REQUIREMENTS AND DESIGN CONSTRAINTS OF A DEMINING ROBOT PROTOTYPE WITH ITS KINEMATIC MODELING, SIMULATION AND EXPERIMENTATION

By

Eng. Hussein Fouad Mohamed Ali

A Thesis Submitted to the Faculty of Engineering at Cairo University in Partial Fulfillment of the Requirements for the Degree of MASTER OF SCIENCE

In

MECHANICAL DESIGN & PRODUCTION ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
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Under the Supervision of

Prof. Dr. Said Mohamed Megahed
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Title of the Thesis:

"**Requirements and Design Constraints of a Demining Robot Prototype with its Kinematic Modeling, Simulation and Experimentation**"

Key Words: Demining - Mine Detection Techniques - Robot - Mechatronics

Summary: Landmine detection and removal is a challenging field for researchers. In demining operations, the phase of Area Reduction is very important in infected regions with Landmines, ERW (Explosive Remnants of War) and UXO (Unexploded Ordnances). This phase has a significant impact on the vegetation removal cost and field preparation for other demining operations. Manual operation is very dangerous, exhaustive and costive (time and money). It is very important to produce assistive mechanisms like Robots to cope with the landmine fields' environment. One of the required design constraints of a robot is its contact pressure with ground in order not to activate the imbedded landmines. In addition, the developed robot must be equipped with Multi-Sensors system to detect the imbedded landmines when scanning the infected areas. This thesis consists of four main chapters with a literature survey of Egypt Landmine Problem in Chapter 1 and Appendices. Based on this survey, the mobile robot basic design requirements are given in Chapter 2. In Chapter 3, a prototype of a mobile platform with a robot arm is developed and manufactured to satisfy these design constraints. The used mechanical components of this prototype are mainly some scrape and Commercial Off-The-Shelf (COTS) parts available at low costs. Using such parts has significantly reduced the overall cost of the developed robot prototype. The necessary Electrical and Electronic components of developed Printed Circuit Board (PCB) used to drive and control the system DC and Stepper Motors are: Microcontrollers (AVR, PIC), control circuits, and power driver circuits. The robot is equipped with the available sensors in the Egyptian market. MATLAB Graphical User Interface (GUI) is developed to control the developed prototype via a Laptop serial port using USB (USB to serial). Variety of communication techniques and protocols are virtually tested and experimentally verified to measure to what level the design requirements are satisfied. In Chapter 4, the kinematic models of the developed robot prototype are obtained using the so called Virtual Robot Approach with the aid of Homogeneous Transformation Matrix (HTM). These models are used to simulate, in MATLAB and SIMULINK the performance of the developed robot prototype when following some desired paths in a virtual infected landmine field. A variety of control algorithms, and Fuzzy Logic techniques are considered. The Landmines locations are assumed to be known. The developed robot prototype, which is cheap, needs more sophisticated multi-sensors systems in order to be tested in real landmine fields.

ABSTRACT

Landmine detection and removal is a challenging field for researchers. In demining operations, the phase of Area Reduction is very important in infected regions with Landmines, ERW (Explosive Remnants of War) and UXO (Unexploded Ordnances). This phase has a significant impact on the vegetation removal cost and field preparation for other demining operations. Manual operation is very dangerous, exhaustive and costive (time and money). It is very important to produce assistive mechanisms like Robots to cope with the landmine fields' environment. One of the required design constraints of a robot is its contact pressure with ground in order not to activate the imbedded landmines. In addition, the developed robot must be equipped with Multi-Sensors system to detect the imbedded landmines when scanning the infected areas. This thesis consists of four main chapters with a literature survey of Egypt Landmine Problem in Chapter 1 and Appendices. Based on this survey, the mobile robot basic design requirements are given in Chapter 2. In Chapter 3, a prototype of a mobile platform with a robot arm is developed and manufactured to satisfy these design constraints. The used mechanical components of this prototype are mainly some scrape and Commercial Off-The-Shelf (COTS) parts available at low costs. Using such parts has significantly reduced the overall cost of the developed robot prototype. The necessary Electrical and Electronic components of developed Printed Circuit Board (PCB) used to drive and control the system DC and Stepper Motors are: Microcontrollers (AVR, PIC), control circuits, and power driver circuits. The robot is equipped with the available sensors in the Egyptian market. MATLAB Graphical User Interface (GUI) is developed to control the developed prototype via a Laptop serial port using USB (USB to serial). Variety of communication techniques and protocols are virtually tested and experimentally verified to measure to what level the design requirements are satisfied. In Chapter 4, the kinematic models of the developed robot prototype are obtained using the so called Virtual Robot Approach with the aid of Homogeneous Transformation Matrix (HTM). These models are used to simulate, in MATLAB and SIMULINK the performance of the developed robot prototype when following some desired paths in a virtual infected landmine field. A variety of control algorithms, and Fuzzy Logic techniques are considered. The Landmines locations are assumed to be known. The developed robot prototype, which is cheap, needs more sophisticated multi-sensors systems in order to be tested in real landmine fields.

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My wife and my sons

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ABBREVIATIONS

APL:	**A**nti-**P**ersonnel **L**andmines
ATL:	**A**nti-**T**ank **L**andmines
COTS:	**C**ommercial **O**ff-**T**he-**S**helf
ERW :	**E**xplosive **R**emnants of **W**ar
REST :	**R**emote **E**xplosive **S**cent **T**racing
UXO :	**U**ne**X**ploded **O**rdnances
UNDP:	**U**nited **N**ations **D**evelopment **P**rogramme
GICHD:	Geneva International Center for Humanitarian Demining

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 Introduction

In the past few years, the problem of landmines becomes one of the hottest research areas. Through decades of wars spread in the world, huge areas are infected with Landmines, ERW and UXO. Egypt is considered one of the most infected countries; it is infected with about 21% of the landmines in the world.

Today's demining is based especially on deminers (humans). The deminer equipment and training take about 20 minutes for every detected signal. Deminer lies about 30 to 40 cm far from the examined object. Statistical data said that one death and 10 seriously injured on each 1000 founded landmines, though the manual demining is the only reliable technique. And with regular, difficult deminers training and good supervision, it is also relatively safe method besides limited equipment. But its basic limitation is the difficulty and the time-consuming, caused by the high amount of metal elements in the soil. These facts, together with the possibility, that deminers can find no mine for days and weeks which may induce tiredness, inattention and also boredom. But all these factors are besides demining highly undesirable.

Many experts and practitioners do not believe in robotical demining. Many are persuaded of the impossibility of the humanitarian deminer replacement and many reject robots as a demining device at once. Even if there are experiments to create demining robot, there is no robotic systems, which would be autonomously able to control its actions and to clear demanded part of the terrain. But nowadays Research and Development in the field of detection techniques, electronics and communication offers new possibilities to design and use demining robots in the near future.

Many researches have been developed to assist or to replace the human in such demining operations which are hazardous, and costive. However, their output didn't yet deliver a complete solution of the problem. This chapter gives a literature survey about the Landmine Problem in Egypt, faced difficulties, and the available methods to solve it.

This survey is organized in four categories: First, the Landmine Problem in Egypt, considering the historical background, different types of landmines, difficulties in demining operations, socio-economic impact of landmines, and efforts for landmine clearance, are considered. Second, the demining techniques, the clearance process, the area reduction techniques, current demining techniques, and neutralization, are presented. Third, a survey is considered about the sensors technology, sensors types, sensors main idea, sensors fusion, and information analysis and selection of sensors. Finally a detailed survey is investigated about the use of mobile robots in demining operations, discussion about mobile robots importance in demining operation and experts' appraisals, basic requirements for a demining robot, Robotization of Humanitarian Demining. This survey includes the possible designs of remotely operated mobile robots used in demining including area reduction, detection, neutralization, removal and the other aspects in order to deal with the demining problem. The design, modeling, simulation and control of such robotic systems used in humanitarian demining is the scope of work of this thesis.

1.2 Literature Survey

1.2.1 Landmine Problem

According to the Civil Right, a landmine is some object placed on or under the ground or any surface, conceived for exploding by the simple fact of the presence, the proximity or the contact of a person or a vehicle [1]. According to published data [2], Landmines problem may be summarized in the following Numbers:

- **33 billion** - Cost in U.S. dollars to remove every mine in the world, if no others are planted
- **250 million** - Stockpiled landmines worldwide
- **110 million** - Landmines in the ground worldwide
- **2.5 million** - New landmines laid each year
- **1 million** - People killed or maimed by anti-personnel mines since 1975
- **100,000** - Americans killed or injured by landmines in the 1900s
- **26,000** - People killed or maimed annually by landmines
- **1,000** - Cost in U.S. dollars to remove one landmine
- **350** - Minimum number of different types of landmines

- **70** - Number of people killed or injured daily by landmines
- **33** - Percent of U.S. casualties caused by landmines during the Vietnam War
- **3** - Cost in U.S. dollars of a cheap landmine

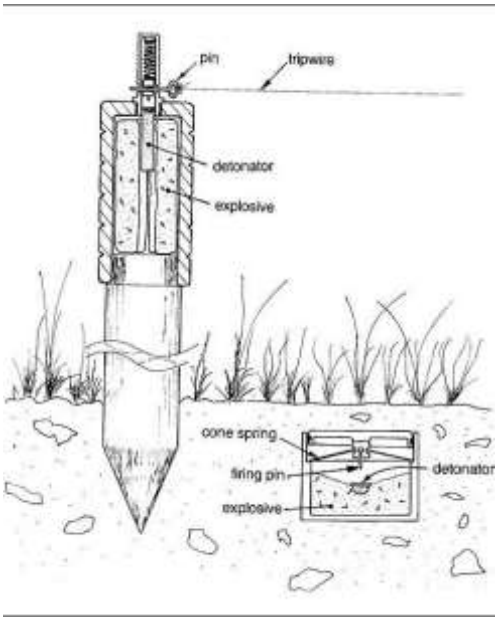
A detailed survey of this landmine problem is given in Appendix A [3]

1.2.2 Types of landmines and UXO [4, 5]

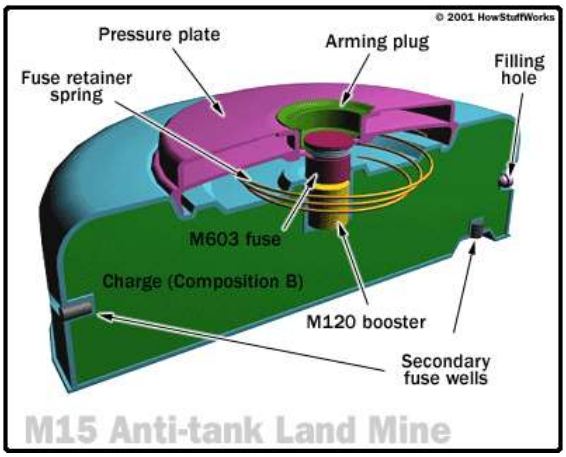
There are many classifications of landmines. They differ one from the other according to: the victim they are addressed to, the activation mechanism, size, explosive charge, type of explosion and location with respect to the ground. In practice, there are two main types of landmines: **Anti Tank (AT)** or Anti Vehicle, landmines and **Anti Personal (AP)** landmines. Table 1.1 lists the main specs of these two types.

Table 1.1: Landmines classification

	AT landmines	**AP landmines**
Description	Designed to detonate when a vehicle drives over them. AT mines are activated by force, magnetic influence or remote control. AT mines are quite big, comparing to the AP mines. Usually, AT mines are laid in unsealed roads or potholes.	Designed to detonate by the presence, the proximity or the contact of a person. AP mines are activated by force directly exerted on them or by pulling tripwires. AP mines can be buried into the ground, fixed to something over the ground or just laid on the ground.
Diameter	300-350mm	70-150 mm
Explosive charge	5-10 Kg	80-250 g
Activation force	>100kg	3-20kg



(a)



(b)

(c)

Figure 1.1: (a) Fragmentation mine, (b) M15 Pressure-operated Blast Mine (c) Cluster Bomb (Photo: Prof. J. Trevelyan)

Although there are more than 700 known types of AP mines, only two types of explosion are enabled: Fragmentation mines (Fig. 1.1-a) and Blast mines (Fig. 1.1 -b).

Fragmentation mines: when they explode, metal fragments are propelled out at high velocity to a radius of 30 or even 100 meters, penetrating up to several millimetres of steel, if close enough. Usually they detonate when the tripwire connected to them it is pulled. Two main types of Fragmentation mines exist, differing one from the other in their location with respect to the ground: (1) Stake mines, which are fixed to a knee-high wooden stake, in order to detonate when a person pull the tripwire while is walking near by the stake; (2) Bounding mines, which are buried into the ground. When their tripwire is pulled, they jump up to groin height before exploding.

Blast mines: which are typically buried into the ground and detonate when a person steps on them. The explosion usually destroys the foot and partially the leg.

In addition to landmines, a Cluster Bomb (Fig. 1.1-c) is a particular kind of bombs, which is dropped out from a plane over the target. Instead of landmines, Cluster Bombs are designed to explode when they impact on the ground, not to be victim initiated. Cluster Bombs affect the mine clearance operations only when they don't work properly and they fail to detonate as they hit the ground. As they lie on the ground and can detonate very easy, sometimes just touching them, they act as landmines. Although the most commonly quoted failure rate of Cluster Bombs is 5 - 9.6 percent or higher.

Smart Landmine: Self-destruct and self-neutralisation features [4]**:** Self-destructing mines are designed to detonate, activated by their own fuzing mechanisms, after a predetermined time period, while self-neutralising mines render themselves inert, so they no longer pose a threat. Self-destruct and self-neutralisation mines increase the uncertainty and hazard as they pose mixed minefields and high failure rates of 5-10 per cent.

1.2.3 Landmine problem in Egypt

Egypt has unique landmine and UXO problems (Figure 1.2): **First**, a huge area of land is affected - some estimates put the total at about 25,000 sq kilometers. **Second**, the age of much of the material: up to 60 years. **Third**, much of the mines and UXO is covered by thick deposits of mud or sand so that conventional detection techniques are often of little value.

Figure 1.2: Egypt – Landmine fields

Broadly speaking the area west of Cairo (El Qahera) was contaminated as a result of hostilities between 1940 and 1943 involving Britain and its allies (including Egyptian forces) fighting German and Italian forces for control of North Africa. The areas to the east, including the Sinai Peninsula were contaminated between 1956 and 1973 due to hostilities between Egypt and Israel. Figure 1.3 presents Western Desert landmines map and Table 1.2 gives the suspected areas (in hectares) with British minefields, Italian minefields and German minefields.

Figure 1.3: The Western Desert landmines

Table 1.2: Suspected areas in the W. Desert (Note: 1 hectare equals 0.01 Km^2)

zone	Suspected areas		Italian German mine fields		British mine fields		Total	
	N million	Area hect	N million	Area hect	N million	Area hect	N million	Area hect
1	0.166	5500	-	-	-	-	0.166	5500
2	0.85	37500	5.3	53000	7.65	76500	13.8	167000
3	1.26	55000	-	-	0.7	7000	1.96	62000
4	0.425	18500	-	-	3.4	34000	3.825	52500
Total	**2.661**	**116500**	**5.3**	**53000**	**11.75**	**117500**	**19.711**	**287000**

Historical background of landmine problem in Egypt: During the 2nd World War, Britain and its allies(the Allied Forces) conducted a series of military campaigns to defend themselves and the vital Suez Canal from several invasion attempts by German and Italian forces (the Axis Forces). Most of the fighting was along the northern fringe of the Western Desert between the Qattara Depression and the Mediterranean Sea, between 1941 and 1943. The well-known battle at El-

Alamein was only one of many. A wide coastal strip is affected by mines and UXO, all the way to the Libyan border (and beyond). As a result of combat operations between the Axis and the Allied Forces during the Second World War, the Arab Republic of Egypt is considered to have been seriously affected by land mines and UXO.

The mine / UXO problem in the western desert started during the Second world war, between 1941 - 1943, as a result of the British Campaigns in north Africa against the Axis troops (German / Italian) attempts to control and occupy the Area . Most of the battles took place in the Area between Qattara Depression, Alamein, and the Mediterranean. The mines / UXO infest a vast coastal strip between Alamein and the Egyptian / Libyan boarders.

In 1956, Israeli forces invaded the Sinai Peninsula and advanced almost to the Suez Canal in a joint operation inspired by Britain and France to attempt to recover the recently nationalized canal. British and French troops occupied the Canal Zone in the face of vigorous Egyptian resistance. Shortly afterwards, Israeli, British and French troops were withdrawn under strong international pressure.

In 1967, Israel again invaded the Sinai Peninsula in a pre-emptive strike. Egyptian and Israeli forces confronted each other along the Canal Zone, with extensive intermittent bombardments between them. In October 1973 Egyptian forces fought a more successful campaign but Israeli forces continue to occupy practically all of the Sinai Peninsula.

Following extensive negotiations, Israeli forces withdrew from Sinai to the current border. In 1979 Egypt and Israel signed a treaty (Camp David Accords) which has ushered in a new era of peace and cooperation.

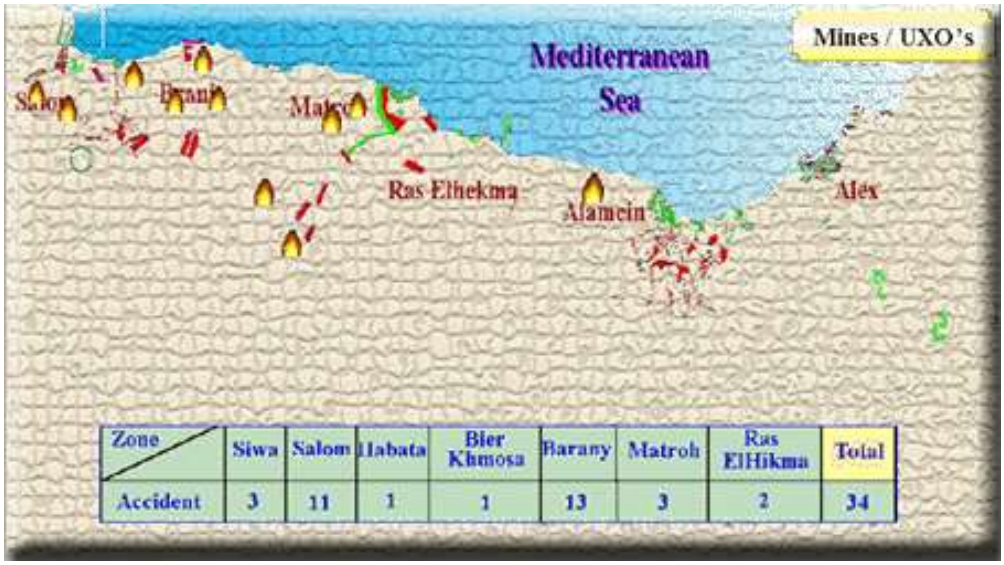
Most of the remaining contamination is in the Suez Canal zone, and nearby coastal regions. Much of the contamination in the coastal region is in salt lakes, salty mud and swamps which are difficult to work in. The local environment is very unpleasant for manual work with high summer temperatures, high humidity and salty dust on windy days. Other mines lie under deep wind-blown sand as in the Western Desert.

Other minefields have been reported along the Red Sea coast, and formerly mined areas along the Israeli border and military strong points in the Eastern Sinai will need to be carefully checked.

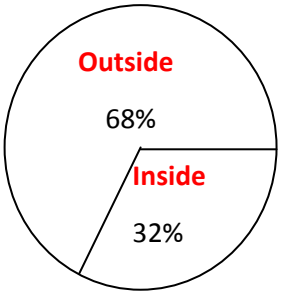
Assessment of the problem [6]: According to UNMAS and RONCO Corporation assessment missions in 2000 and 2002, there are two main ERW/mine affected areas in Egypt: (1) A strip of land in the western desert from Borg Alarab to the Libyan border in the west, bordered by the Mediterranean Sea to the north and stretching between 25 and 30 kilometers to the south. Urban areas close to contaminated zones include Al-Alamein, Al-Dab'aa, Fouka, Marsa Matruh, Sidi Barani, Al-Salloom, with an estimated area of 248,000 hectares; (2) The Sinai peninsula and the Red Sea coast (eastern area), including north Sinai governorate, south Sinai governorate (Sinai peninsula), and coast areas of Port Said, Ismailia, Suez, and Hurgada (Red Sea coast), with an estimated area of 20,000 hectares.

Egyptian officials have reported that only 20 to 25 percent of the estimated 23 million mines in Egypt are actually AP or AV mines and the rest are in fact ERW. There are 500,000 inhabitants in the western desert and 300,000 inhabitants in the Sinai Peninsula. No in-depth assessment mission has been undertaken to document the specific socio-economic impact of ERW and mines on these communities. Figure 1.4 presents recorded accidents in Western Desert

Egypt landmines clearance efforts: Since 1946, according to the Egyptian Official Authorities, 7 million mines have been cleared from the western desert in the past 15 years and 3 million from the Sinai desert. That leaves at least 20 million others. Egypt has set the year 2017 as the target for finally ridding its sands of land mines, but it is anxious not to left alone in paying for and carrying out this huge task. The fact that over the years many reference points and landmarks have disappeared by rain and sandstorms added to the complexity of drawing a comprehensive picture of the Landmine situation. The complete marking and fencing of huge areas in the western desert is not considered feasible by the Egyptian Military due to climatic conditions, sandstorms and scrap traders. Next are some other official acts:



Zone	Siwa	Salom	Habata	Bier Khmosa	Barany	Matroh	Ras ElHikma	Total
Accident	3	11	1	1	13	3	2	34



Last 50 Accidents inside /outside the suspected areas

Figure 1.4: Recorded accidents in Western Desert

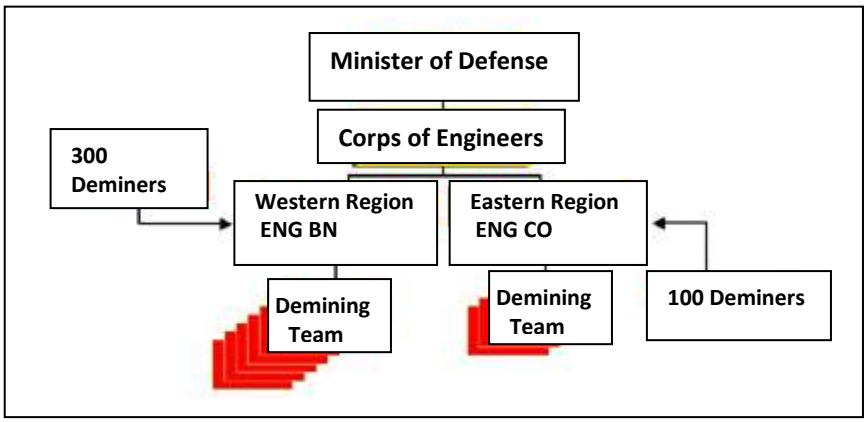


Figure 1.5: Egypt's Military Demining Organization

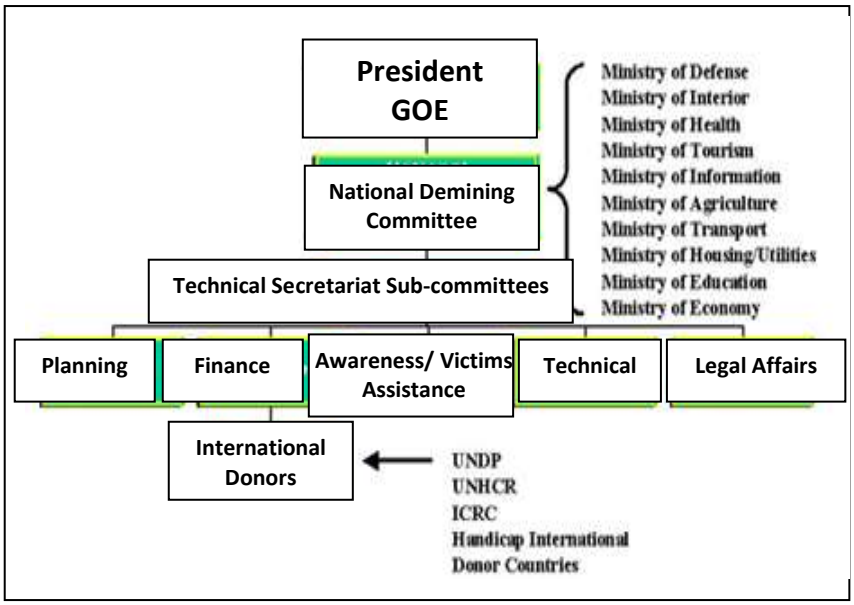


Figure 1.6: Egypt's Civilian Demining Organization

- The Government of Egypt has established the National Committee for the Northwest Coast Development and Demining Programs aiming to propose and implement regional developmental programs for the Northwest Coast and its desert back areas up to the year 2017. Figure 1.5: presents Egypt's Military Demining Organization and Figure 1.6: Egypt's Civilian Demining Organization.
- Clearance activities severely hampered by having only limited maps, sketches and minefield records. Maps and data sources that have been provided by Germany, Italy and Britain have proven to be inaccurate or incomplete.
- All Demining work is handled by a division of the Ministry of Defense in Cairo the Egyptian Military Engineering Organization **(EMEO)**.

