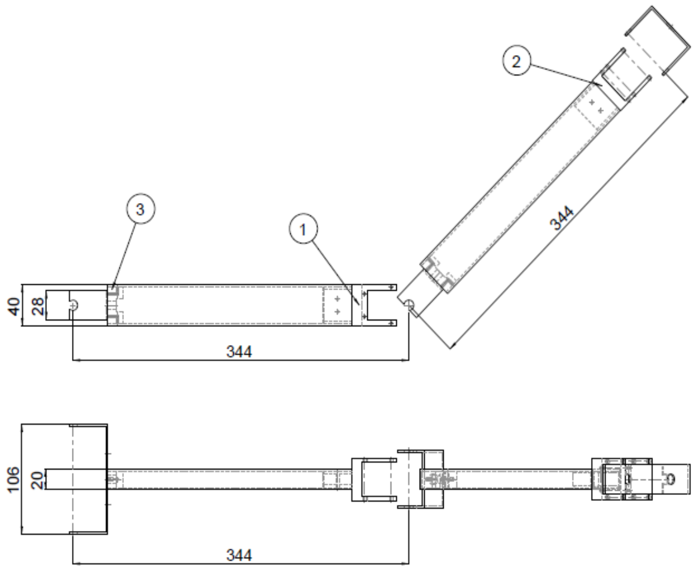

Fig.35 CAD sketch of the third-fourth link (scale 1:1)

Designed by Massimo Piscopo

In order to connect the motor with the links, has been made, always at INFN-LNS workshop, a support clamp of the same dimension of the motors, to avoid any yokes.

Fig.36 Detail of the clamp

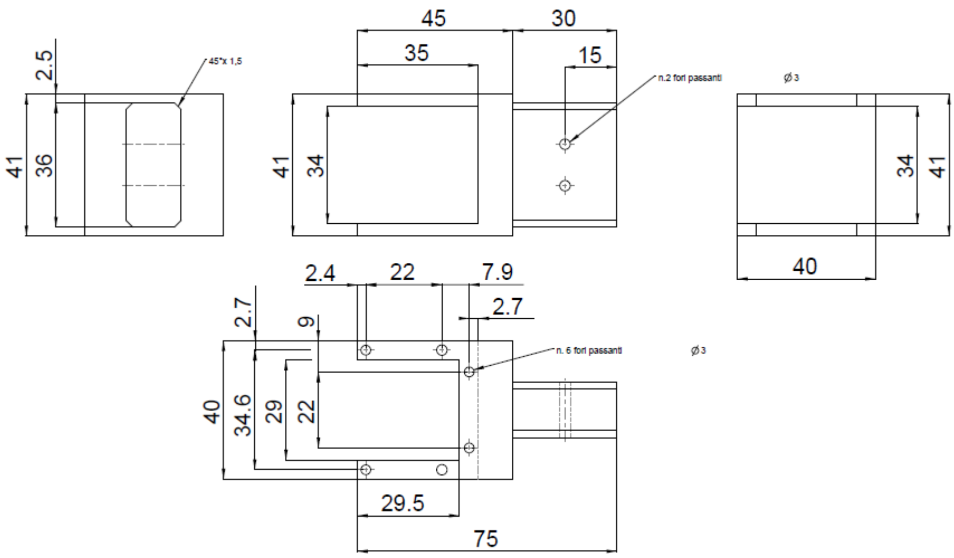

Fig.37 CAD sketch of clamp (scale 1:1)

Designed by Massimo Piscopo

The **end-effector** is composed by a camera, a radiation sensor and a rectangular structure of 10 cm of length and 30 g of weight.

It has one degree of freedom (left and right), and the tools are directly connected to the computer via USB connection. The camera used was a commercial TOSHIBA camera, with a resolution of 640 x 480.

Fig.38 End-effector with camera

4.2.2 The engines

The choice of engines has been difficult because it had to solve the problem of high torque required, in relation to the length of the arm (65 cm, without the static first link, and 1kg of payload at the end effector).