Until recently, all aspects of minefields and Demining are classified. However, the Egyptian government is now pursuing a more open policy, recognizing that information is needed to help secure assistance.

1.2.4 Demining processes and demining techniques:

The Demining techniques can be classified into two main categories: Military demining and humanitarian demining as stated below in figure 1.7.

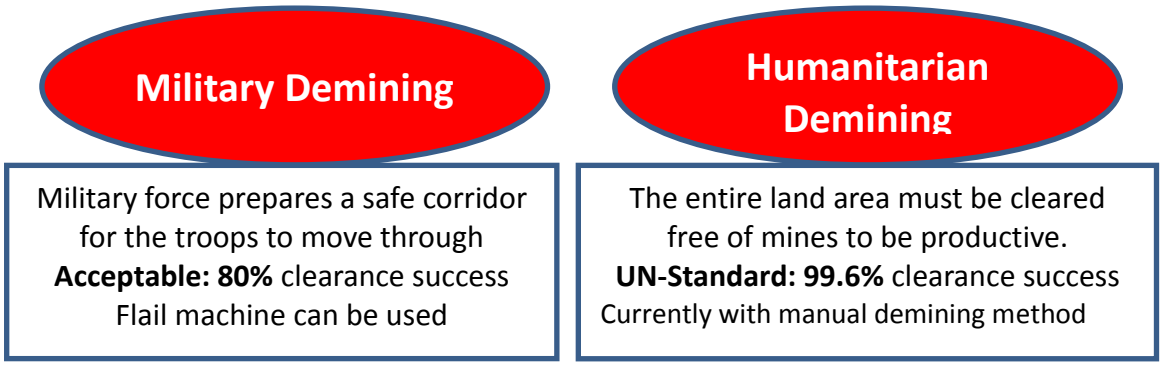


Figure 1.7: Demining classification

In the coming sections we will start with the techniques and methodologies which are used currently in the field by the demining organizations in the infected countries. Then we will present the recent research efforts related to demining operations. Finally we will discuss the importance of the selected points which I would like to conduct my research about.

Humanitarian mine clearance process [13]: can be divided into the following essential five phases. Figure 1.8.

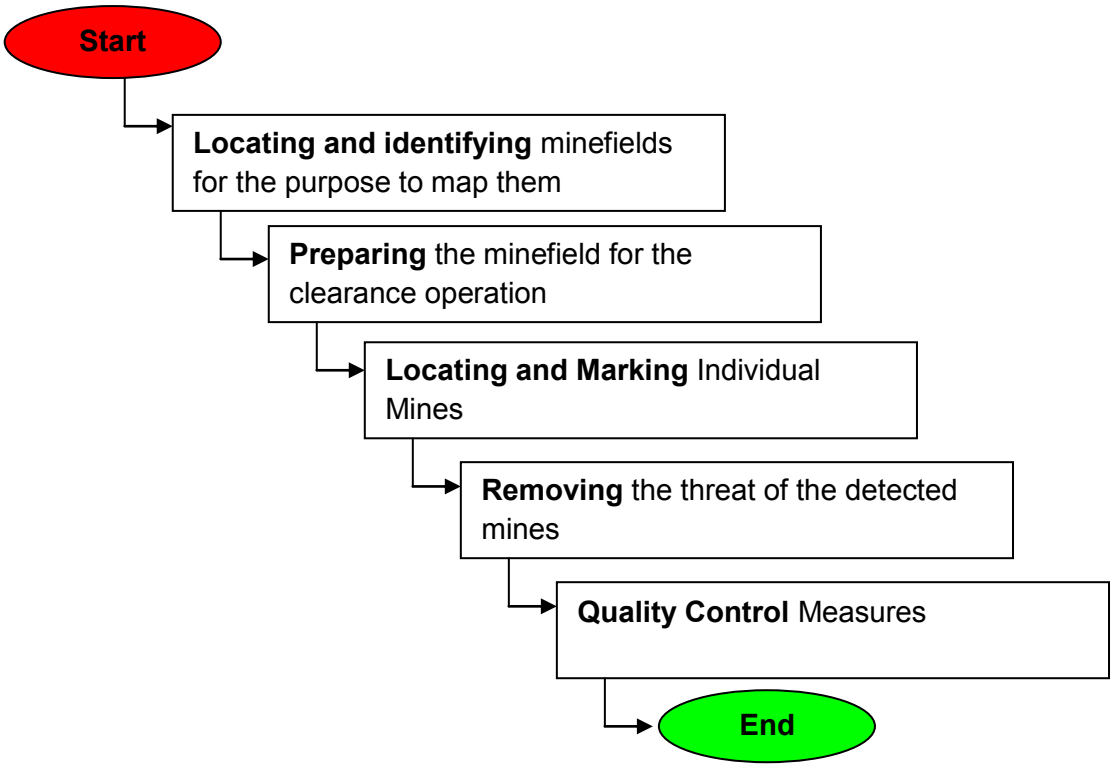


Figure 1.8: Humanitarian mine clearance process

Locating and identifying minefields for the purpose to map them: Demining is very costly and searching unmined area is adding extra high cost. Therefore, it is important first to identify and mark what areas are mined using different approaches through survey and remote sensing along with other techniques. A clearance priority rating should be given to each suspected mined area to reflect the urgency for clearance while considering social and economical factors.

Preparing the minefield for the clearance operation: The normal obstacles facing deminers that considerably slow down the operation are: surface vegetation and subsurface metal contamination. Currently, as much as 70% of deminer's time spent in checking for tripwires and cutting back vegetation through the demining process.

Locating and Marking Individual Mines: Different ways are used to detect individual mines such as manual probing, dogs, metal detectors, thermal imaging, electromagnetic technologies, nuclear technologies, chemical techniques, biosensors, etc. Generally, such methods are limited by soil conditions, vegetation, mine size and composition, soil minerals, burial depth, and grazing angle. Some of these technologies are still under development and

experimentation. Cost and size is among the difficulties in deploying advanced and high-tech sensors.

Removing the threat of the detected mines: Once a mine has been located and marked, it must be neutralized to render its harmless. Detection and neutralization of landmines are difficult tasks, as there are a lot of different types of mines. These differences can be situated on different levels, the geometry of the mines with the materials used for the casing, or the fusing of the mine ranging from simple pressure fuses to more sophisticated ones as magnetic, acoustic, seismic, etc. The most difficult mines to detect are the pressure mines. Among the available demining methods, there exist different means of mine neutralization.

Quality Control Measures: There is a need to verify that the required demining standards have been achieved, i.e., to assure with high level of confidence that the cleared area is free from mines and UXOs. The weather and environmental conditions along with ground surface movement should be considered as factors to schedule demining activities, due to its impact on deminer's and equipment reliable performance.

Area reduction [8, 9]: is to declare the minefields when exist inside larger unrecognized area. Area reduction is defined by the IMAS as "the process through which the initial area indicated as contaminated is reduced to a smaller area". Generally, the reduction is conducted on the basis of collecting more reliable information on the extent of the hazardous area.

Area reduction is a component of the technical survey process. In all clearance tasks, the great majority of efforts are conducted on ground that subsequently proves not to contain mines or UXO. Clearance data gathered by the GICHD from 15 countries suggests that of suspect areas cleared, less than three percent actually contained mines or other ordnance (individual items of ordnance were allocated a ground coverage of one square meter). This suggests that: effective area reduction is the phase of demining where the greatest increases in efficiency can be made. Thanks to their speed of operation, machines are best placed to achieve such increases. Manual survey cannot possibly cover the same area in as little time and should be used only where extremes of topography rule out the use of machines. Dogs are good at area reduction, but are far more affected by such vagaries as

weather, soil conditions and vegetation. The importance of improving the speed and reliability of area reduction operations is recognized by deminers and is reflected in the research findings of the GICHD publication, Mine Action Equipment: Study of Global Operational Needs.

Imaging: Air borne and satellite Using satellite images and images from balloons and helicopters figure 1.9 to reduce the expected area where the next demining phase will act.

Figure 1.9: Imaging: (http://www.arc.vub.ac.be/images/camcopter.jpg)

Mechanical: Rollers [10]: The area reduction roller figure 1.10 is a vehicle-mounted roller for rapid identification of the presence of AP mines in suspect areas and for area reduction. The roller is normally mounted on the front of a minefield intrusive prime mover such as the Minefield Tractor or an armored loading shovel. It is then pushed through the minefield. Operation methodologies are discussed in UNMAS Technical Notes for Mine Action (TNMA) 09.50/01 and in a study of Mechanical Applications in Demining (GICHD May 2004).

The roller works by detonating any near-surface or surface pressure-activated mines. It is designed to withstand AP mine blasts only. The roller consists of a series of individually “floating” steel discs, each exerting a load of 50 kg on the ground. This feature ensures that the roller is effective on uneven ground. The roller weight is approximately 1,000 kg per meter width. It is not only manufactured for the Minefield Tractor but is also available in any width up to 3.5

m for other prime movers. No special training, few spares and no routine maintenance required. The HALO Trust has approximately ten rollers in service in Abkhazia, Afghanistan, Cambodia, Georgia, Kosovo, Mozambique and Somaliland and confirms their robust construction and versatility. The U.S. Department of Defense owns three rollers, two with the Thailand Mine Action Centre and one in Nicaragua.

Figure 1.10: Mechanical Rollers

Sampling: Remote Explosive Sent Tracing (REST) [11]: is a process of taking scent from a source for remote analysis. The scent is obtained by using a pump to draw air containing scent or particles from the soil surface through an absorbent filter. Filters are analyzed using specially trained sniffer dogs or rats, or potentially any other natural or artificial odor sensing system. Fig. 1.11 shows the test and Fig. 1.12 shows the sampling process. The REST concept was originally conceived and developed in South Africa (Joynt 2003). First used to detect explosives, weapons and drugs in contained units (cars, containers, houses); the system was adapted by Mechem, South African demining company, for detecting landmines and UXO. Originally known as the "Mechem Explosives and Drugs Detection System" - MEDDS - it has since been given many names, although the official name in the demining arena today is REST. The system has five principal components: (a) Breaching, (b) Scent trapping, (c) Analysis, (d) Follow-up investigation, and (e) Data management.

Figure 1.11: REST, samples test

Figure 1.12: REST, sampling vapor

Current Demining Techniques [11]: Until 2001 the UN standard for an area declared cleared of mines was that there was at least 99.6 per cent probability that all mines have been removed or destroyed. From 2001, the UN standard has changed in "Land shall be accepted as "cleared" when demining organization has ensured the removal and/or destruction of all mine and Unexploded Object (UXO) hazards from the specified area to the specified depth".{ www.mineactionstandard.org}. The issue is how thoroughly to check and verify that all mines and UXO have been removed or destroyed. Unfortunately, in most of the cases, after mine clearance operations have finished, the area cleared cannot be considered totally free of mines and the accuracy of the operation of landmines removal cannot be stated. Although current demining methods cannot guarantee that the land is effectively free of mines after it has been cleared, they are still used; this means that by now, a solution that reduces the risk to a reasonable level is accepted as the best available. Current demining methods are based on manual demining. Depending on the different situations, machines and trained animals can be used in combination with manual demining. Before demining can start,

surveys are needed to produce detailed maps of minefields to be cleared. The survey team verifies a one or two meter wide safe lane around each minefield in order to define the minefield itself. A minefield can be surrounded with unknown land or other minefields. Typical minefields are 100-200 m width and 0.1-10 hectares in area.

Manual Demining [11]: Manual demining is a procedure in which mines are manually detected and neutralized by a human deminer. The tools used by human deminers are: (1) A thin rod, which is gently swung or lifted to check for tripwires; (2) A metal detector, which is swung from side to side to check for metal object, and (3) A prodder (typically a bayonet, screw, driver or knife), which is used to probe the ground at an angle of about 30 degrees to the horizontal position and to excavate earth around a suspected object. Usually a prodder is used to investigate a suspect metal object. Figure 1.13: shows the manual demining and some hand tools.

Figure 1.13: Manual demining and hand tools

The manual approach to mine clearance poses a lot of problems:

(1) The work of human deminers is dangerous and severe: human deminers can be killed or seriously injured while working, they have to wear heavy special protective cloths while the weather can be very hot, they have to work lying on the ground and the work itself is tiring and boring.

(2) The time needed to investigate a minefield is very high: analysis of statistics from a selection of 70 Afghan minefields reveals that deminers typically find 1 to 30 suspect objects for every 10 square meters, and clear 6 to 50 square meters per hour; on average for a 30-man team, between 1 and 15 hours pass between finding each

mine or UXO, meaning that an individual deminer can work for months without finding a mine.

(3) Metal detectors are not reliable: recent tests (ITC2001) have shown the weakness of this technology, several mines were missed even though the mines were well within the specified clearance limits used in most mine clearance operations.

Trained Dogs [12]**:** The use of dogs for demining purposes began in World War II, but dogs have only become established as a significant contributor to the global humanitarian demining effort in the last few years. Today, over 600 dogs are used in humanitarian demining programs in about 23 countries. Why dogs are used for mine and UXO detection [13]: MDD (Mines Detection Dogs) are now a commonly used mine detection technology. There are three major reasons for this:

(1) Detection by MDD can be faster and more cost effective than manual demining, if implemented correctly;

(2) MDD can detect mines with a low metal content and mines in areas with high metal contamination or background, such as on railway lines; and

(3) Many mine clearance organizations use a variety of demining 'tools', such as mechanical pre-clearance, manual clearance, and detection by dogs, in a complementary role.

Machines [13]**:** Machines used on demining operations can be divided into three general categories; (a) Mine clearance machines, (b) Ground preparation machines, and (c) Mine Protected Vehicles (MPV) when used in detection and survey operations.

Mine clearance machines are those machines whose stated purpose is the detonation, destruction or removal of landmines. A consequence of their use is that the necessity for post mechanical follow-up clearance is reduced to the minimum possible, or in certain cases, eliminated i.e. where the perceived hazard was nonexistent, where the machines removed the hazard or where the remaining hazard forms a tolerable residual risk.

Ground preparation machines are primarily designed to improve the efficiency of demining operations by reducing or removing obstacles. Ground preparation tasks may include: (a) Vegetation cutting and clearing; (b) removal of tripwires; (c) Loosening the soil; (d) removal of metal contamination; (e) Removal of building debris, boulders, rubble, defensive wire obstacles etc; and (f) sifting of soil and debris. Ground preparation may or may not involve the detonation, destruction or removal of landmines.

MPV are vehicles specifically designed to protect the occupants and equipment from the effects of a mine detonation. MPV are commonly used during detection and survey operations, where they may carry equipment such as detector arrays, vapour sampling devices or in some cases push or pull a roller. While these operations are not strictly mechanical demining operations involving 'machines' and 'mechanical tools' some of the work carried out by MPV falls into the category of mechanical demining. For example: (a) heavy MPV using their wheel tracks to provide an access path for manual sampling teams (a ground preparation role); and (b) MPV pushing or towing rollers (a mechanical mine clearance role). When used on demining operations, the requirements of MPV are similar to those for mechanical demining. Accordingly, the requirements of this standard shall apply equally to the use of MPV on detection and survey operations. Machines may also be used for other functions in support of demining operations. Such functions may include preparing tracks to permit access into areas for demining operations, excavation in support of deep search operations and the removal of debris to enable access to suspected hazards (e.g. under collapsed buildings etc.).

Armtrac 75 in action [11]

Figure 1.14: Flail Machines

Flail machines for Demining [11]: Figure 1.14 shows number of flail machines in operation. Armtrac Limited produces the Armtrac 25 Light Flail. The machine is a four-wheel, remote controlled skid steer equipped with a quick-hitch system allowing the fitting of the flail system, the milling drum or other manufacturer's attachments in approximately 5 minutes. A clearance depth of up to 150mm can be achieved and the Armtrac 25 is designed to withstand blasts of 8.8kg explosive. The remote control system has two radio control options. At option one the useable radius of the machine is restricted by the line of sight of the operator and the system is able to achieve an average range of 300m. At option two, using a camera, an average range of 1,000m can be accomplished. The vehicle has a 50hp diesel engine. The clearance methodology is the same as the Armtrac 75. Two machines are in service with the UK Ministry of Defense.

1.2.5 Sensors technologies used for demining

The most expensive and complex part in the demining process is the sensor. Many sensors available in the market stand on various scientific theories. A metal detector is a device which responds to metal that may not be readily apparent. The simplest form of a metal detector consists of an oscillator producing an alternating current that passes through a coil producing an alternating magnetic field. If a piece of electrically conductive metal is close to the coil, eddy currents will be induced in the metal, and this produces an alternating magnetic field of its own. If another coil is used to measure the magnetic field, the change in the magnetic field due to the metallic object can be detected. There are three technologies: Very low frequency (VLF), Pulse induction (PI), Beat-frequency oscillation (BFO). A magnometer is a scientific instrument used to measure the strength and/or direction of the magnetic field in the vicinity of the instrument. Magnetism varies from place to place and differences in Earth's magnetic field (the magnetosphere) can be caused by the differing nature of rocks and the interaction between charged particles from the Sun and the magnetosphere of a planet. Magnometers are a frequent component instrument on spacecraft that explore planets. Magnetometers can be divided into two basic types: Scalar magnometers measure the total strength of the magnetic field to which they are subjected, and Vector magnometers have the capability to measure the component of the magnetic field in a particular direction, relative to the spatial orientation of the device.

Anatomy of a Metal Detector: In figure 1.15, a typical metal detector is light-weight and consists of just a few parts: (1) **Stabilizer** (optional) - used to keep the unit steady as you sweep it back and forth; (**2) Control box** - contains the circuitry, controls, speaker, batteries and the microprocessor; (3) **Shaft** - connects the control box and the coil; often adjustable so you can set it at a comfortable level for your height; and **(4) Search coil** - the part that actually senses the metal; also known as the "search head," "loop" or "antenna".

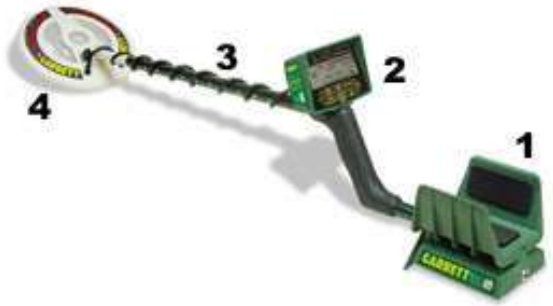


Figure 1.15: Photo courtesy Garrett Electronics,
Garrett GTI 1500 metal detector

Sensors Fusion: As all the available sensors in the market has certain false alarm, so it will be more efficient if a decision is taken based on two or more types of sensors, that in order to minimize the positive and negative false alarm. Where: Positive false alarm: sensor gives alarm that it detected something, but actually there is nothing. Negative false alarm: sensor doesn't give alarm, but actually there is something missed.

1.3 Scope of Work

The utilization of an automated or semi-automated solution for the landmine problem has a good potential instead of the manual demining which is dangerous, exhaustive, and costive (time and money). This work aims to define the Landmine Problem in Egypt, set objectives and criteria, investigate the available alternatives, analyze alternatives and select the most feasible alternative with planning, implementation and control. Investigation of the possible designs of remotely operated mobile robots for demining includes area reduction, detection, neutralization, removal and the different aspects in order to deal with the demining problem. The thesis subject is the analysis of the demining problem and, modeling, simulation and control of mobile robot which assist in the demining operations. A literature survey of the demining problem, the used demining techniques, sensor technology, and the research work for automated solutions are performed.

This thesis is organized in five chapters and four Appendices. It starts in the first chapter, with a literature survey about: the landmine problem in Egypt, demining techniques, use of robots and sensors technology then the scope of work. The second

chapter discusses the requirements and constraints of demining robots and investigates some robotic models. In the third chapter the system architecture is presented and the control strategy is developed using embedded system programming. In the fourth chapter a mathematical model is provided with virtual robot approach. While chapter five gives the thesis conclusion and future work. Appendix A presents a survey paper entitled "Egypt Landmine Problem: History, Facts, Constraints and Demining Techniques". Appendix B presents some tables of the Available Sensors' Information with Analysis and Selection while Appendix C presents some Tables of Available Sensors with Cost Estimates. Appendix D presents the Available demining Robots in the Market while Appendix E presents a Market Survey versus Robot Parts List. Appendix F presents the Computational Methods of Robot Arm Jacobean matrix.