It were chosen two engines of the manufacturer Dynamixel: MX106R and RX64.

The **MX106R** is a very powerful engine. It has a torque of 106 km-cm, a baud rate of 8000 bps ~ 4.5 Mbps, a rotation angle of 360 degrees, PID control, absolute encoder (12bit, 360 degree), resolution of 0.088°, possibility of communication with RS485, feedback in Position, Temperature, Load, input Voltage, etc..

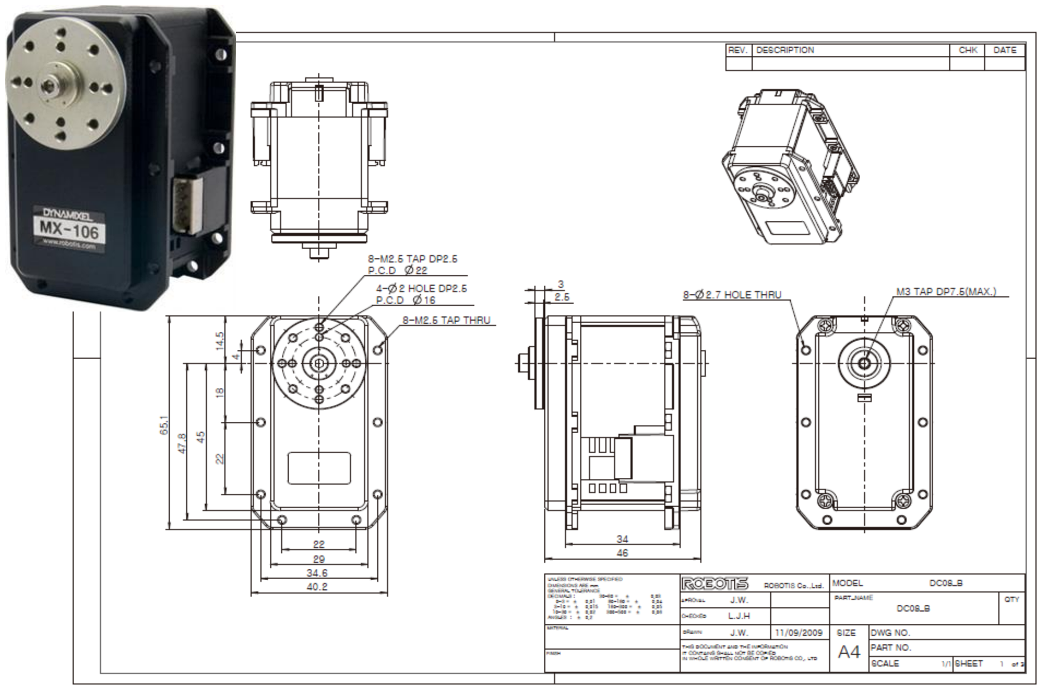

Fig.39 Dynamixel MX106R

This engine has been chosen for the possibility to use two of them in parallel to double the torque, through the dual mode joints, that will be discussed later.

So two of these engines have been used to actuate the link two, that support all the weight of the arm.

The **RX64** have a torque of 64 kg-cm, a rotation angle of 300 degrees, resolution of 0.29°. Possibility of communication with RS485, feedback in Position, Temperature, Load, Input Voltage, etc..

It is an engine less accurate than MX106R, but can be used to move the end-effector or to actuate the third and subsequent link, that not requires very high torque.

The power supply recommended for both engines is 12V.

The dissipation of current of the motors is of the order of few amperes under load, so the robot will be powered with a 12V battery that allows a high current consumption.