CHAPTER 2

REQUIREMENTS AND CONSTRAINTS OF DEMINING ROBOTS

2.1 Introduction

In this chapter the basic requirements and constraints of demining robots are discussed and the landmines activation pressure is analyzed. Available robots in the market are also presented. The system architecture with a study about the sensors selection using a fuzzy logic rule is presented.

2.2 Mobile Robots in Humanitarian Demining

Robot utilization in demining operation causes debates in the scientific communities. One of them is that below: "**Robots are not a solution to the global landmine problem!!!. Is this statement true?**

Several research efforts have failed, so far, to develop an effective mine clearance alternative to the existing manual technique. Robots have been tried at great expense, but without success due to the following reasons**:** **First,** there is little likelihood of sensing improvements in the short term. **Second,** the huge variety of mines and minefields defies any automated solution. **Third,** robotic solutions are likely to be too expensive to be practical for humanitarian demining operations in countries like Angola, Afghanistan and Cambodia.

The effort devoted to robotic solutions would be more helpful if it were directed at simple equipment improvements and low-cost robotic devices might provide some useful improvements in safety and cost-effectiveness in the short to medium term. Understanding why "high tech" research efforts have failed, so far, may help to avoid similar mistakes in other ambitious robotics research programs [14].

In fact, many don't agree with this argument, and we can analyze the reason:

1- Human life is more expensive than the cost of automation.

2- Some people and even researchers expect that the robots will deliver a complete solution of their problem including the demining problem. This is not true as the fact the computers will not think for us. It is just a tool to assist the user and to minimize the effort done. And if mistakes happened, the direct reason will be us (humans).
3- Accurate analysis of the problem is needed and we can rely on robot in realistic definite tasks not in the whole problem solution.
4- No problem in customizing certain mechanism for certain environment.
5- As we mentioned earlier in the REST section, robot could be used in the sampling mechanism which will be helpful in area reduction and some other definite task as well, but not a solution of the whole problem.
6- All the problem solution must be under the human analysis and control.
7- All over the world, research output indicates lot of success in robotic solution in some tasks related to the demining problem. And more is expected with more research.

For sure, we agree it's vital to direct the research in low cost robotic devices. So, **we conclude** that we can rely on robots in certain planed task. And this can happen only after detailed analysis to the environment variables.

2.3 Robotization of Humanitarian Demining

Many efforts have been recognized to develop effective robots for the purpose to offer cheap and fast solutions. The main directions can be recognized as:

(1) Tele-operated machines.
(2) Multifunctional tele-operated robot.
(3) Demining service robots.
(4) Unmanned Aerial Vehicles and Airships.
(5) New Robotic Systems (lizard, warm).
(6) Multi-Robot System.

Robots can handle certain tasks in the demining operation. The figure 2.1 shows the mind map which abstracts our survey results. The survey paper in the appendix A presents the usage of robots in demining.

2.4 Basic Requirements of a Demining Robot [68]

Many efforts have been recognized to develop effective multi operational mode robots for the purpose to offer flexible, modular, reliable, cheap and fast solutions for the demining operations. The development and implementation of robotics in mine and UXO clearance is attractive and it is building up momentum to spare human lives and enhance safety by avoiding physical contact with the source of danger in mined area, improve accuracy, help in mined area reduction, increase productivity and enhance effectiveness of repetitive tasks such as, probing/prodding, searching patter with sensors, digging, sifting, vegetation removal, etc. Solving this problem presents challenges in robotic mechanics and mobility, sensors and sensor fusion, autonomous or semi-autonomous navigation and machine intelligence. In spite of some reported level of success research into individual, mine-seeking robots is still at the early stages. In their current status, they lack flexibility and yet they represent a costly solution for mine clearance operation. But, if designed and applied at the right place for the right task, they can be effective solutions. Four main directions can be recognized in development: tele-operated machines, multifunctional tele-operated robot, demining service robots, and unmanned aerial vehicles. Figure 2.2 presents the requirements and constraints of a demining robot, which can be categorized in 7 main braches: (a) Design; (b) Power; (c) Components; (d) Control modes and navigation; (e) Sensors; (f) Interaction with mines; and (g) Maintenance

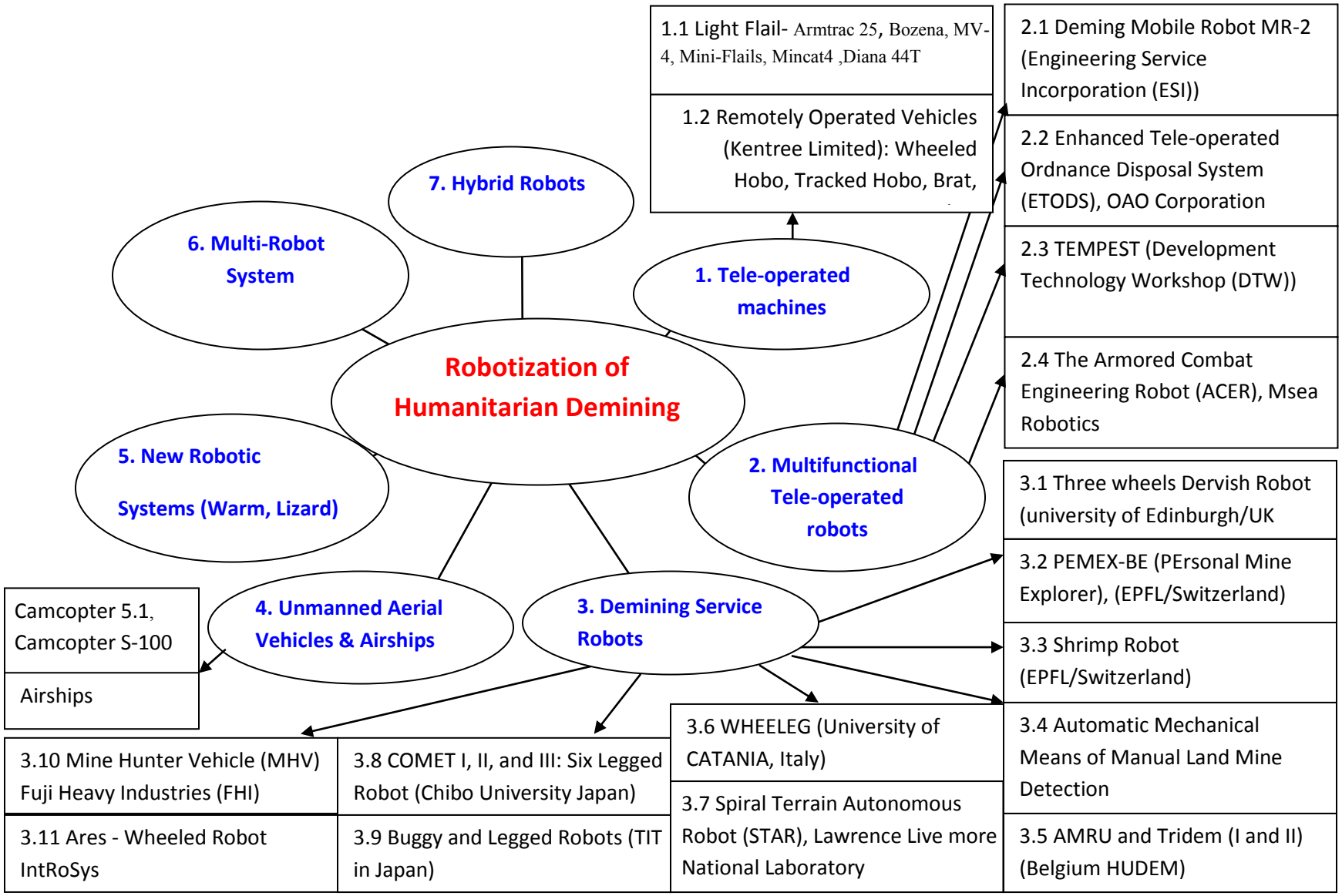


Figure 2.1: Mind map of the: Robotization of Humanitarian Demining [Add/Modify, Mapping (13)]

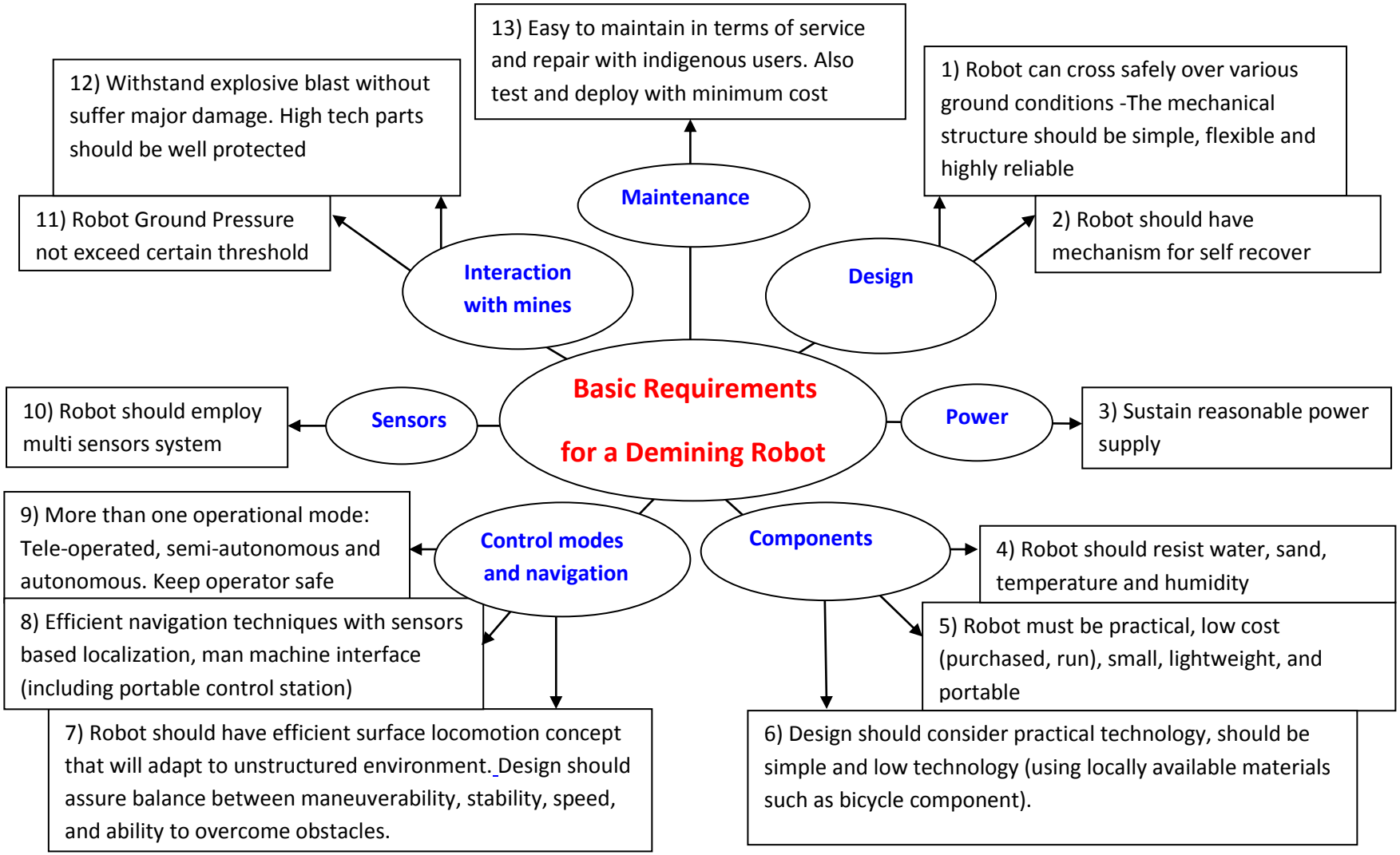


Figure 2.2: Representation Mind map of the: Basic Requirements for a Demining Robot

2.5 Proposed Robot Main Requirements

Based on the general requirement introduced in the previous section, in table 2.1 we will state the main requirements our research aiming to meet.

Table 2.1: The Robot Main Requirements

#	Title	Description
Requirement 001	Sensors selection	Based on the survey about sensors and evaluating the linguistics with fuzzy grading
Requirement 002	Track / Low pressure tires	A Mobile robot can navigate on rough terrain with low contact area pressure.
Requirement 003	Arms of extreme reach	It has the capability to scan the ground surface. (almost horizontal)
Requirement 004	Wireless remote control from Laptop	Robot operator must be away from the robot
Requirement 005	Movables wireless Camera	In order to deliver quiet view of the robot surroundings to the user of the Laptop
Requirement 006	GUI, motion Patterns	Give the user graphical user interface (GUI) to command the robot through it.
Requirement 007	Test scenarios	Prepare test scenarios in order to verify that the robot will meet the required command.

2.6 Landmine Activation Pressure Analysis [69, 70]

The activation pressure is one of the most important requirements in robot design. Based on the information available about the Landmines (the dimensions and activation load (kg)) the activation pressure is calculated for each landmine as given in Table 2.2. From this table, the contact pressure threshold is 1.9 kPa, which is the main design parameter of the robot.

Table 2.2: Landmines activation pressure calculations

Country	Mine Type	Dimensions	Activation load (kg)	activation pressure = Force/Area
British	MK5 (AT)	Diam: 20.3 cm	114.45 kg	34.6 kPa
British	MK7 (AT)	Diam: 32.5 cm	150 to 275 kg	17.7 kPa
German	Rieglmine 43 (AT)	Length: 80 cm Width: 9.5 cm	180 to 360 kg	23.2 kPa
German	S mines (AP)	Diam: 10.2 cm	3 - 5.5 kg	3.5 kPa
German	Tellermine 35, 42, 43 (AT)	Diam: 31.8 cm	90- 180 kg	11.1 kPa
Italian	B-2 (AT), V-3,(like)TMB2	Diam: 27.3 cm	115/9.8 kg	1.9 kPa
Egypt	M71 copy of TM46,	Diam: 30.5 cm	120–400 kg	16 kPa
Egypt	T79 copy of TS50, (AP)	9 cm	12.5 kg	19.2 kPa
Extremes for AP		7 cm	3 kg	7.6 kPa
		15 cm	20 kg	11 kPa

2.7 Available Sensors Information Analysis and Selection

Sensors are one of the main requirements of a demining robot. There are two important studies on sensors comparisons: The first study was done by Prof. Yvan Baudoin [57], and the second one was done by Cristian Keller [20]. They build their tables using linguistic. We select the sensors based on the data processing with fuzzy logic concepts.

Using the 1st study and the fuzzy grading table 2.2, we calculated the Table B.1 (see Appendix B) which applies a fuzzy logic values (grades) to replace the linguistic value assigned for each linguistic variable: Maturity, Cost, Speed, and Effectiveness are calculated using the following Formula:

S1 = ∑grade

Using the 2nd study and the fuzzy grading Table 2.3 we calculated Table B.2 (see Appendix B) which applies a fuzzy logic values (grades) to replace the linguistic value assigned for each linguistic variable: kind of terrain, speed, false alarms rate, cost and complexity, maximum depth, kind of mines are calculated using the following Formula:

S2 = Ny*2+Nb*1+Nr*(-1)

Where Ny is the number of very good occurrences, (yellow), Nb is the number of good occurrences, (blue), and Nr the number of bad occurrences, (red).

Aggregation of the fuzzy grading of the two studies: In this fuzzy grads of the sensors are aggregated and the five sensors with highest score are selected as shown in Table B.3 (see Appendix B). Calculations are based on the following Formula:

T=S1*17+S2*10,

Where S1: study1 grades, S2: study2 grades, T: Aggregation of S1, S2 grades.

The details of these analyses are available in the Appendix B. Also sensors market survey is available in the Appendix C.

Table 2.3: Fuzzy Grading key

Maturity		Cost		Speed		Effectiveness	
Fuzzy Grade	Linguistic	Fuzzy Grade	Linguistic	Fuzzy Grade	Linguistic	Fuzzy Grade	Linguistic
6	OK	6	Low	4	Medium to high	6	Very High
5	In Use	5	Low to medium	3	Medium	5	High
4	In Use, In devel.	4	Medium	2	Low to medium	4	High(in wet soil)
3	In devel	3	Medium to high	1	Very low	3	Medium to high
2	R&D Prototype	2	High			2	Medium
1	R&D	1	Very High			1	Low
0	--					2	Unknown

Table 2.4: Fuzzy Grading key

Terrain	Speed	Alarms rate	Cost & complexity	Depth	Kind of mine	Con's	Pro's	state of the Criteria	Color	Fuzzy Grade
All	High	Low	Low	Deep	All	X	Very reliable	**very good**	**yellow**	2
Only for dry soil	X	X	X	Changeable	Metallic	X	Reliable	**Good**	**blue**	1
X	Low	High	High	X	X	Heavy	X	**Bad**	**red**	-1
other	Other	other	other	other	other	other	other	**other**	**white**	0

Note: X: not used

2.8 Summary

In this chapter the basic requirements and constraints of demining robots are discussed and the landmines activation pressure is analyzed. Two studies about the sensors comparisons are summarized and a sensors selection process is proposed based on fuzzy logic rule.

CHAPTER 3

SYSTEM CONTROL AND EXPERIMENTAL WORK

3.1 Introduction

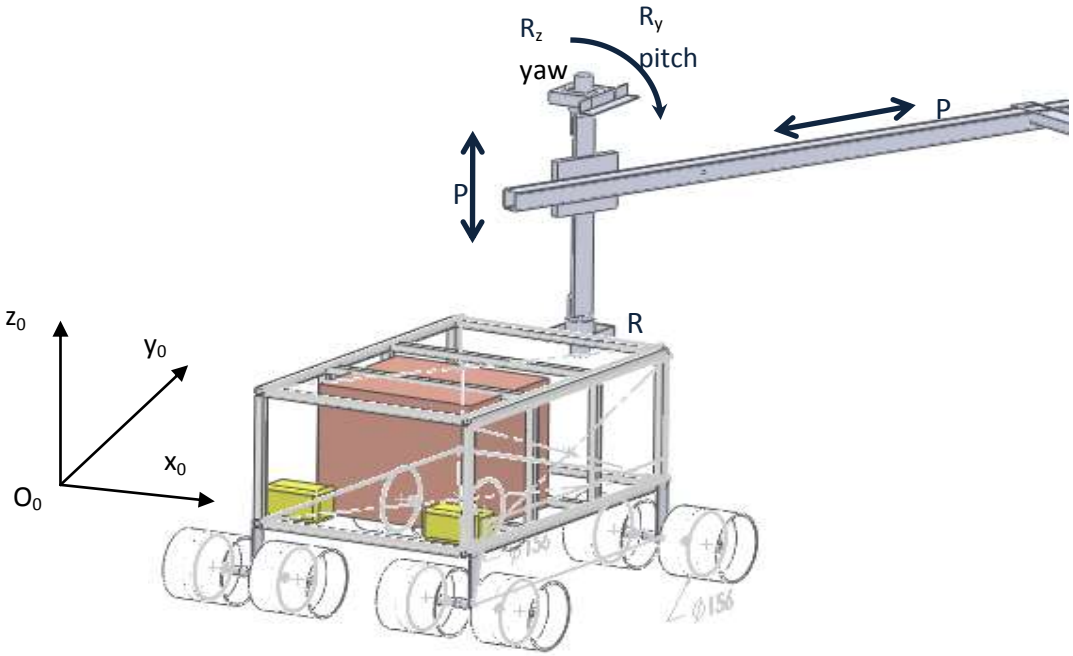
Through this chapter, the overall work flow is discovered through the Mechatronics synergistic integration work life cycle. The system architecture and the control algorithm are fully described. The microcontroller pin utilization for command the actuator and feedback from sensor is also illustrated. The Matlab GUI and the test scenarios are also figured. The experimental work in order to manufacture the robot and to implement the control circuits is also fully investigated. The difficulties and lessons to be leaned in each subsystem are also investigated. And after that, the market locations are distinguished and compared with each other and the advantages are mentioned (cost, type of components, status, how to reach, and comments).

3.2 System Architecture and Control Strategy

The proposed system is a mobile robot with arm and camera. This system is a complete example for utilizing Mechatronics approaches (Mechanical, Electrical, Control, and Software). As in Fig. 3.1, the mechanical hardware consists of: carriage with two actuators one for each side, and robot arm (RPP), with revolute joint around z axis (yaw) and prismatic joint in the z direction and prismatic joint in the horizontal direction, and a camera (RPRR) with revolute joint around z axis (yaw: for the arm and the camera) and prismatic joint in the z direction (for the arm and the camera) and another revolute joint around z axis (yaw: for the camera alone) and revolute joint around y axis (pitch: for the camera alone). Beside the mechanical and electrical hardware, the control system is composed of Laptop installed with Matlab GUI Fig. 3.1.

The user command the robot though this GUI as will be described later. As in Fig. 3.2, a command is transferred through the serial port or USB2serial to the Control Unit 1 which is a microcontroller AVR: ATMEGA32 circuit (low power) designed and developed in order to transform the command (from serial communication) to the RF transmitter 4-channels (parallel communication). As the RF receiver 4-channels (which are fixed on the robot carriage) receive a command it will be delivered to the Control Unit 2 which is a

microcontroller AVR: ATMEGA32 circuit (low power) designed and developed in order to command the actuators and to collect information from the sensors. Simply, it selects the actuator and the movement direction. The driving circuits (high power) are 5 H-Bridges to drive the DC motors (2 for the carriage sides and 3 for the arm) and ULN2003 circuit to drive the stepper motors (2 for the camera).



(a) Robot: Solidworks model

(b) GUI (c) Robot: Manufactured

Figure 3.1: Matlab GUI and the Robot (Carriage Arm) hardware

The control strategy is described in Fig. 3.3, the RF-4 channels are used to select which motor to actuate through a menu, where 2 channels are used to make interrupt to select certain motor and/or reset. The remaining two channels are used to decide the direction. Note that the interrupts just count pulses while the directions are always needed to move.