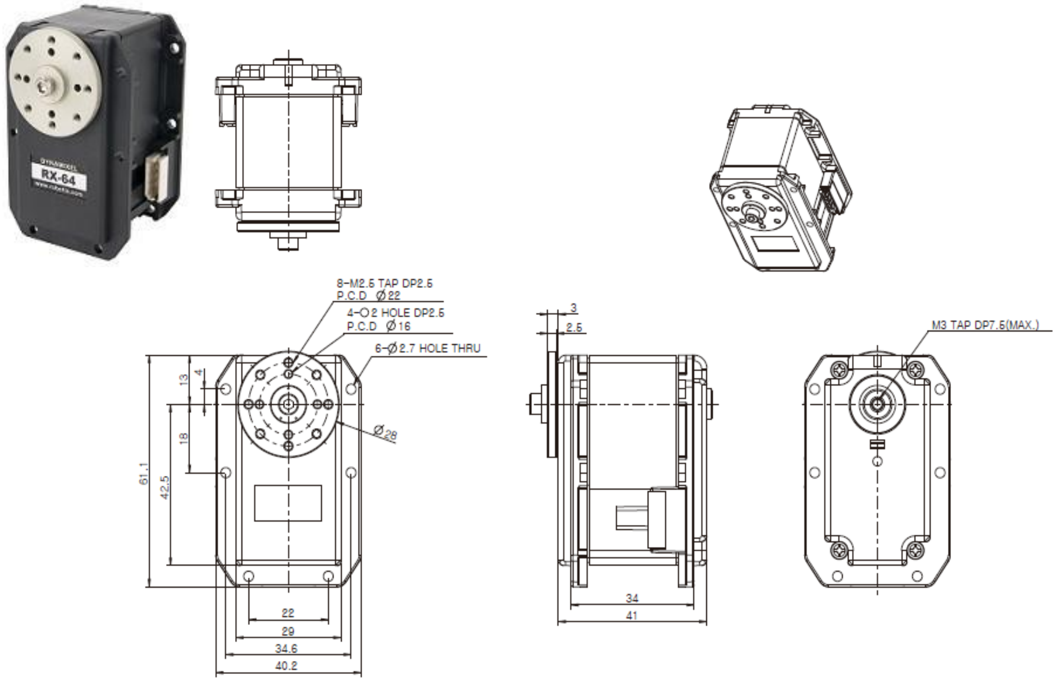

Fig.40 Dynamixel RX64

4.3 Electronic components

The manipulator interact with an environment harmful for the electronics, so to use external electronic components could lead to problems of consumption on the time.

It was decided to use engines that limited electronics.

In fact it is possible to interface dynamixel engines in master-slave configuration, also with high level interfaces as LabView or MatLab, without additional electronics.

The computer is the master that controls the motors, linked together through 4pin cables (slaves).

This approach is perfect for a machine-operator system. Through the master is then possible for the operator to collect important information or move/stop directly the manipulator.

4.3.1 USB2Dynamixel

The communication between the engines and the PC has been realized through the device USB2Dynamixel.

Fig.41 USB2Dynamixel

USB2Dynamixel is a device used to program Dynamixel directly from PC. It is connected to USB port of PC, and 3Pin and 4Pin connectors are installed, so various Dynamixels can be connected.

It is a USB/RS485 converter, so systems using a simple USB port, receive and transmit data to the engines.

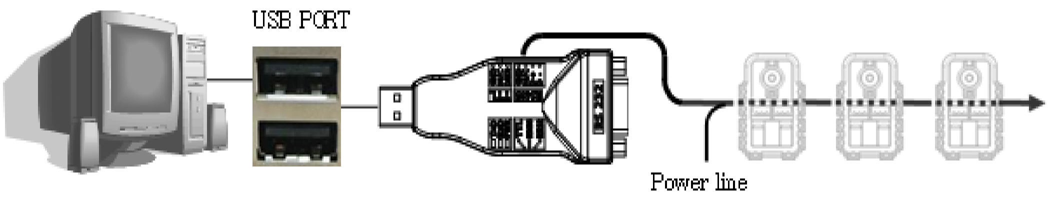

Fig.42 Dynamixel Control Using PC

To use the device, the correct drivers and the Dynamixel SDK have been downloaded and installed from the Dynamixel website.

Dynamixel SDK contains a lot of functions, for many high-level programming languages, which allow to transmit and to receive information from the engines.

4.4 *Software development*

There are many functions that can be used to communicate with the engines, and come from the API Reference of Dynamixel. Here it will list the most important that have been used. The functions are the same for supported programming languages.

- **dxl_initialize :** Initialize the communication, between PC and engines. It was defined port and baudrate of the engine;
- **dxl_set_txpacket_id :** The ID is inputted into instruction packet. It is possible give to the motor an ID or a BROADCAST_ID (for the execution of the same command by two or more engines);
- **dxl_set_txpacket_instruction :** Command codes are inputted into instruction packet. The most used instructions are INST_SYNC_WRITE (it is used to control several Dynamixels simultaneously) and INST_ACTION (it initiates motions registered in the Dynamixel);

- **dxl_tx_packet** and **dxl_rx_packet :** Commands that transmits/receives instruction packet to/from Dynamixel;
- **dxl_write_word** and **dxl_write_byte :** Commands to write value from Dynamixels;
- **dxl_read_word** and **dxl_read_byte :** Commands to read value from Dynamixels.

4.4.1 Example of code

This is a simple example in MatLab of code that allows to synchronize two motors, providing same reference for position, speed and torque.

The code will be analyzed in the three most important parts: Begin, Middle and final.

```
-------------------------------------------------------
   loadlibrary('dynamixel','dynamixel.h')

    DEFAULT_PORTNUM = 4;    % Com Port
    DEFAULT_BAUDNUM = 1;    % Baud rate
    INST_SYNC_WRITE=131;
    INST_ACTION=5;
    BROADCAST_ID    = 254;


    Goal_Pos = 512;      % Position to move to
    Speed = 200;       % Speed to set
    Goal_index = 30;     % Index of Command in Library
    Speed_index = 32;    % Index of Command in Library
    torque_index = 14;   % Index of Command in Library


    pause on;
-------------------------------------------------------
```

The first part of the code contains the call of the library (contained in the SDK), the definition of port and baud rate, the various instructions, the variables to read and to write, and finally the indices of the variables.

```
-------------------------------------------------------

while(1)

         response1 =
calllib('dynamixel','dxl_initialize',DEFAULT_PORTNUM,DEFAULT_B
AUDNUM)

calllib('dynamixel','dxl_set_txpacket_id',BROADCAST_ID);

calllib('dynamixel','dxl_set_txpacket_instruction',INST_SYNC_W
RITE);
        %Move to position

calllib('dynamixel','dxl_write_word',BROADCAST_ID,Goal_index,G
oal_Pos)           % Set goal position
pause(0.01);


calllib('dynamixel','dxl_write_word',BROADCAST_ID,Speed_index,
Speed)               % Set movement speed

calllib('dynamixel','dxl_write_word',BROADCAST_ID,torque_index
,1023)

calllib('dynamixel','dxl_write_word',id,Goal_index,Goal_Pos)
% Set goal position
        pause(0.01);

calllib('dynamixel','dxl_write_word',id,Speed_index,Speed)
% Set movement speed

calllib('dynamixel','dxl_write_word',id,torque_index,1023)


-------------------------------------------------------
```

The central part of the code defines the set of instructions to create packages to be sent to the RS485. Each statement refers to a motor.

```
-------------------------------------------------------
 end
calllib('dynamixel','dxl_terminate');
unloadlibrary('dynamixel');
 -------------------------------------------------------
```

The final part of the code closes the communication and disassembles the library.

P.S. To understand the meaning of the values , can be read the Control Table on the Dynamixel website.

CHAPTER V

RadIBot Users Interface

5.1 Introduction at the interface

To interact with the robot is designed an operator interface, which contains the various windows presented in Chapter 3 and adds new functions, useful in a robotic system for monitoring. It is important to have a high-level interface, to manage something complex like a robotic arm. The operators (also without radiation protection experience) can use the interface to move robot and to make simple inspection activities.

It will be possible only command the revolute joints and the end effector, while for vertical movement the control system has already been developed by the company that built the crane and so it was not analyzed in detail.