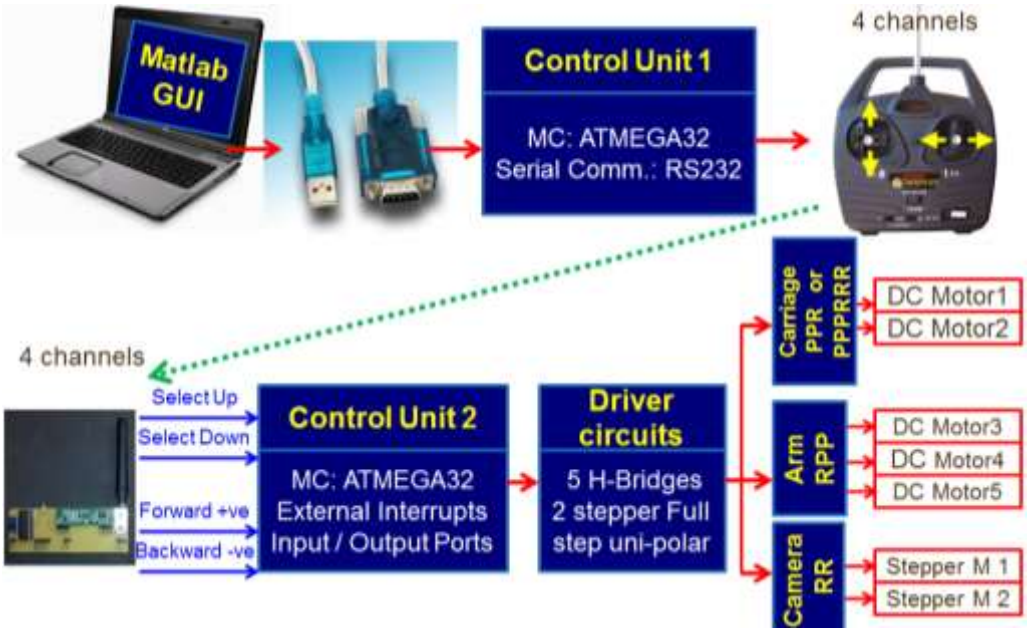


Figure 3.2: System Architecture

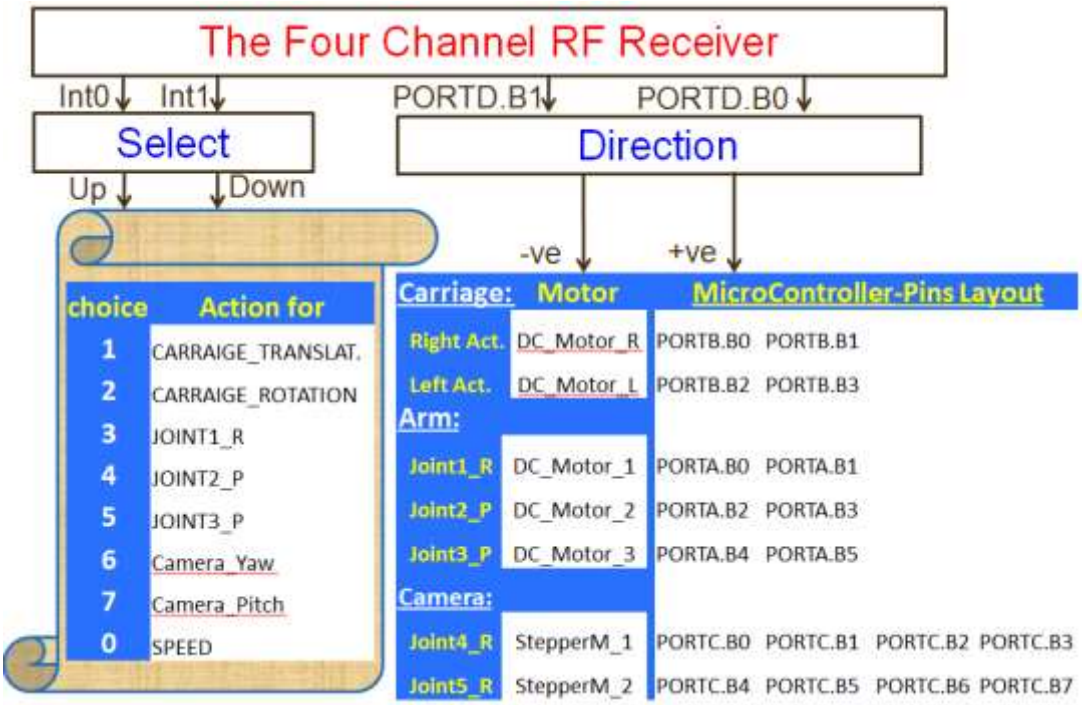


Figure 3.3: Control Strategy

Figure 3.4 shows the pin utilization of the microcontroller AVR: ATMEGA32 in the Control Unit 2 (Main Brain).Interrupts pins (16, 17) are used to select the motor form the menu shown before. The directions are decided from the pins (14, 15). Each DC motor has two pins one for each direction +ve and –ve. While the stepper motors each one has four pins where the sequence is applied. Also each limit switch has single pin when pressed in gives low 0v (active low). The ultrasonic and metal detector signals are input in pins (20, 21). When the sensors set are in the operating mode the green led lights and when metal detector detect metal the red led lights and the alarm is raised.

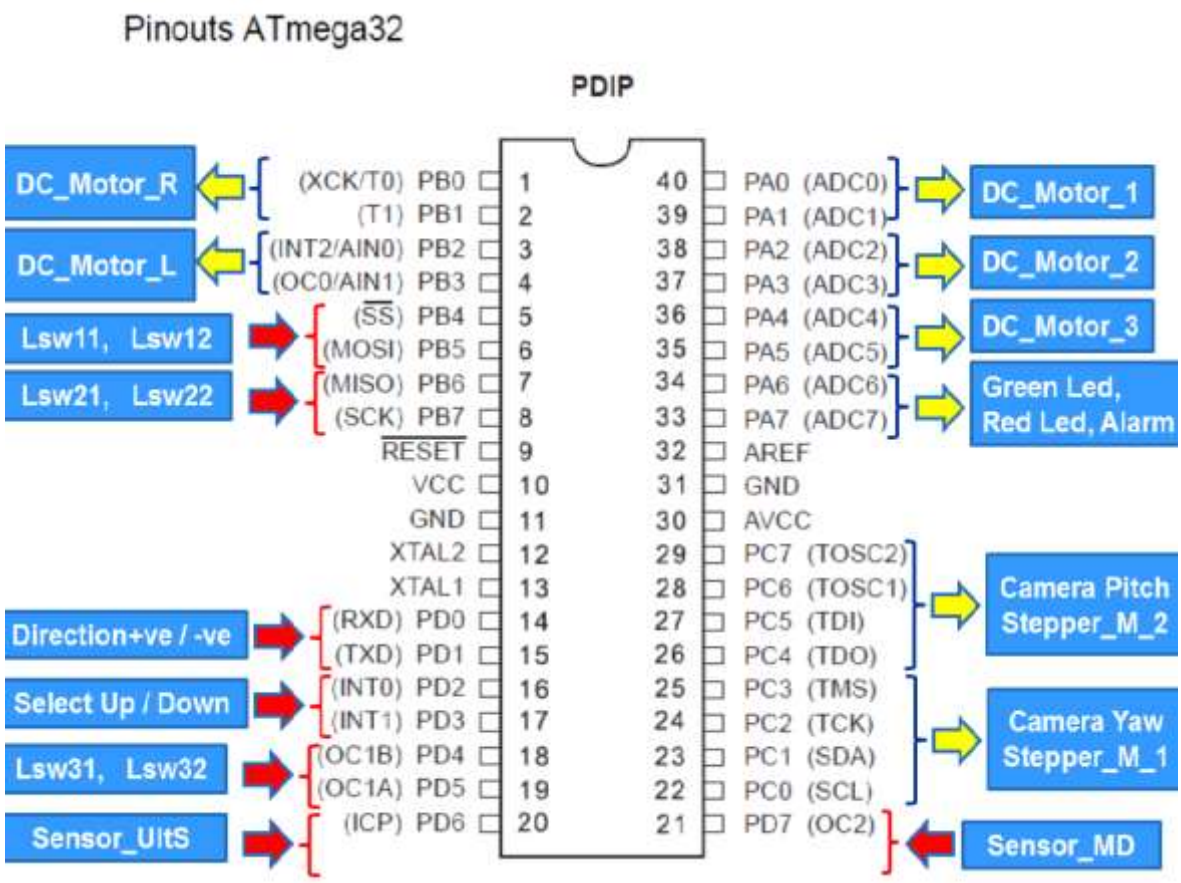


Figure 3.4: Main Brain, Microcontroller pins utilization

3.3 Control Circuits

Figure 3.5 shows an H bridge is an electronic circuit that enables a voltage to be applied across a load in either direction. These circuits are often used in robotics and other applications to allow DC motors to run forwards and backwards. H bridges are available as integrated circuits, or can be built from discrete components especially when high current is expected so we use power transistor like TIP family. Resistors R2, R4, R5 and R10 have to be 1-2 WATT rated, to support high currents, especially if a 24V power supply is used. The

wire connection W1, W2 are the wires between this H-bridge module and the controller board (Main Brain) that provides the logic signals for direction control, while W3, W4 are the wires which supply the H-Bridge the 12/24V power supply. In Table 3.1, a truth table is given below showing the effect of every combination of the logic states of W1 and W2. Diodes D2 to D4 are simple rectifier diodes, with forward current ratings of at least 4A. Actually, as you can see in figure 1.b, each pair of TIP122 and TIP127 share the same heat sink, without any risk of short circuits, since their collectors are already connected together in the circuit (If the schematic in figure 3.5 , Q5 and Q6 have their collector connected together, as well as Q7 and Q8).

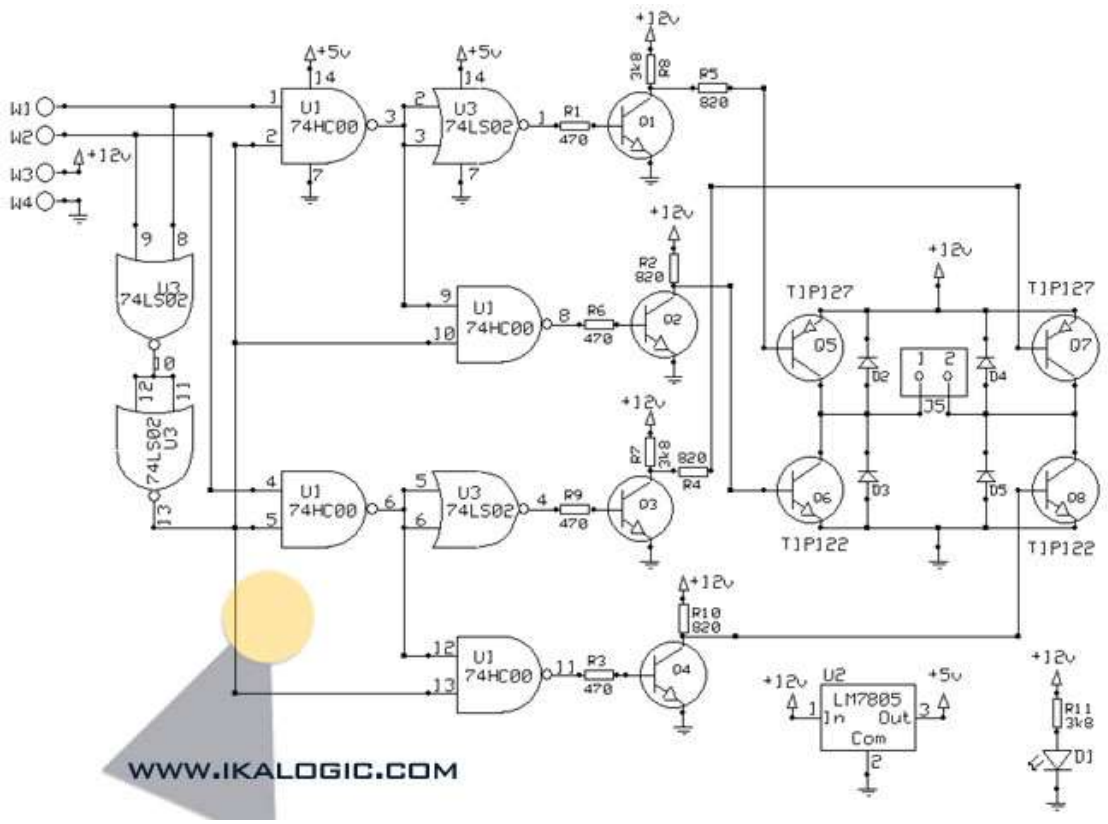
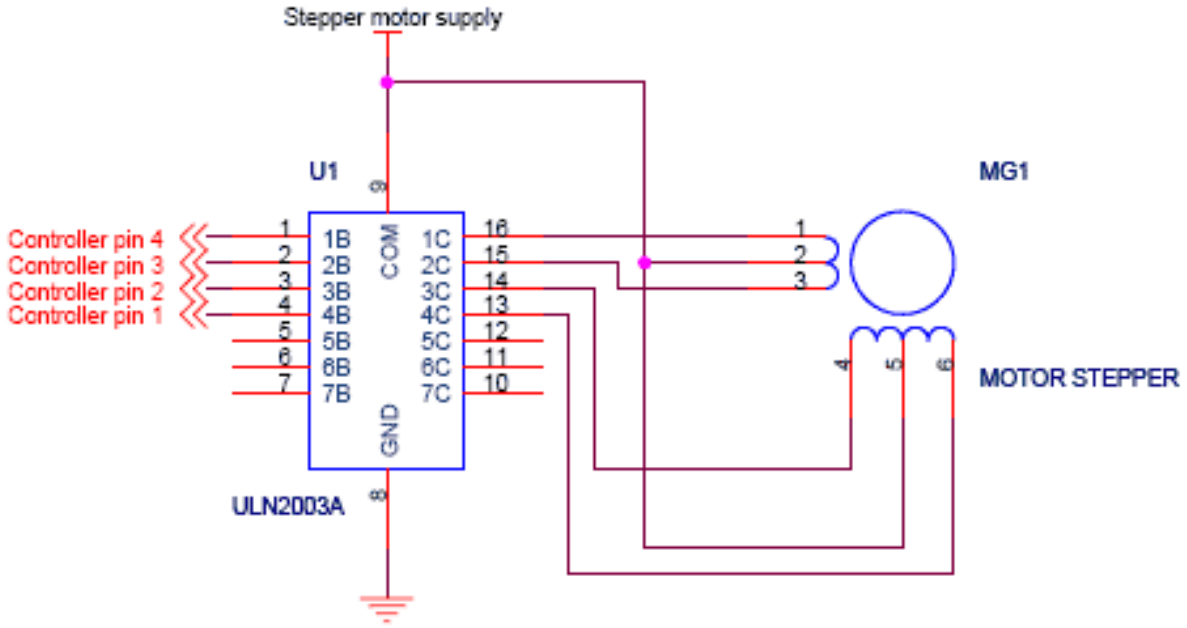


Figure 3.5: H-Bridge, DC Motor driving circuit

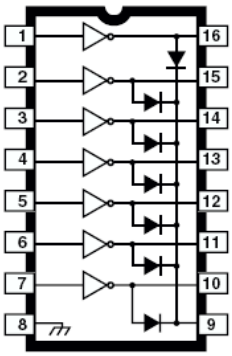
Table 3.1: H-Bridge driving command W1, W2

Inputs		Result on the connected motor
W1	W2	
0	0	Motor is freewheeling (disconnected, High impendence)
0	1	Turn the motor clockwise
1	0	Turn the motor anti-clockwise
1	1	breaking the motor

In Fig. 3.6, Stepper motor controlled using ULN2003A (Seven Darlington Arrays) circuit. The motor moves when sequence of pulses is applied. The holding torques and delay time between sequences are both critical issues. For ULN2003A, in order to support current more than 0.5A we can use two or more of channel for each coil.



(a) ULN2003A drive stepper motor in simulation



(b) ULN2003A pin layout

Full step / high torque	Coil A	Coil B	Coil C	Coil D
Step 1	1	1	0	0
Step 2	0	1	1	0
Step 3	0	0	1	1
Step 4	1	0	0	1

(c) Controlling sequence "Full step"

Figure 3.6: UL2003A, Stepper Motor driving circuit (unipolar), and Full step sequence

3.4 Work Flow

In Fig. 3.7, this work is done by applying an approach aiming at the **synergistic integration** of mechanics, electronics, control theory, and computer science (fields that make up Mechatronics) within the system design and manufacturing, in order to improve and/or optimize its functionality. This Iterative approach needs the next work life cycle.

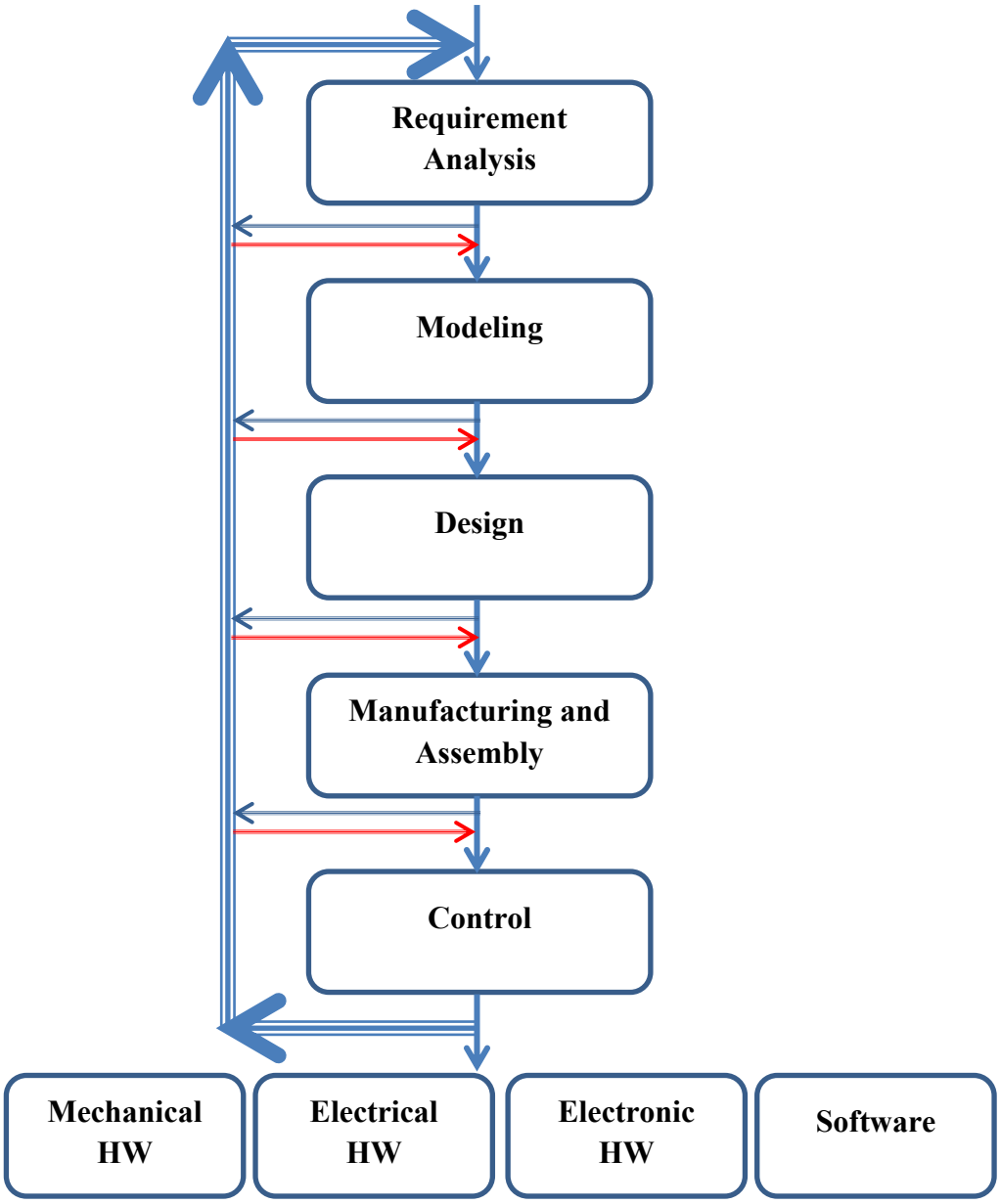


Figure 3.7: System Synergistic Integration "Mechatronics"

3.5 Faced Difficulties and Learned Lessons

In the table 3.2, the main items are stated in brief and will be described in more details below about (1) Mechanical structure; (2) Electrical hardware; (3) Driving circuits; (4) Electronic Circuit, and (5) Software.

3.5.1 Mechanical hardware:

Carriage: In Fig. 3.8, the carriage chassis was manufactured using square pipes (20 mm x 20 mm) welded using arc welding machine. The chassis dimensions were (500mm X 800mm X 300mm).The wheels axes manufactured using 1 inch pipes, with suspension of L

section (30 mm X 30 mm). The suspension of each wheel is individually adjustable in XYZ. For each side, two sprocket-chain sets are used to increase the torque and decrease the rotational velocity delivered from the motors to the wheels (constant Power = T*W).

The 1st sprocket-chain set is adjusted by couple of sprockets tensioned with springs while the 2nd sprocket-chain set is adjusted by couple of table plates which align the chain parts before matching with the sprocket. The base of the arm is fixed on the carriage front and pulled to its back to minimize arm vibration.

Table 3.2: Mechatronics Subsystems main items in our robot

Mechanical HW	Electrical HW	Electronic HW	Software
Carriage **Tracks** **Arm**	**DC Motors** **Stepper Motors** **Market locations** **Self locking** **Driving circuits** **H-Bridge** **ULN2003**	**Main Brain** **AVR:** ATMEGA32 **Pull down resistor** **External Interrupt** **Master clear bit** **Tools, lib** **Communication:** • IR Tr/Rx IR Remote control /Receiver /Remote control extender < 60m • RF remote control , car (4 channel) < 10 m • For future work ZIGBEE module wireless>100m	**Matlab GUI** **Embedded SW** -IR control on PIC - Transmitter - Receiver - Main Brain software

Figure 3.8: Carriage

Tracks: Figure 3.9, two tracks, one for each side, manufactured to distribute the load on larger contact area and to transfer motion from the back wheel to the front wheel for each side. The use material was scrape tires from different sizes. We used curtains tabs, chains, emery sheets, revolute joints (windows), and scissors**.** There are many problems in aligning the track with the wheel (even using tabs, wood clogs) because of: (1) small wheel width which is the widest in the market, and (2) only single wheel is used in each corner. A proposed solution is to use a pair of wheels with certain gap width in each corner, while the track has the opposite of this gap, so the pairs are forced to follow the track.

Figure 3.9: Track

Arm: Figure 3.10, the base of the arm is fixed on the carriage front and pulled to its back to minimize arm vibration. The arm is designed to be (RPP) and its base is fixed in the carriage front. The 1st joint is revolute, the 2nd joint is prismatic (car glass lifting machine, linear bearing from copier machine papers holder), and the 3rd joint is prismatic. The six Artelon wheels are aligned, moved linearly on the edges of the 1.5 meter arm of Aluminum rectangular box (8 cm X 2 cm). In the 1st iteration an RRRRR arm was proposed but the hardness constraints of the arm light materials prevents the usage of revolute joints as loads are concentrated on small area. This makes the advantages in using the prismatic joint as a surface with specified area slides on another surface, so RPP is our final design.

Figure 3.10: Mobile Robot with Arm RPP

3.5.2 Electrical hardware

Stepper Motors: Printers scrape stepper motors are used. Figure 3.11 presents a 2 stepper motors for rotating the camera around the z-axis (yaw) and y-axis (pitch). In the 1st iterations, stepper motors were used to give arms the required angle through the stepper motor steps, but the DC motors of the same weight give self-locking mechanism and also relatively higher torque.

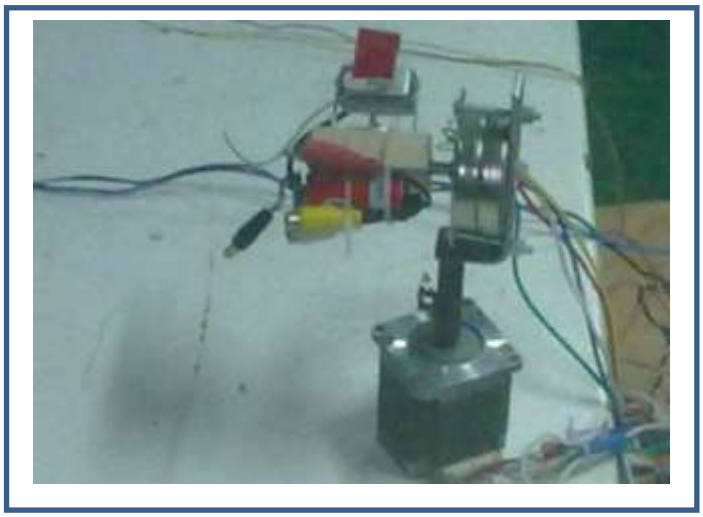


Figure 3.11: Camera Stepper Motors

DC Motors: These motors are from (copier machines) and (car glass lifting machines, figure 3.12) scrape.2 DC motors for moving the carriage, one for each side**.** Next are some motor characteristics performances

24 Volt,	5 Ampere	
43 Kg.cm,	150 RPM,	1:40 gear

The motor Torque may be calculated as follows:

Torque=43kg.cm=43*9.8/100 N.m =4.21 N.m

w=150 rpm=150*2*pi/60 rad/s=15.71 rad/s

Power = T*w = 4.21 * 15.71 = 66.13 watt

Another 3 DC motors for moving the arm joints RPP:

12 volt, no more info was available

Self-locking: Figure 3.12, those 3 DC motors (from car: glass lifting machines) connect to worm-gear which increase output torque and decrease the rotational velocity, and produce self-locking inherently. For the DC motor responsible to move the arm in z-axis against its load, we found that the motor dead (even powered) after loading and unloading for long time. We found that the brushes cages were crashed; we adjusted these cages and the motor work correctly.

For worm-gear in the DC motor responsible to move the arm in z-axis against its load, we found that the material of the gear is plastic and had wear after loading and unloading for long time. The solution is to manufacture a gear with same dimensions, material: steel, which gives better results.

Figure 3.12: DC motor, H-Bridge

3.5.3 Driving circuits

Those circuits are analyzed and produced to give the motors the motive power dependent on the command received from the main brain (micro-controller), figure 3.13.

H-Bridge: used to drive the DC motors

ULN2003: used to drive the unipolar stepper motors when the driving current is low 0.5 ampere and multi-channels are connected to carry multiples of this current.

Figure 3.13: Circuits, Circuits integration

3.5.4 Electronic hardware:

Main Brain: The Main Brain is the microcontroller circuit which commands the motors driving circuits based on the implemented logic in the embedded software on the target microcontroller ATMEGA32.The Embedded software is designed, coded, and tested through v-life cycle.

AVR Microcontroller: ATMEGA32

Pull down resistor: The pull down resistors are needed in the microcontroller circuit to prevent the noise effect on the port (to ensure zero voltage when required).

External Interrupt: External interrupt in the microcontroller ATMEGA32 is used to switch the command effect from actuation set to the next.

Master clear bit: The Master clear bit (MCLR) in the PIC microcontroller PIC16F628A trials is an active low Reset to the device. (This means it must be connected to the VCC with 10k resistant otherwise it will reset and give unpredictable results)

Communication:

- IR Tr/Rx (couldn't be implemented, complex algorithm)
- IR Remote control - Receiver
- Remote control extender: 60m
- RF remote control ,4 channel (implemented, simple algorithm)
- ZIGBEE module wireless: 100m (Inshaa-Allah for future work)

Microcontroller1:

Figure 3.14, this microcontroller is AVR: ATMEGA32 and it is responsible to receive and command through the PORTA to the RF transmitter circuit.

Figure 3.14: Circuits, test scenario 1, test scenario 2

3.5.5 Software

Matlab GUI: Figure 3.15, the Matlab GUI is used to program the HMI that interface with the user. The user can select the required action from this GUI. The can select the motor and the motion direction. The command is sent through the PC/Laptop serial port/USB2Serial RS232 to the microcontroller1 which is responsible to receive and command through the PORTA to the RF transmitter circuit.

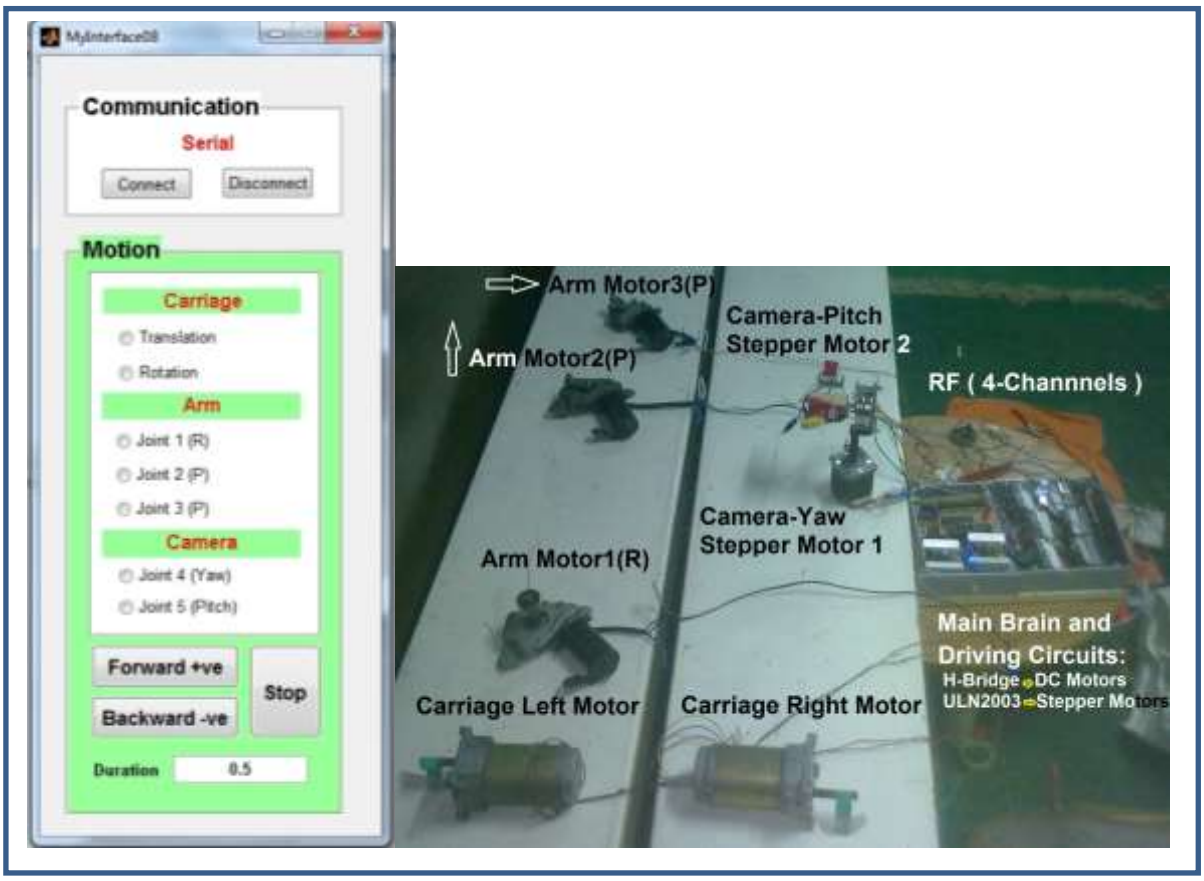


Figure 3.15: Graphical User Interface (GUI), Test scenario 3

Embedded SW

- IR control on PIC microcontroller (couldn't be implemented, complex algorithm)

- Transmitter in microcontroller 1 (AVR: ATMEGA32) to the transmitter part of the RF 4channels (parallel)

- Receiver in microcontroller 2 (AVR: ATMEGA32) from the receiver pare of the RF 4 channels, Main Brain software which is responsible to command the motors driving circuits and get status from the limit switches and Ultrasonic and metal detector sensors. Figure 3.16 shows the software items and its interfaces.

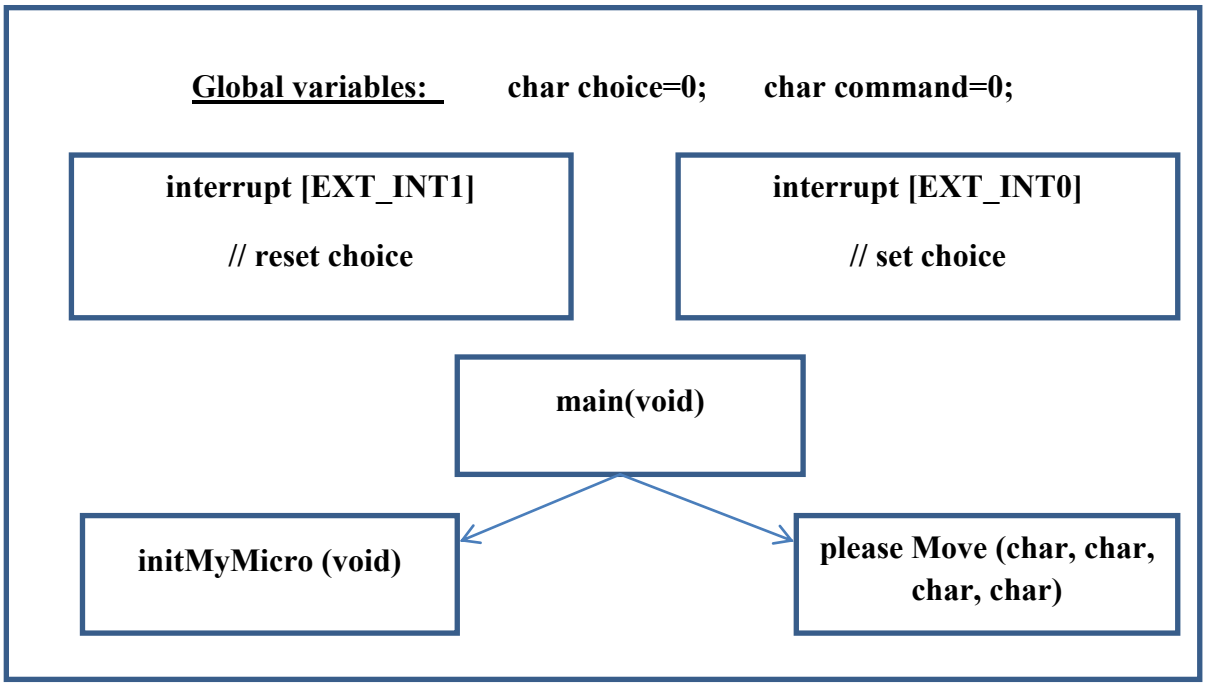


Figure 3.16: functions and API's interface

3.6 Repeatability Test

Repeatability is the variation in measurements taken by a single person or instrument on the same item and under the same conditions. A measurement may be said to be repeatable when this variation is smaller than some agreed limit. According to the Guidelines for Evaluating and Expressing the Uncertainty of NIST (National Institute of Standards and Technology) Measurement Results, repeatability conditions include:

- the same measurement procedure
- the same observer
- the same measuring instrument, used under the same conditions
- the same location
- repetition over a short period of time.

The responses of the robot actuators are not the same when a command is repeated specially in the open loop systems. In this part, two repeatability tests are executed:

- Repeatability test 1: Carriage translation
- Repeatability test 2: Arm Joint3 (P)

3.6.1 Repeatability test 1: Carriage translation

In the table 3.3, 20 commands are given to the robot to translate (Forward and Backward) in order to test the repeatability. It is also illustrated in the figure 3.17.

Table 3.3: Repeatability Carriage Translation (Forward and Backward)

Trip	Duration	Direction	From	to	Distance (mm)	Speed (mm/s)	Error = (speed -avSp)/avSp
1	5 sec	Backward	S1	S2	2452	490.4	-0.69%
2	5 sec	forward	S2	S3	2466	493.2	-0.12%
3	5 sec	Backward	S3	S4	2490	498	0.85%
4	5 sec	forward	S4	S5	2515	503	1.86%
5	5 sec	Backward	S5	S6	2400	480	-2.79%
6	5 sec	forward	S6	S7	2470	494	0.04%
7	5 sec	Backward	S7	S8	2443	488.6	-1.05%
8	5 sec	forward	S8	S9	2465	493	-0.16%
9	5 sec	Backward	S9	S10	2445	489	-0.97%
10	5 sec	forward	S10	S11	2478	495.6	0.36%
11	5 sec	Backward	S11	S12	2417	483.4	-2.11%
12	5 sec	forward	S12	S13	2477	495.4	0.32%
13	5 sec	Backward	S13	S14	2454	490.8	-0.61%
14	5 sec	forward	S14	S15	2524	504.8	2.23%
15	5 sec	Backward	S15	S16	2504	500.8	1.42%
16	5 sec	forward	S16	S17	2474	494.8	0.20%
17	5 sec	Backward	S17	S18	2508	501.6	1.58%
18	5 sec	forward	S18	S19	2466	493.2	-0.12%
19	5 sec	Backward	S19	S20	2466	493.2	-0.12%
20	5 sec	forward	S20	S21	2466	493.2	-0.12%
Average					**2469**	**493.8**	
Extreme positive Error							**2.23%**
Extreme negative Error							**-2.79%**

Average Distance	2469 mm	Extreme positive Error	2.23%
Average Speed	493.8 mm/s	Extreme negative Error	-2.79%

Average Distance	2480.1 mm	Extreme positive Error	1.77%
Average Speed	496.02 mm/s	Extreme negative Error	-0.61%

Average Distance	2457.9 mm	Extreme positive Error	2.04%
Average Speed	941.58 mm/s	Extreme negative Error	-2.36%

Figure 3.17: Repeatability Carriage Translation

comment: beside translations 20 times little rotation occurred

counter clock wise tan-1(36/90) = 21.79 deg.

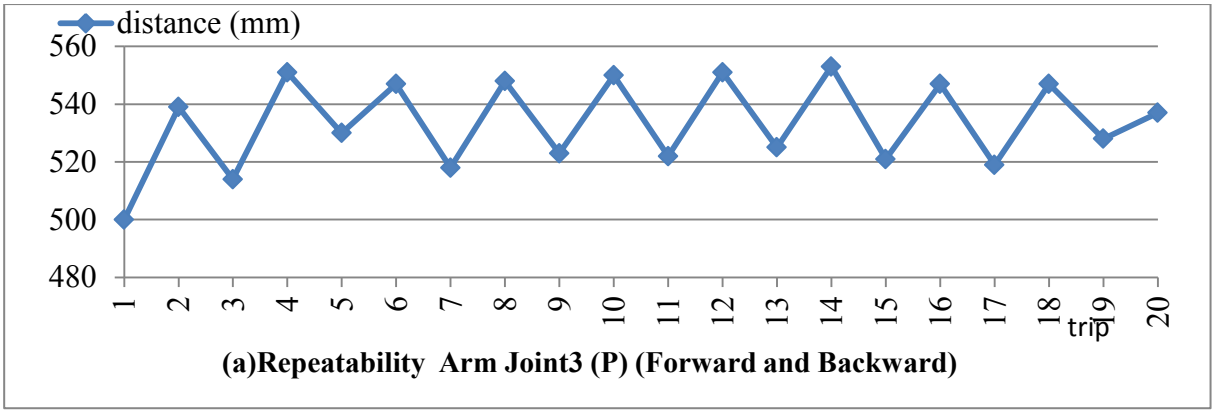
this means on the average each translation trip suffers: 1.1 deg

3.6.2 Repeatability test 2: Arm Joint 3 (P)

In the table 3.4, 20 commands are given to the robot to move the prismatic joint (Forward and Backward) in order to test the repeatability. It is also illustrated in the figure 3.18.

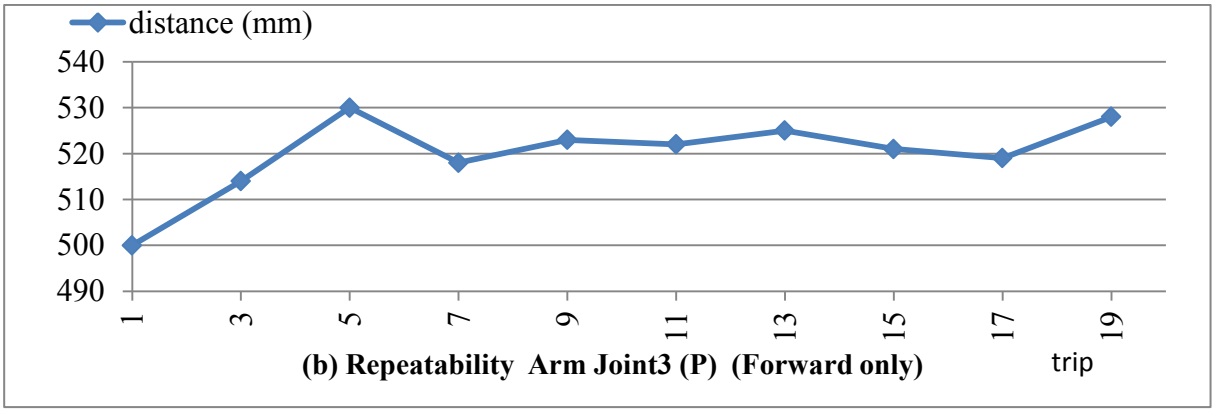
Table 3.4: Repeatability Arm Joint3 (Forward and Backward)

Trip	Duration	Direction	from	to	Distance (mm)	Speed (mm/s)	Error = (speed - avSp)/avSp
1	5 sec	forward	S1	S2	500	100	-6.28%
2	5 sec	Backward	S2	S3	539	107.8	1.03%
3	5 sec	forward	S3	S4	514	102.8	-3.66%
4	5 sec	Backward	S4	S5	551	110.2	3.28%
5	5 sec	forward	S5	S6	530	106	-0.66%
6	5 sec	Backward	S6	S7	547	109.4	2.53%
7	5 sec	forward	S7	S8	518	103.6	-2.91%
8	5 sec	Backward	S8	S9	548	109.6	2.72%
9	5 sec	forward	S9	S10	523	104.6	-1.97%
10	5 sec	Backward	S10	S11	550	110	3.09%
11	5 sec	forward	S11	S12	522	104.4	-2.16%
12	5 sec	Backward	S12	S13	551	110.2	3.28%
13	5 sec	forward	S13	S14	525	105	-1.59%
14	5 sec	Backward	S14	S15	553	110.6	3.66%
15	5 sec	forward	S15	S16	521	104.2	-2.34%
16	5 sec	Backward	S16	S17	547	109.4	2.53%
17	5 sec	forward	S17	S18	519	103.8	-2.72%
18	5 sec	Backward	S18	S19	547	109.4	2.53%
19	5 sec	forward	S19	S20	528	105.6	-1.03%
20	5 sec	Backward	S20	S21	537	107.4	0.66%
Average					**533.5**	**106.7**	
Extreme positive Error							**3.66%**
Extreme negative Error							**-6.28%**



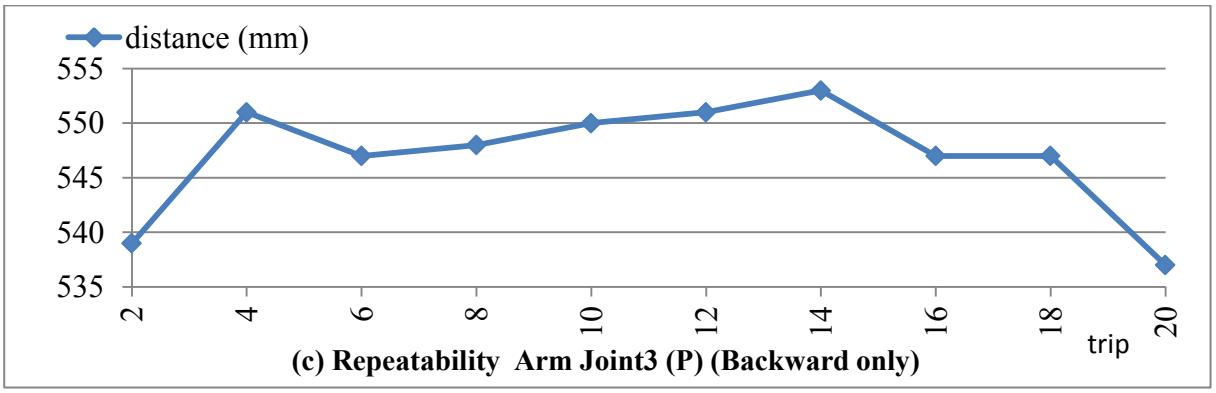
(a)Repeatability Arm Joint3 (P) (Forward and Backward)

Average Distance	533.5 mm	Extreme positive Error	3.66%
Average Speed	106.7 mm/s	Extreme negative Error	-6.28%



(b) Repeatability Arm Joint3 (P) (Forward only)

Average Distance	520 mm	Extreme positive Error	1.92%
Average Speed	104 mm/s	Extreme negative Error	-3.85%



(c) Repeatability Arm Joint3 (P) (Backward only)

Average Distance	547 mm	Extreme positive Error	1.10%
Average Speed	109.4 mm/s	Extreme negative Error	-1.83%

Figure 3.18: Repeatability Arm Joint3 (P) Translation

3.7 Used Sensors

Many sensors can be used for demining operations as stated in chapter 1 section 1.2.5 and also in the appendices A, B and C. In this part we state the used sensors for our demos. The sensors head contains the Ultrasonic Sensor and the Metal Detector.

3.7.1 Ultrasonic Sensor

In figure 3.19, The Ultrasonic sensor is to detect that the sensors head is close to the ground.