5.2 Description of the interface

The interface is divided into four panels:

- AUTOMATIC
- MANUAL
- CAMERA
- CONTROL MANUAL

Fig.43 RadIBot Users Interface

5.2.1 Automatic

The section AUTOMATIC allows, according to the choice of a point in 2d space, the calculation of the optimal configuration of the manipulator and the calculation of the joint angles for inverse kinematics of a planar two-link manipulator (chapter 3).

The **POSITION** button opens a window that allows to choose the point where the radioactive leak occurred (Fig.44). After the calculation of the joint angles, the value of angles are plotted on the interface in order to verify the correctness of the kinematics (Fig.45) and also the trajectory of the manipulator in ARM MOTION section. The motors can be actuated through **MOVE** button.

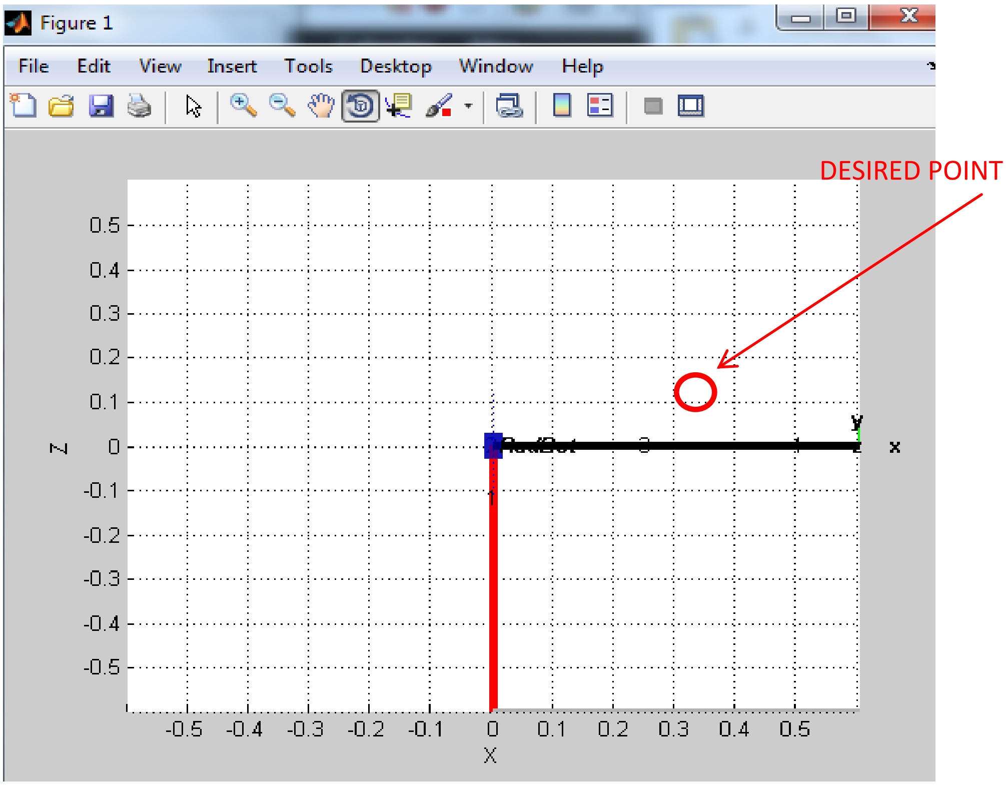

Fig.44 Desired point of inspection

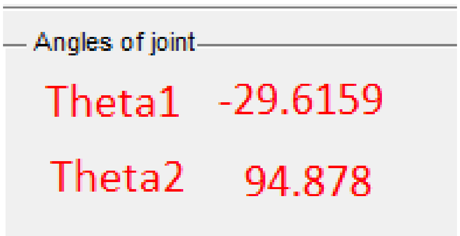

Fig.45 Detail of interface that shows Angles of joint to reach the desired point

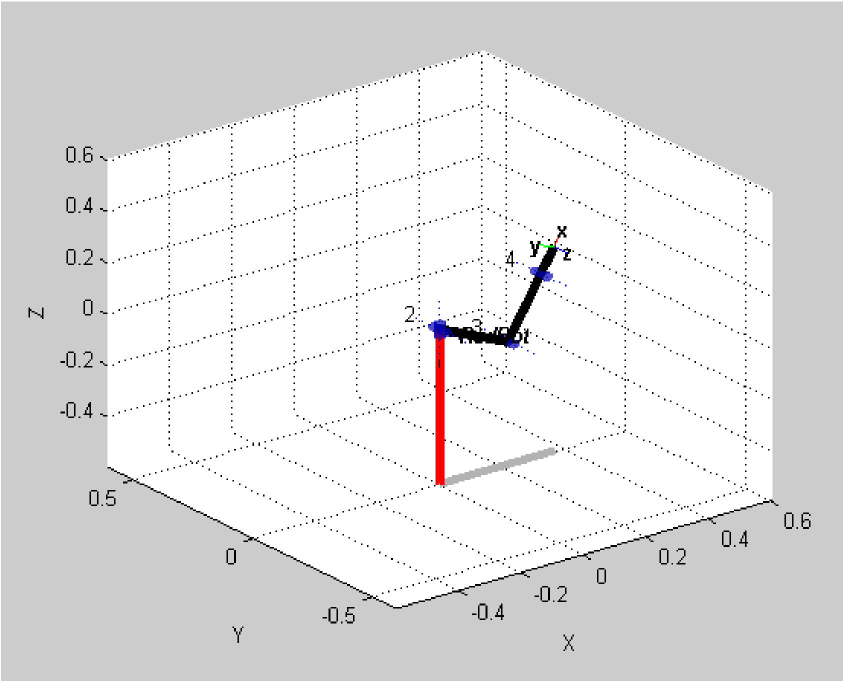

Fig.46 3D View of the final pose of the manipulator to reach the point desired in ARM MOTION

The Button **RESET** allows to the manipulator to achieve a basic configuration, that can be modified by the designer, according to the workspace of the manipulator.

The **HALT!** button is used for safety and immediately stops the manipulator.

5.2.2 Manual