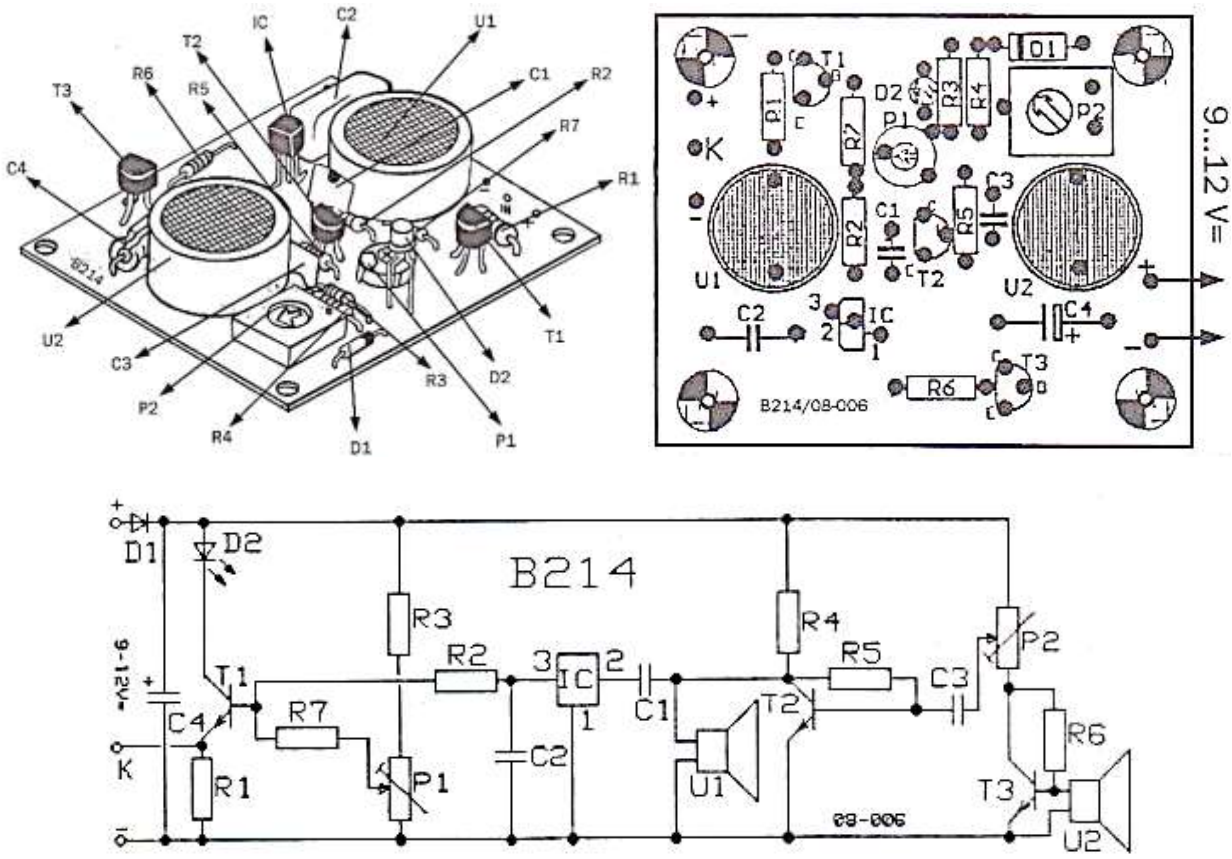


Figure 3.19: Ultrasonic Sensor circuit diagram

Parts List: U1, U2: ultrasonic microphone

IC: 41BF T1, T2, T3: transistors SC238B, BC548CB or CA3C38

D1: 1 diode BAY93, or TFK6520 D2: 1 light emitter diode 3 mm

P1: trimming potentiometer 250 k P2: trimming potentiometer 4 k7

C1: 220 pF C2: 100 nF C3: 22 nF C4: electrolytic 10µF 35 V

R1: 820 Ω R2: 10 kΩ R3, R7: 680 kΩ R4: 2.2 kΩ R5: 560 kΩ R6: 39 kΩ

3.7.2 Metal Detector

In figure 3.20, The Metal Detector is to detect the presence of metal when it scans the ground surface (in range of 1 cm).

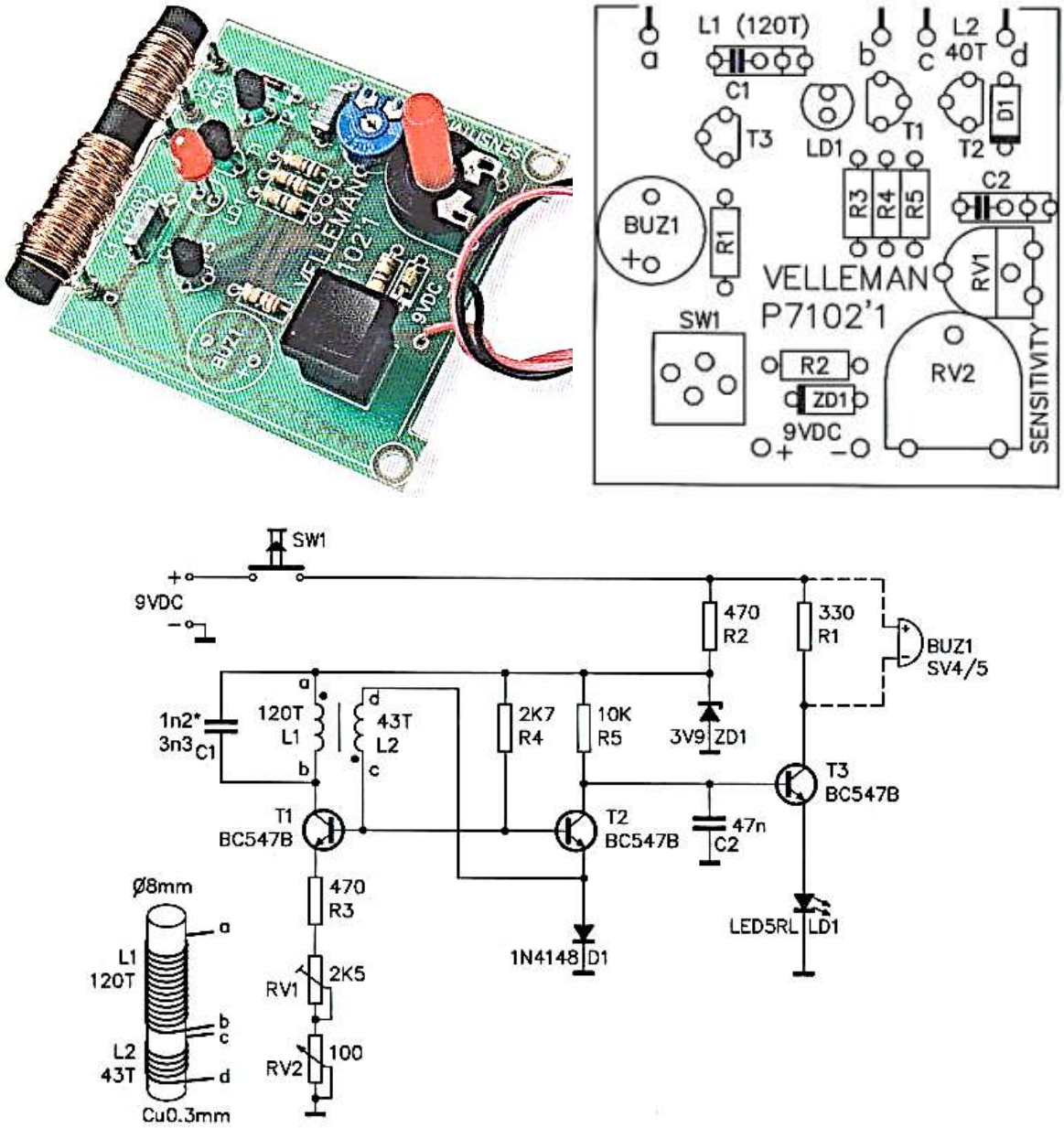


Figure 3.20: Metal Detector circuit diagram

3.8 Summary

Through this chapter, the overall work flow is discovered through the Mechatronics synergistic integration work life cycle. The system architecture and the control algorithm are fully described. The microcontroller pin utilization to command the actuator and feedback from sensor is also illustrated. The Matlab GUI and the test scenarios are also figured. The experimental work in order to manufacture the robot and to implement the control circuits is also fully investigated. The difficulties and lessons to be leaned in each subsystem are also investigated. Repeatability tests for the carriage translation and arm joint 3 are fully documented. Sensors head (Ultrasonic Sensor & Metal Detector) circuits are also illustrated.

CHAPTER 4
DEMINING ROBOT MATHEMATICAL MODELING AND SIMULATION

4.1 Introduction

After designing, manufacturing and controlling a demining mobile robot to satisfy the design constraints, it is time to study its kinematics. This is the subject of this chapter. The kinematics and control of simple mobile platforms are well understood and have become part of the standard curriculum for students studying robotics [60], but most of the literature dealing with mobile robot arms focuses on methods to decouple the control of the two sub-sets (vehicle and robot arm). An underlying assumption throughout the literature is that the mobile platform is a means of transporting the robotic arm to the vicinity of the task. Once there, the operation proceeds as it would normally proceed with a stationary robot arms.

The system understudy is a mobile robot with a robotic arm. The mission of this robot is to navigate on rough terrain to assist the human deminers in certain definite tasks such as:

- navigate and monitor the working area using cameras placed on the robotic system.
- carry sensors head and scan certain area (even rough terrain).
- get samples from sand particles and vapor from certain grid positions. These samples will be chemically analyzed and/or using trained dogs smell in order to draw large map of the expected infected regions.
- handle parts like landmark, … etc.
- more tasks can be planned and customize for demining operation in order to enhance the operation performance precession quality and cost: time, and money.

This specific purpose only needs the kinematic modeling of such a robot.

Most of literatures deal with the modeling and control of mobile robot arms as two sub-systems: the mobile platform (3 DOF) and the arm (3-6) DOF and only the linear displacements and velocities of the robot Tool Center Point (TCP) are obtained but its orientation is not included. Hence, it is a real challenge to deal with the problem of insufficient DOFs of the arm and the redundant DOFs of the platform by the integration of both the mobile platform and the robotic arm as one system instead of two sub-systems. This

chapter presents a systematic modeling technique of wheeled mobile robot arms (platform + arm) as one system.

This chapter uses the virtual robot approach for the kinematics modeling of mobile robot arm systems. This new approach was used for kinematics and dynamics modeling of missile-Camera system as a virtual robot [61]. This approached is summarized in the next section.

4.2 Virtual Robot Approach

The main research issue of a mobile robot arm is how to coordinate the mobility of a mobile platform and the manipulability of a manipulator. Most previous works assume that a mobile platform transports a robot arm to a proper location and a robot arm alone performs a given task, which makes control and planning problems easier. However, it will be more flexible if either or both of two subsystems can operate depending on situations.

The equivalent virtual robot, representing the carriage and the real ones of the robot arm is studied in two levels of complexity:

- 1st: Spatial platform (carriage): include six joints (three prismatic and three revolute) with virtual links.
- 2nd: Planar platform (carriage): include three joints (two prismatic and one revolute) with virtual links.

In the **Spatial Platform Virtual Robot Representation (PPPRRR) the** six joints of the equivalent virtual robot represent the transnational motion of the mobile robot and the orientation of the mobile robot in the (XYZ) reference coordinate frame. This system is modeled and simulated in details as it represents the general case of the virtual robot in space in any environments.

In the planar platform: Assembled **Carriage –Arm (Virtual Robot PPR-RPP)** the 1st three joints of the equivalent virtual robot represent the transnational motion of the mobile robot and the orientation of the mobile robot in the (XYZ) reference coordinate frame. The 4th joint represents the revolute joint of the base of the robot arm and the 5th and 6th joints represent the two prismatic joints of the robot arm links. This virtual robot has both revolute and prismatic joints arranged in a manner, which enables it to exactly act as the original mobile robot arm system.

Also for the Assembled **Carriage-Arm-Camera Modeling (PPR-RPRR):** the 1st three joints of the equivalent virtual robot represent the transnational motion of the mobile robot and the orientation of the mobile robot in the (XYZ) reference coordinate frame. The 4th

joint represents the revolute joint of the base of the robot arm and the 5th joint represents the vertical prismatic joint and the 6th and 7th joints represents yaw and pitch angles of the robot arm-camera. This virtual robot has both revolute and prismatic joints arranged in a manner, which enables it to exactly act as the original mobile robot arm system.

4.3 Coordinate Frames and Generalized Coordinates

A commonly used convention for selecting frames of reference in robotics applications is the Denavit and Hartenberg (D-H) convention which was introduced by Jaques Denavit and Richard S. Hartenberg. In this convention, each homogeneous transformation is represented as a product of four basic transformations. The common normal between two lines was the main geometric concept that allowed Denavit and Hartenberg to find a minimal representation (Fig. 4.1).

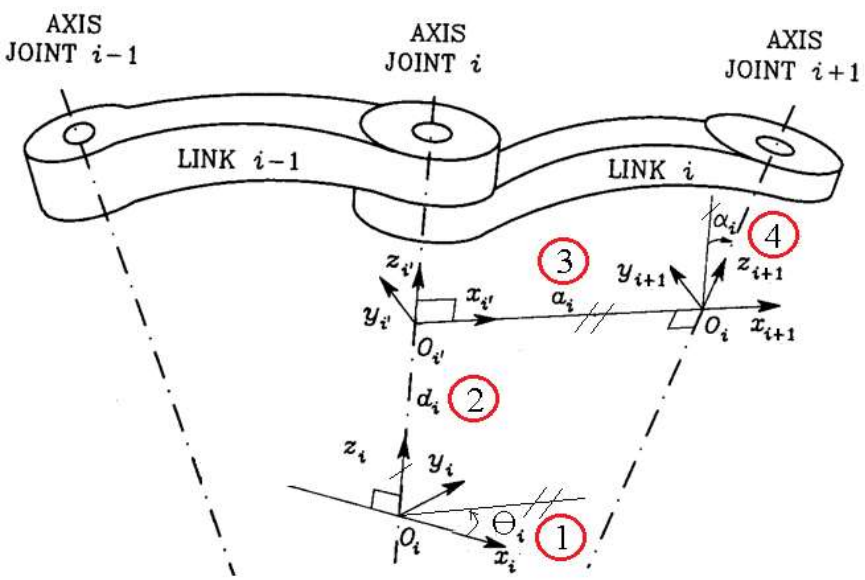


Figure 4.1 Denavit-Hartenberg Representations

In order to use robot-modeling techniques, a coordinate system must be attached to each link of the virtual robot. In Fig. 4.1, R_i=, (O_i, x_i, y_i, z_i) is attached to link (i-1). The position and orientation of coordinate system (R_{i+1}) attached to link (i) may be completely defined with respect to coordinate system (R_i) attached to link (i-1) using the Denavit-Hartenberg (D-H) notation [60]. In this notation, four parameters (a_i, α_i, θ_i and r_i) are required, where: a_i: is the arithmetic length along the common perpendicular between the axes z_i and z_{i+1}, α_i: is the angle between z_i and z_{i+1} measured about x_{i+1}, θ_i: is the angle between x_i and x_{i+1}

measured about z_i, and r_i: is the algebraic distance along z_i from x_i to x_{i+1}. The ith joint generalized coordinate q_i is defined by either θ_i or r_i according to the type of joint.

The coordinate frames representing our robotic system equivalent virtual robot links and joints are set as shown in the figures 4.2, 4.3 and 4.4. The arm in figure 4.3 the Planar Platform Virtual Robot generalized coordinates (q_1, q_2, q_3) represent the virtual robot prismatic joints and revolute joint in plan. The generalized coordinates (q_4, q_5, q_6) are the arm joints: revolute joint represent arm yawing angle and two prismatic joints for vertical and horizontal motions. The frame (R_8) represents the detector (end-effector) frame.

For the Carriage-arm-camera in figure 4.4 the Planar Platform Virtual Robot generalized coordinates (q_1, q_2, q_3) represent the virtual robot prismatic joints and revolute joint in plan. The generalized coordinates (q_4, q_5) are the arm joints: revolute joint represent arm yawing angle and prismatic joints for vertical motions. The generalized coordinates (q_6, q_7) are the camera revolute joints represent the camera yawing angle and pitching angle. The frame (R_8) represents the detector (end-effector) frame.

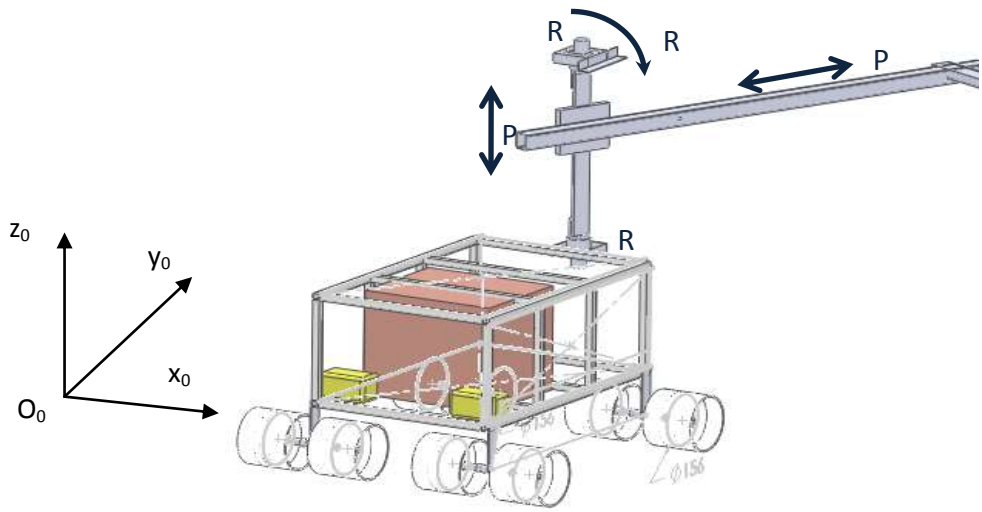


Figure 4.2: Robot: drawing in Solidworks

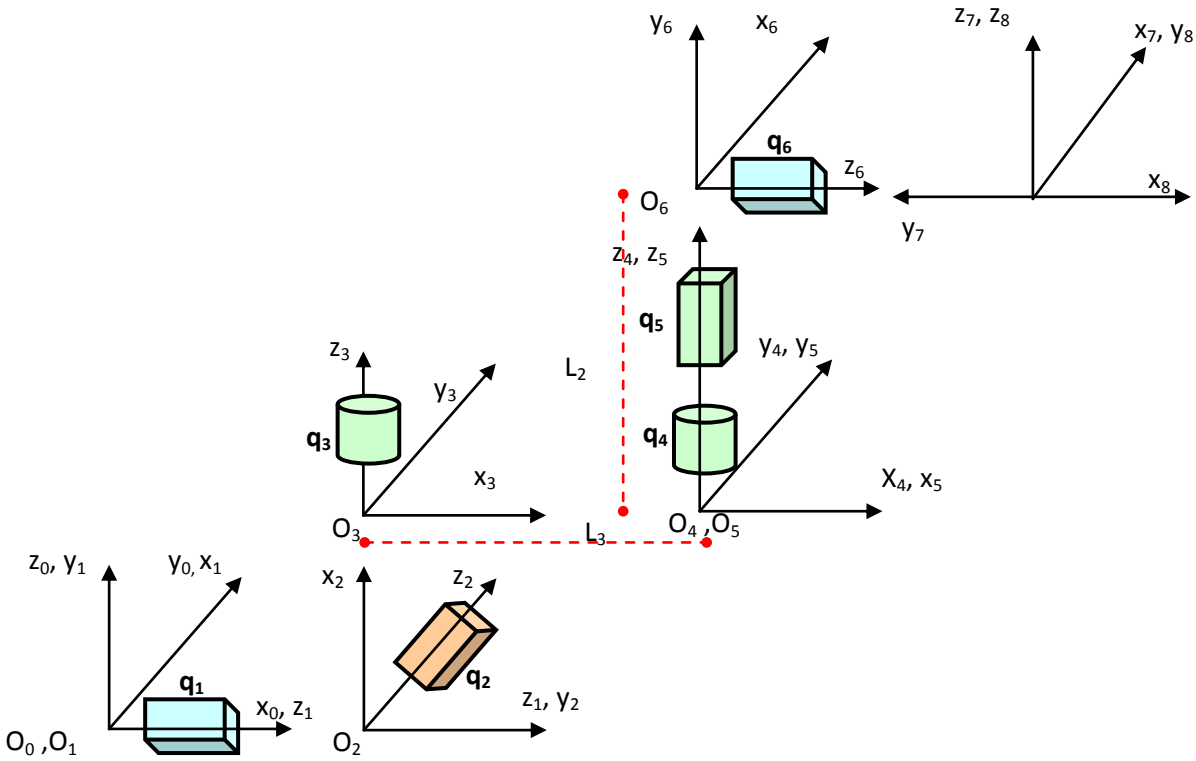


Figure 4.3: Robot: Carriage –Arm (Virtual Robot PPR-RPP)

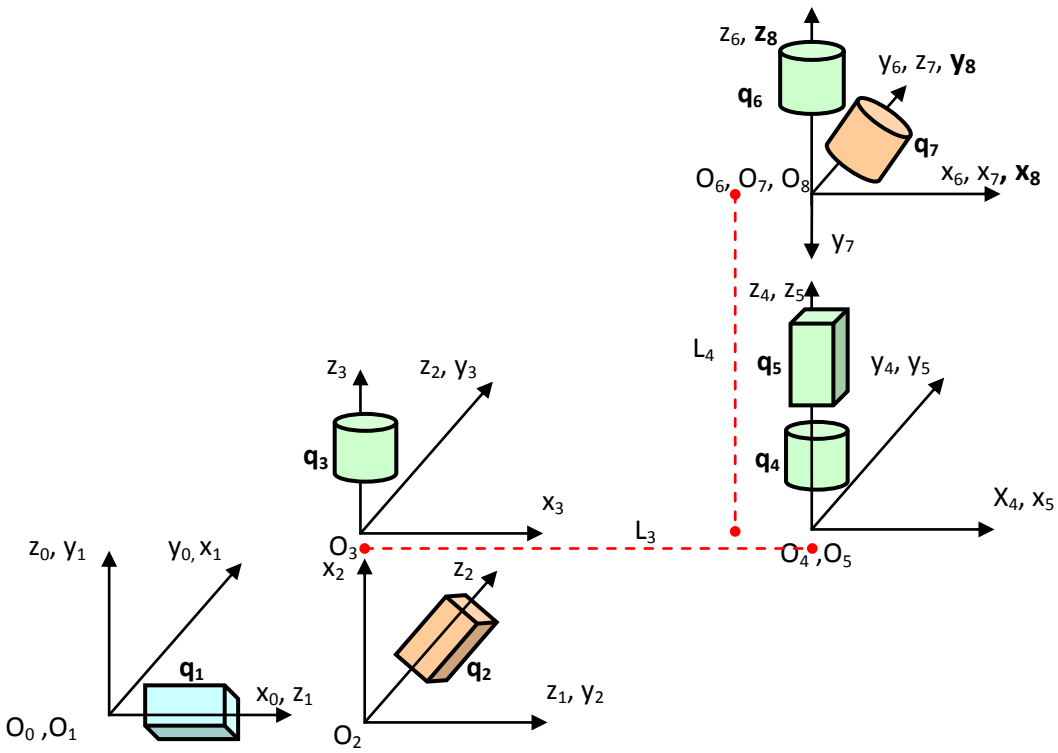


Figure 4.4: Robot: Carriage-Arm-Camera Modeling (PPR-RPRR)

4.4 Homogenous Transformation Matrices (HTMs)

The most usual way to model a robotic arm consists in using Denavit-Hartenberg (D-H) modified parameters [60]. Using the Denavit-Hartenberg four parameters, the elementary HTMs can be represented as presented in the following form:

$$T_{i,i+1}(q_i)=\begin{bmatrix}\cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & a_i\cos\theta_i\\ \sin\theta_i & \cos\alpha_i\cos\theta_i & -\sin\alpha_i\cos\theta_i & a_i\sin\theta_i\\ 0 & \sin\alpha_i & \cos\alpha_i & r_i\\ 0 & 0 & 0 & 1\end{bmatrix}=\begin{bmatrix}R_{i,i+1}(q_i) & P_{i,i+1}(q_i)\\ 0 & 1\end{bmatrix} \quad \textbf{...(4.1)}$$

Where: $P_{i,i+1}(q_i)$ is vector 3X1 and $R_{i,i+1}(q_i)$ is matrix 3X3

$$\begin{bmatrix}x_i & y_i & z_i & 1\end{bmatrix}^t = T_{i,i+1}\begin{bmatrix}x_{i+1} & y_{i+1} & z_{i+1} & 1\end{bmatrix}^t \quad \textbf{(4.2)}$$

The elementary HTMs $T_{i,i+1}(q_i)$ for i = 1,2,…,n allow the computation of the matrix $T_{1,i+1}$ which defines the transformation between the coordinate frame R_1 attached at the earth and the coordinate frame R_{i+1} attached to the ith link. This matrix has the form

Such that [x

$$T_{0,n+1}= T_{01}\, T_{12}\, T_{13} \,\ldots\, T_{n,n+1} \quad \textbf{...(4.3)}$$

$$T_{0,n+1}=\begin{bmatrix}t_{11} & t_{12} & t_{13} & t_{14}\\ t_{21} & t_{22} & t_{23} & t_{24}\\ t_{31} & t_{32} & t_{33} & t_{34}\\ t_{41} & t_{42} & t_{43} & t_{44}\end{bmatrix} \quad \textbf{...(4.4)}$$

$$\begin{bmatrix}x_0 & y_0 & z_0 & 1\end{bmatrix}^t = T_{0,i+1}\begin{bmatrix}x_{i+1} & y_{i+1} & z_{i+1} & 1\end{bmatrix}^t \quad \textbf{...(4.5)}$$

4.5 Direct Kinematics Position Modeling

The position of any point P in space is defined by three quantities with respect to any reference frame. Also the orientation of a coordinate system attached to point P with respect to the reference frame is defined by another three quantities. A homogenous vector X of m components defining the unconstrained robot workspace can specify this position and orientation. The robot configuration is defined by the generalized coordinates of its joints (q) where [60]:

X= f(q) ...**(4.6)**

Let X=[X_1 X_2 X_3 X_4 X_5 X_6]^t where X_1 X_2 X_3 are the translations for the end effect w.r.t x_0,y_0,z_0 and also X_4 X_5 X_6 are the rotations yaw, pitch, and roll.

$$\begin{bmatrix} X_1 & X_2 & X_3 & X_4 & X_5 & X_6 \end{bmatrix}^t = \begin{bmatrix} t_{14} & t_{24} & t_{34} & \alpha & \beta & \gamma \end{bmatrix}^t \quad \text{...(4.7)}$$

$$\left.\begin{array}{lll} to\ \ get\ \ \beta & = a\tan 2(\sin\beta, \cos\beta) & : \ \sin\beta = -t_{31}, \quad \cos\beta = \pm\sqrt{1-\sin^2\beta} \\ to\ \ get\ \ \alpha & = a\tan 2(\sin\alpha, \cos\alpha) & : \ \cos\alpha = t_{11}/\cos\beta, \quad \sin\alpha = t_{21}/\cos\beta \\ to\ \ get\ \ \gamma & = a\tan 2(\sin\gamma, \cos\gamma) & : \ \sin\gamma = t_{32}/\cos\beta, \quad \cos\gamma = t_{33}/\cos\beta \end{array}\right\} \text{...(4.8)}$$

α, Rotation about z (yaw), β, Rotation about y (pitch) , and γ Rotation about x (roll).

4.6 Direct Kinematics Velocity Modeling

This relation defines the so-called direct kinematics position model DKPM. The DKVM for any robot arm is given by [60]. More details in the computation methods are in appendix E.

$$\dot{X}_{mx1} = J_{mxn}(q)\dot{q}_{nx1} \quad \text{...(4.9)}$$

Where J(q) is the robot arm Jacobean matrix.

$\because X_{mx1} = f(q_{nx1})$

where m : is degree of freedom of the EE in space (max 6) and n: is number of joints

$$\Delta X = [J(q)]\Delta q$$
$$dX = [J(q)]dq$$
$$X^{\bullet} = [J(q)]q^{\bullet}$$

where $$J_{ij}(q) = \frac{\partial X_i(q)}{\partial q_j} \quad \text{..(4.10)}$$

This means for each column j of Jacobean Matrix J $\begin{bmatrix} \frac{\partial X_1}{\partial q_j} & \frac{\partial X_2}{\partial q_j} & \frac{\partial X_3}{\partial q_j} & \dots & \frac{\partial X_m}{\partial q_j} \end{bmatrix}^t$

where i={1, 2, …, m}, j={1, 2, …, n}

The differentiation of the DKVM Eq.4.20 with respect to time gives the definition of the direct kinematics acceleration model (DKAM) in the form [60].

$$\ddot{X}_{mx1} = H_{mxn}(q)\ddot{q}_{nx1} + J_{mxn}(q)\dot{q}_{nx1} \quad \text{...(4.11)}$$

Where H(q) is the robot arm Hessian matrix.

4.7 Inverse Kinematics

The computations of the inverse Kinematics models of robots are relatively complex compared to the direct ones. This difficulty is due to the high non-linearity of the basic kinematic equations of the robot. The aim from inverse Kinematics is to get the required joints generalized coordinates which results to have a certain homogenous vector where

$q = f^{-1}(X)$ ...**(4.12)**

Position: IKPM $\{\text{given } X_1, X_2, \ldots \text{we want to get } q_1, q_2, \ldots\}$

Velocity: IKVM $\{\text{given } \dot{X}_1, \dot{X}_2, \ldots \text{we want to get } \dot{q}_1, \dot{q}_2, \ldots\}$

Recalling that DKVM for any robot arm is given by [60]

$$\dot{X}_{mx1} = J_{mxn}\dot{q}_{nx1}$$

Multiplying the above equation by J^t produces

$$J^t_{nxm}\dot{X}_{mx1} = \left[J^t J\right]_{nxn}\dot{q}_{nx1}$$
$$\left[J^t J\right]^{-1}_{nxn} J^t_{nxm}\dot{X}_{mx1} = \dot{q}_{nx1}$$

$$\dot{q}_{nx1} = \left[J^t J\right]^{-1}_{nxn} J^t_{nxm}\dot{X}_{mx1} \quad \text{...(4.13)}$$

This relation defines the so-called inverse kinematic velocity model

Direct and Inverse Kinematics Acceleration Models DKAM & IKAM:

The DKAM for robotic arm can be given by

$$\ddot{X}_{mx1} = J_{mxn}\ddot{q}_{nx1} + \dot{J}_{mxn}\dot{q}_{nx1}$$
$$\ddot{X}_{mx1} = J(q)\ddot{q} + H(q)\dot{q}\dot{q} \quad \text{...(4.14)}$$

From above equations the IKAM can be given by

$$q^{\bullet\bullet} = J^{-1}(q)[X^{\bullet\bullet}_{mx1} - H(q)q^{\bullet}q^{\bullet}] \quad if \quad J\,is \quad square$$

$$q^{\bullet\bullet} = G(q)[X^{\bullet\bullet}_{mx1} - H(q)q^{\bullet}q^{\bullet}] \quad generally \qquad \text{...(4.15)}$$

$$Where: \qquad G(q) = \left[J^t J\right]^{-1}_{nxn} J^t_{nxm}$$

4.8 Kinematic Modeling of Robot Components

4.8.1 Component # 1-a: Spatial Platform Virtual Robot Representation (PPPRRR)

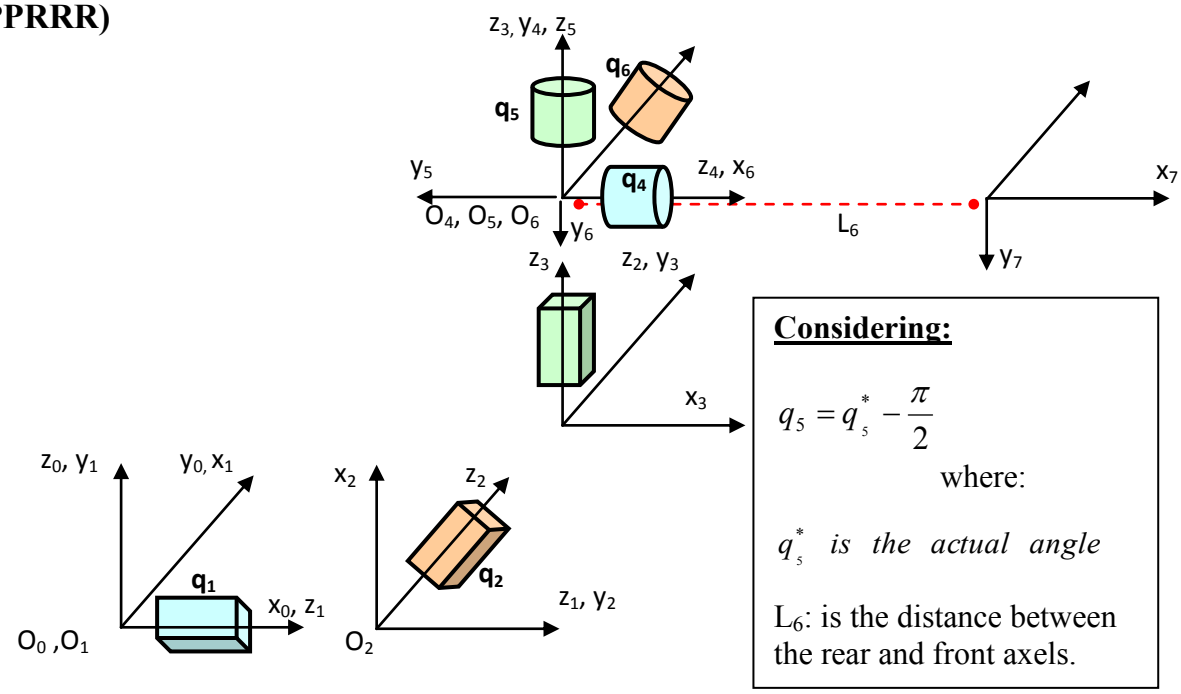


Figure 4.5: Spatial Platform (carriage) Virtual Robot Representation (PPPRRR)

Table 4.1: PPPRRR virtual robot D-H parameters

Parameters		Virtual Robot (PPPRRR)					
		Translations			Rotations		
	0	1	2	3	4	5	6
a_i	0	0	0	0	0	0	L_6
α_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$-\frac{\pi}{2}$	$-\frac{\pi}{2}$	0
θ_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	q_4	q_5	q_6
r_i	0	q_1	q_2	q_3	0	0	0

Based on figure 4.5 and table 4.1 and by substitution in the HTM eq. 4.1, we can state the elementary HTMs:

$$T_{01}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&0\\0&0&0&1\end{bmatrix},\ T_{12}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_1\\0&0&0&1\end{bmatrix},\ T_{23}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_2\\0&0&0&1\end{bmatrix},T_{34}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_3\\0&0&0&1\end{bmatrix},$$

$$T_{45}=\begin{bmatrix}C4&0&-S4&0\\S4&0&C4&0\\0&-1&0&0\\0&0&0&1\end{bmatrix},\ T_{56}=\begin{bmatrix}C5&0&-S5&0\\S5&0&C5&0\\0&-1&0&0\\0&0&0&1\end{bmatrix},\ T_{67}=\begin{bmatrix}C6&-S6&0&L_6C6\\S6&C6&0&L_6S6\\0&0&1&0\\0&0&0&1\end{bmatrix},$$

Transformation matrix:

$$T_{0,7}=\begin{bmatrix}t_{11}&t_{12}&t_{13}&t_{14}\\t_{21}&t_{22}&t_{23}&t_{24}\\t_{31}&t_{32}&t_{33}&t_{34}\\t_{41}&t_{42}&t_{43}&t_{44}\end{bmatrix}=\begin{bmatrix}\text{-s5*c6}&\text{s5*s6}&\text{-c5}&\text{-s5*L6*c6+q1}\\\text{c4*c5*c6+s4*s6}&\text{-c4*c5*s6+s4*c6}&\text{-c4*s5}&\text{K1*c5+K4+q2}\\\text{s4*c5*c6-c4*s6}&\text{-s4*c5*s6-c4*c6}&\text{-s4*s5}&\text{K3*c5-K2+q3}\\0&0&0&1\end{bmatrix}$$

Sin-Cosines buffers:

c4=cos(q4); s4=sin(q4); c5=cos(q5); s5=sin(q5); c6=cos(q6); s6=sin(q6);

let sTh = sin θ, cTh = cos θ, cPh = cosϕ, sPh = sin ϕ; cEp = cos ψ, sEp = sinψ;

By substitution in the Orientation Representation eq. 4.8 (yaw-pitch-roll Angles)

sin(θ)=-t31; cos(θ) =(1- sin(θ)* sin(θ))^0.5; cos(ϕ)=t11/ cos(θ); sin(ϕ)=t21/ cos(θ);

sin(ψ)=t32/ cos(θ); cos(ψ)=t33/ cos(θ);

where:

K1= L6*(c4*c6); K2=L6*(c4*s6); K3= L6*(s4*c6);

K4=L6*(s4*s6); G1=(cPh*c5 + sPh*c4*s5);

are the auxiliary symbolic equation

The Jacobean matrix:

$$J = \begin{bmatrix} 1 & 0 & 0 & 0 & -L6*c5*c6 & s5*L6*s6 \\ 0 & 1 & 0 & -K3*c5+K2 & -K1*s5 & K3-K2*c5 \\ 0 & 0 & 1 & K1*c5+K4 & -K3*s5 & -K1-K4*c5 \\ 0 & 0 & 0 & cPh*tTh & c4-s4*sPh*tTh & -tTh*G1-s4*s5 \\ 0 & 0 & 0 & -sPh & -cPh*s4 & sPh*c5-cPh*c4*s5 \\ 0 & 0 & 0 & cPh/cTh & -sPh/cTh*s4 & -G1/cTh \end{bmatrix}$$

$$\dot{X}_{mx1} = J_{mxn}\dot{q}_{nx1}$$

Computation procedure can be presented in the figure 4.6 and the flow charts below.

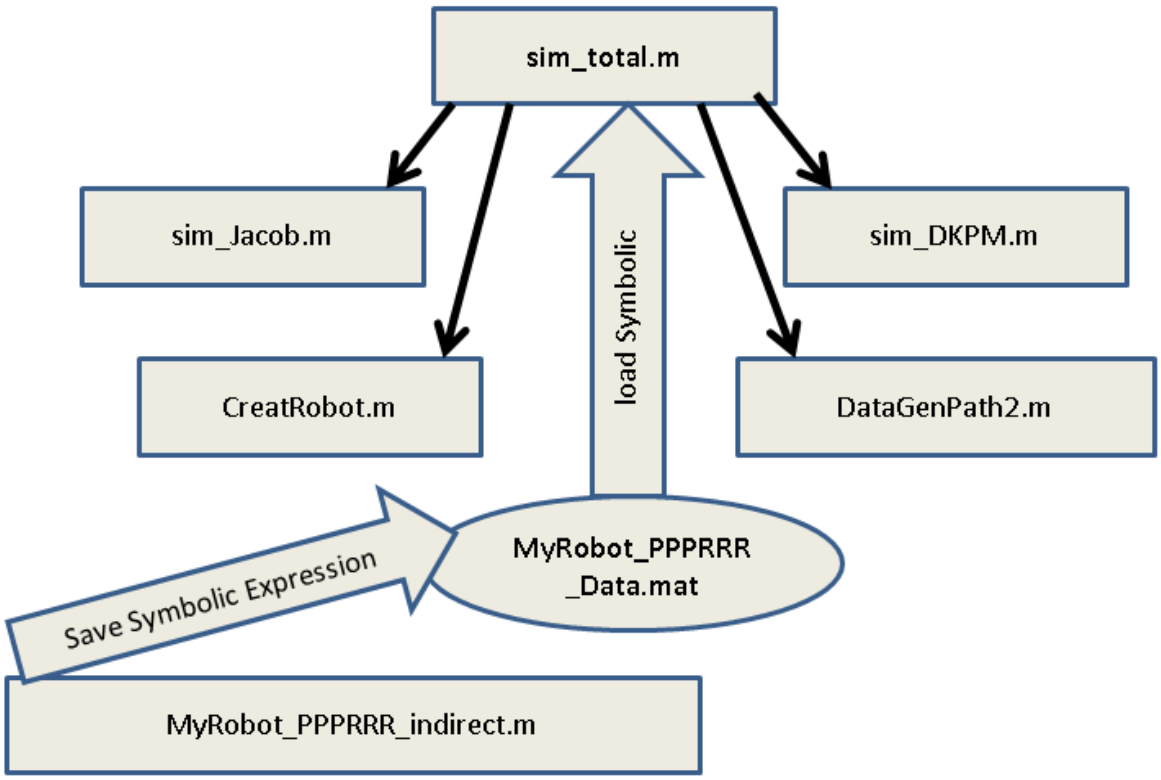
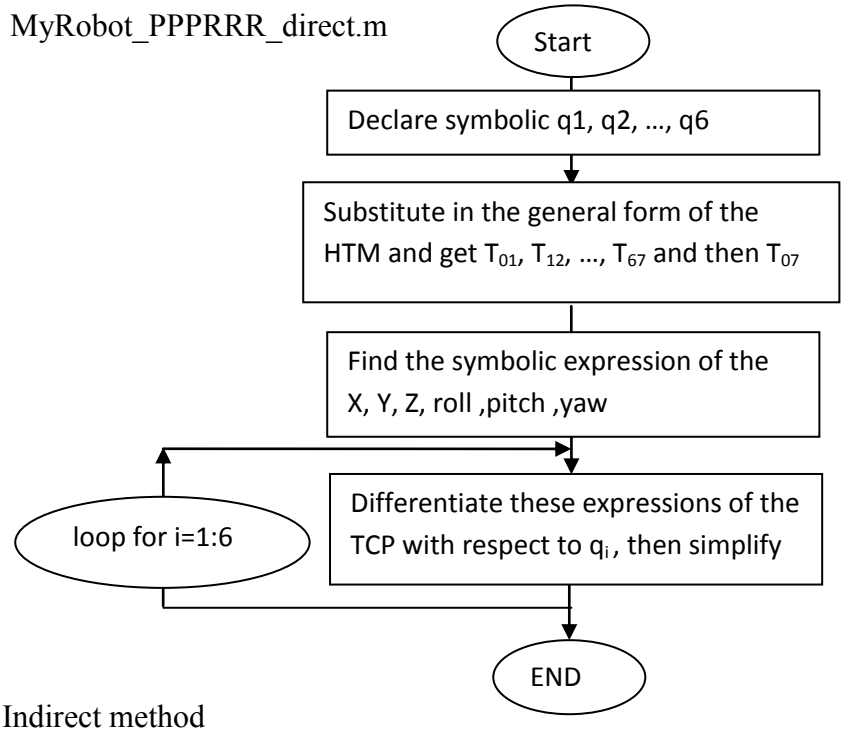


Figure 4.6: Files Hierarchy in Modeling

HTM, DKPM, Jacobean matrix

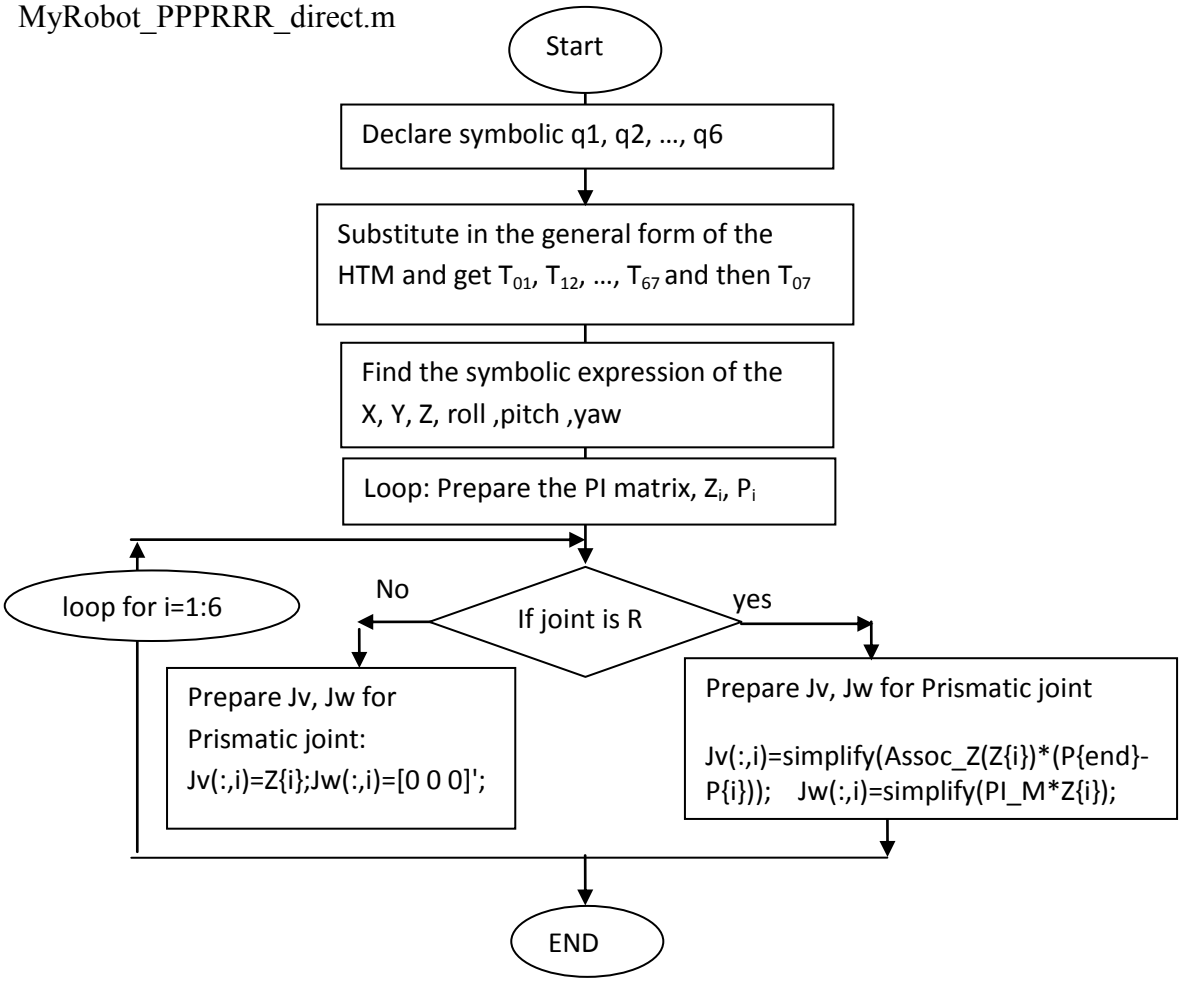
Direct method

MyRobot_PPPRRR_direct.m



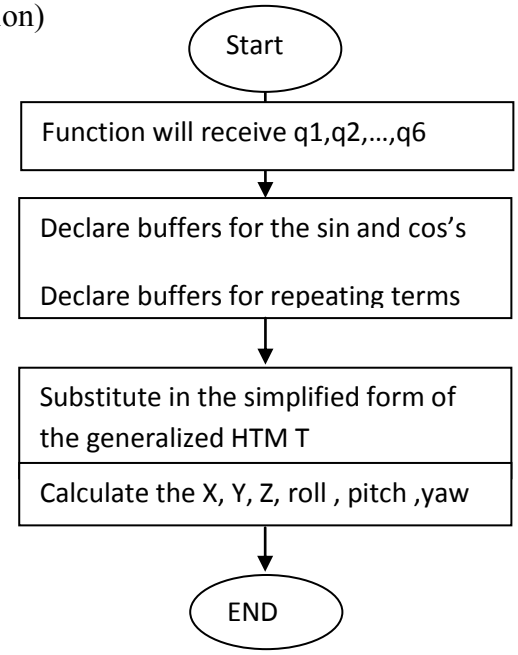
Indirect method

MyRobot_PPPRRR_direct.m



Direct kinematics (function)

sim_DKPM.m



Simulation examples: Robot Trajectories

Using a third part toolbox [71] and by modification, a number of robot trajectories are simulated in the following figures 4.7, 4.8, 4.9, 4.10, and 4.11. Also a Simulink model is test in figure 4.12.