The section MANUAL allows to the operator a manual inspection . It is possible to choose the joint to move through a joypad (It has been used a simple economic joypad with 4 axes and 10 buttons Fig.47).

Fig.47 Joypad for manual inspection

Below the map of joypad buttons to handle the robot:

- Push button 1 to increase speed of all link
- Push button 2 to decrease speed of all link
- Push button 3 + Up or Down to move the first link
- Push button 4 + Up or Down to move the second link
- Push button 5 + Right or Left to move the end effector

Extreme care is required in this case, because the user decides the trajectories of the robot, that may have contact with the workspace or with their stroke end.

Also in this case **HALT!** button stops the manipulator.

5.2.3 Camera

The section CAMERA has been designed to control the camera on the end effector of the robot. It is compatible with any usb camera on the market.

Through the three buttons you can start the camera, stop the camera and with the button **SNAPSHOT** it is possible take a picture of the damaged area of the drum. The photos are then stored on the computer.

Fig.48 Detail of Camera View panel

5.2.4 Control Manual

This section gives information about the status of the manipulator. Theta1, theta2, theta3 and speed are the most important values to understand the status of a motor. It works when Joypad ON button is pressed, and the initial values of angles come from the Manual Mode. The three figures of the manipulator on the right of the interface help to understand the rotation of the link.

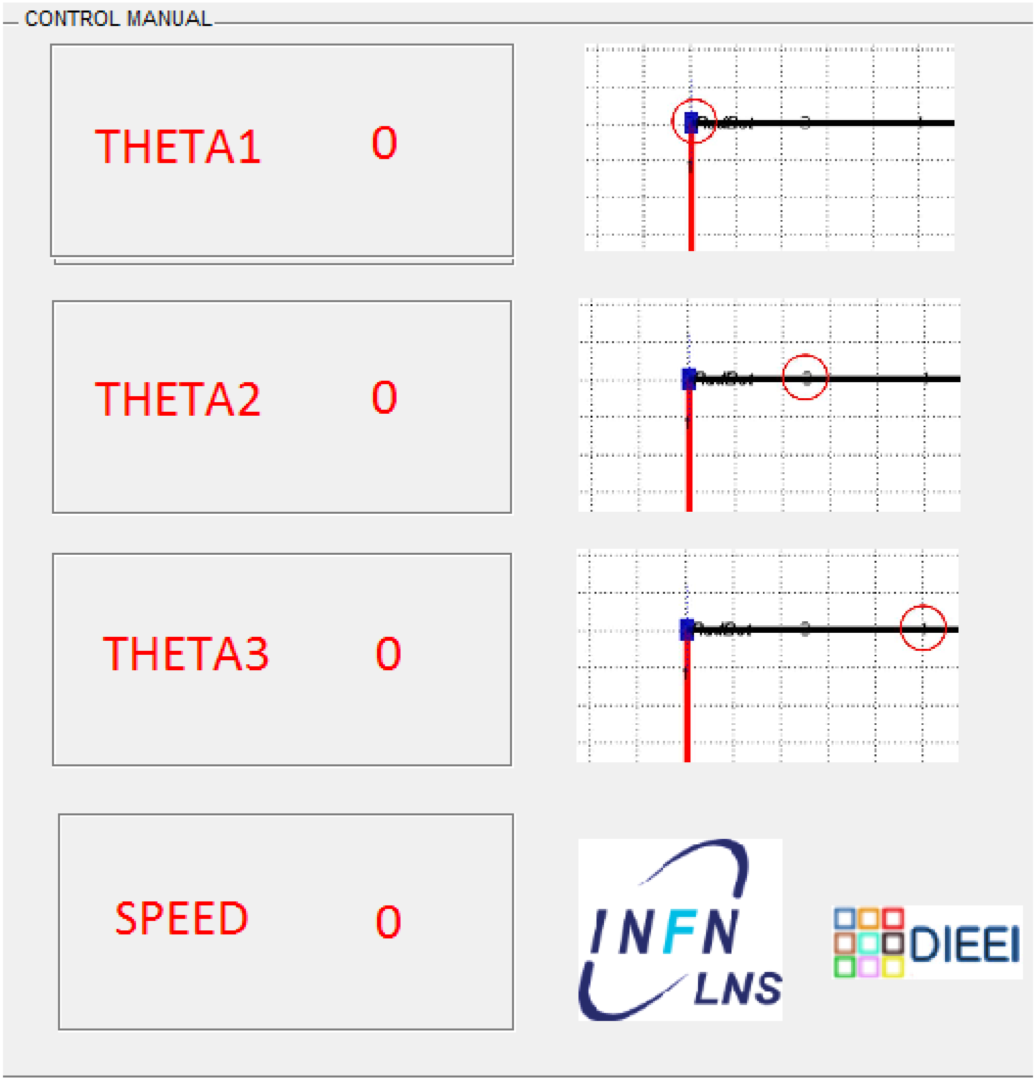

Fig.49 Control Manual panel

CONCLUSION

This thesis work has been addressed to the study and the realization of a robotic arm for radwaste inspections.

The problem of waste disposal is very important at national and international level. Several associations finance projects in order to sensitize the younger generations, to understand how to solve problems linked to radwaste and how to find alternative solutions.

Disposal sites are currently the only viable approach and it is implemented in several countries, even though the problem of reducing the risk for the radwaste operators and the surrounding population is still present.

A strategy of continuous monitoring is therefore recommended for an early detection of possible leaks and to prevent more severe accidents. In this framework a policy of periodic inspections without the physical presence of operators, along with on-request remote inspections in case of anomalous behavior signaled by the monitoring system, would be very welcome.

The robotic arm is a tool that comes closest to a human arm, most widely used (among the various limbs) for the manipulation of objects and to establish a direct contact between man and environment.

Like the human arm, the robotic arm is used to explore, and in this case an environment dangerous for people.

Finally, it should be noted that the robotic arm is proposed as a complement to a monitoring system and not as a replacement.

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