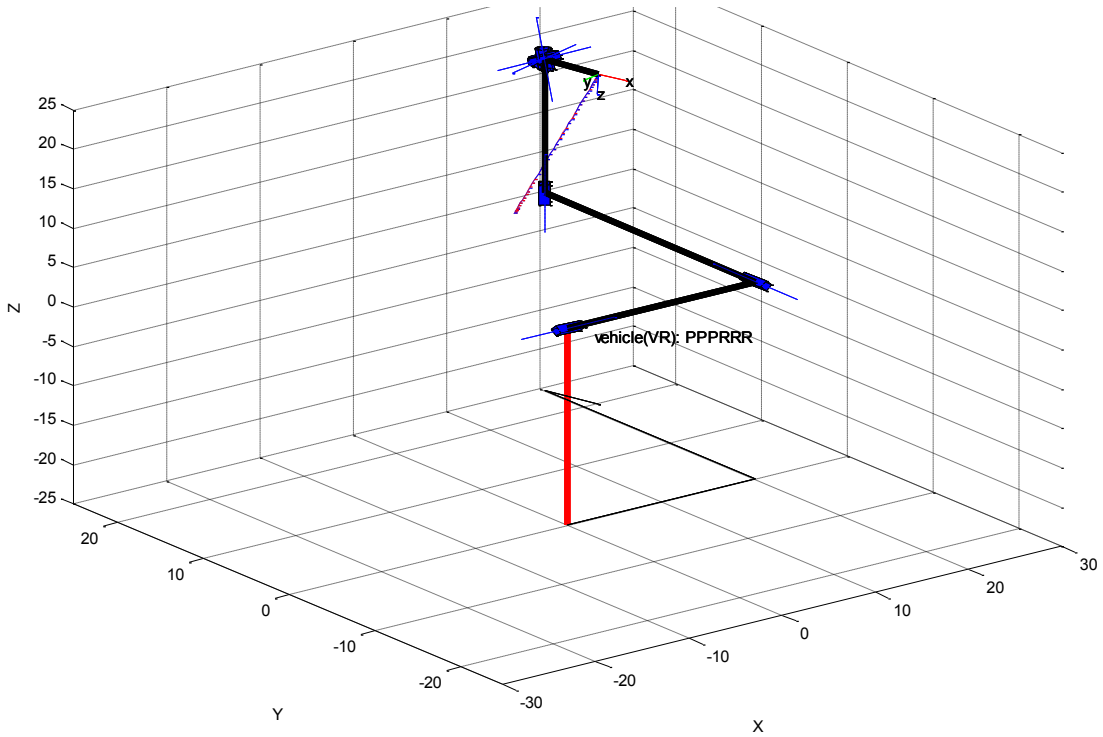


Figure 4.7: Virtual Robot Representation (PPPRRR) track spline

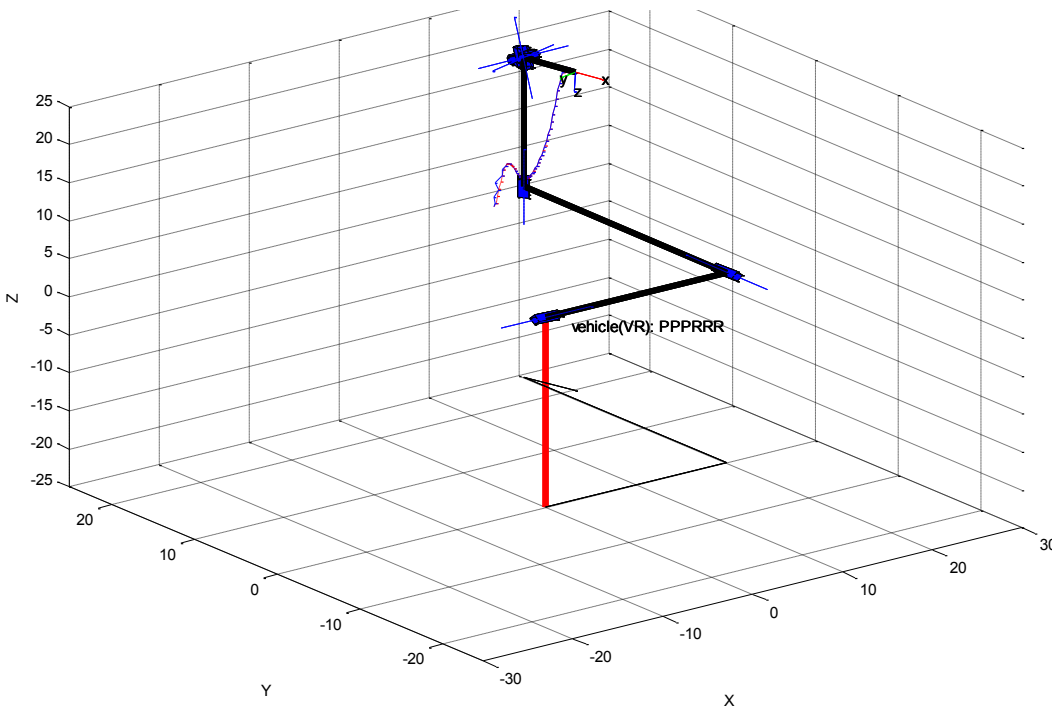


Figure 4.8: Virtual Robot Representation (PPPRRR) track sin-sin in plan

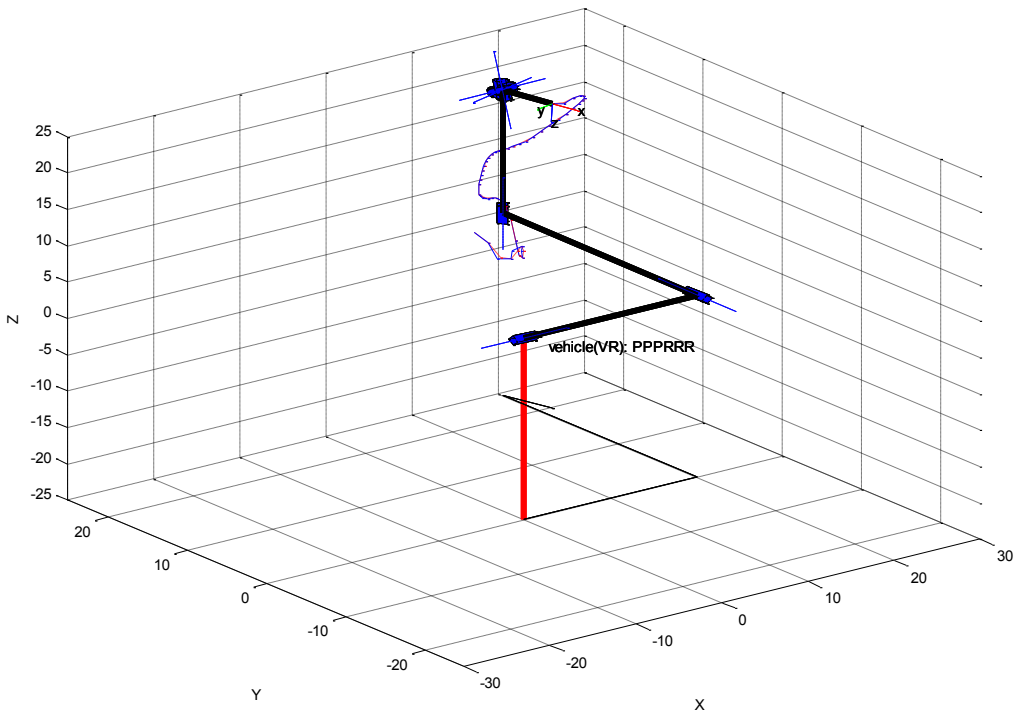


Figure 4.9: Virtual Robot Representation (PPPRRR) track sin-sin in 3D

Robot carriage will follow circular path in a plan, Robot will follow the command: x, y, z, yaw

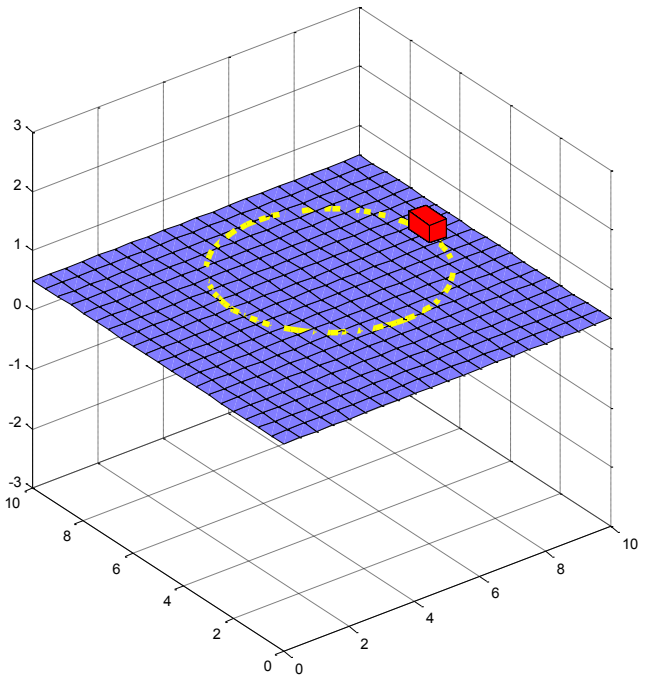


Figure 4.10: Virtual Robot Representation (PPPRRR) track circular path in plan

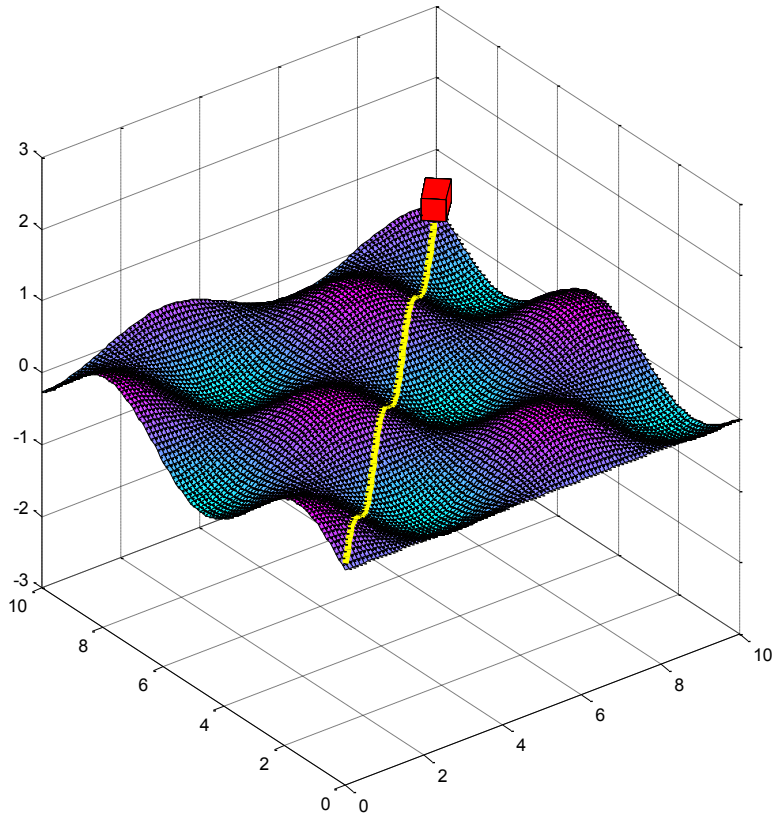


Figure 4.11: Virtual Robot Representation (PPPRRR) track path on terrain in 3D

Simulink Model for system Direct Kinematics

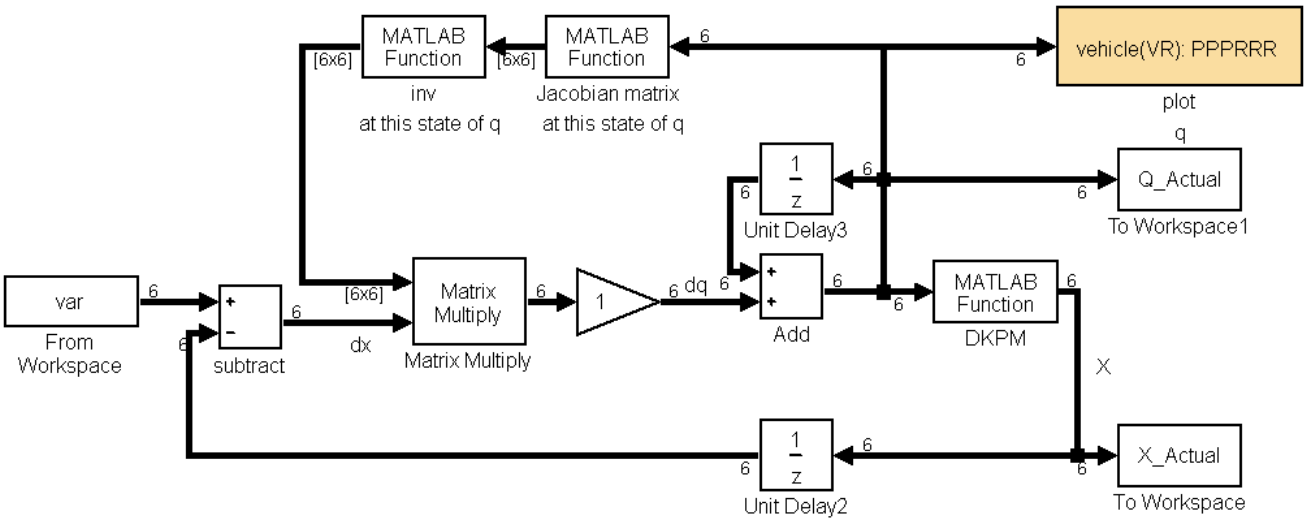


Figure 4.12: Virtual Robot Representation (PPPRRR)

SIMULINK model tracking paths

4.8.2 Component # 1-b: Planar Platform Virtual Robot Representation (PPR)

Virtual Robot: PPR

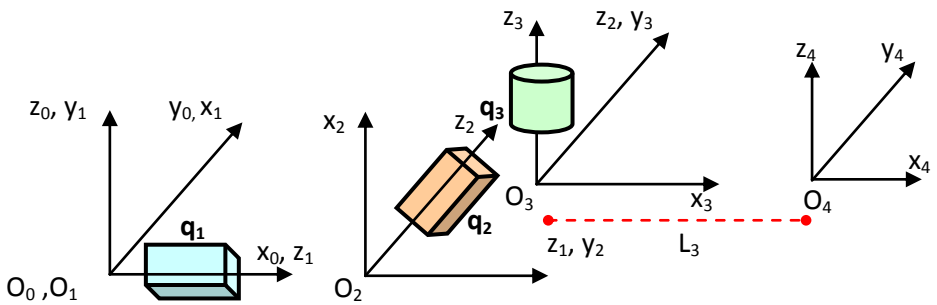


Figure 4.13: Robot carriage modeling (planar virtual robot: RPP)

Table 4.2: PPR virtual robot D-H parameters

Parameters	Ref-Base	Virtual Robot (PPR)		
	0	1	2	3
a_i	0	0	0	L_3
α_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0
θ_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	q_3
r_i	0	q_1	q_2	0

Base on figure 4.13 and table 4.2 and by substitution in the HTM eq. 4.1, we can state the elementary HTMs:

$$T_{01} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{12} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & q_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{23} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & q_2 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_{34} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & q_3 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

Sin-Cosines buffers:

c3=cos(q3); s3=sin(q3);

Transformation matrix

$$T_{0,4} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ t_{41} & t_{42} & t_{43} & t_{44} \end{bmatrix} = \begin{bmatrix} c_3 & -s_3 & 0 & q_1 + L_3 * c_3 \\ s_3 & c_3 & 0 & q_2 + L_3 * s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

By substitution in the Orientation Representation eq. 4.8 (yaw-pitch-roll Angles)

sin(θ)=-t31; cos(θ) =(1- sin(θ)* sin(θ))^0.5;

cos(ϕ)=t11/ cos(θ); sin(ϕ)=t21/ cos(θ);

sin(ψ)=t32/ cos(θ); cos(ψ)=t33/ cos(θ);

$$TCP_DKPM = \begin{bmatrix} X \\ Y \\ Z \\ \phi \end{bmatrix} = \begin{bmatrix} q_1 + L_3 * c_3 \\ q_2 + L_3 * s_3 \\ 0 \\ a\tan 2(s_3, c_3) \end{bmatrix},$$

note: ψ=0, θ=0

The Jacobean matrix

$$J = \begin{bmatrix} 1 & 0 & -L_3 * s_3 \\ 0 & 1 & L_3 * c_3 \\ 0 & 0 & 1 \end{bmatrix}$$

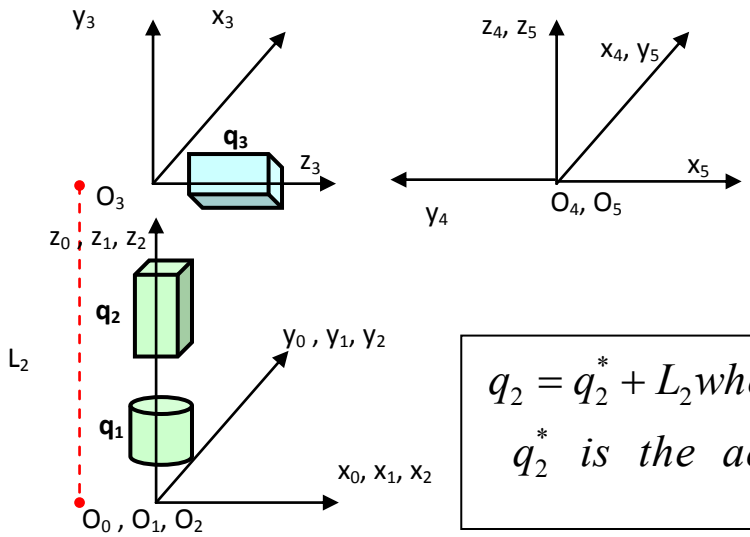
$$X^{\bullet}_{mx1} = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = \begin{bmatrix} X^{\bullet} \\ Y^{\bullet} \\ Z^{\bullet} \\ \phi^{\bullet} \end{bmatrix} = \begin{bmatrix} q_1^{\bullet} - L_3 * q_3^{\bullet} * s_3 \\ q_2^{\bullet} + L_3 * q_3^{\bullet} * c_3 \\ 0 \\ q_3^{\bullet} \end{bmatrix}$$

Note: $\theta^{\bullet} = 0, \ \psi^{\bullet} = 0$

4.8.3 Component #2: Arm of type RPP



$$q_2 = q_2^* + L_2 where:$$
$$q_2^* \ is \ the \ actuators \ movement$$

Figure 4.14: Robot Arm Modeling (RPP)

Table 4.3: RPP Robot Arm D-H parameters

Parameters	**Ref-Base**	**Arm (RPP)**			**End Eff.**
	0	**1**	**2**	**3**	**4**
$\mathbf{a_i}$	0	0	0	0	0
$\boldsymbol{\alpha_i}$	0	0	$\frac{\pi}{2}$	$-\frac{\pi}{2}$	0
$\boldsymbol{\theta_i}$	0	q_1	$\frac{\pi}{2}$	0	$-\frac{\pi}{2}$
$\mathbf{r_i}$	0	0	q_2	q_3	0

Base on figure 4.14 and table 4.3 and by substitution in the HTM eq. 4.1, we can state the elementary HTMs:

$$T_{01} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{12} = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{23} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & q_2 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_{34} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & q_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{4,EE} = T_{45} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Sin-Cosines buffers:

c1=cos(q1);s1=sin(q1);

Transformation matrix

$$T_{0,5} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ t_{41} & t_{42} & t_{43} & t_{44} \end{bmatrix} = \begin{bmatrix} c_1 & -s_1 & 0 & q_3 * c_1 \\ s_1 & c_1 & 0 & q_3 * s_1 \\ 0 & 0 & 1 & q_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

<u>By substitution in the</u> Orientation Representation <u>eq. 4.8</u> (yaw-pitch-roll Angles)

sin(θ)=-t31; cos(θ) =(1- sin(θ)* sin(θ))^0.5;

cos(ϕ)=t11/ cos(θ); sin(ϕ)=t21/ cos(θ);

sin(ψ)=t32/ cos(θ); cos(ψ)=t33/ cos(θ);

$$TCP_DKPM = \begin{bmatrix} X \\ Y \\ Z \\ \phi \end{bmatrix} = \begin{bmatrix} q_3 * c_1 \\ q_3 * s_1 \\ q_2 \\ a\tan 2(s_1, c_1) \end{bmatrix},$$

note: ψ=0, θ=0

The Jacobean matrix

$$J = \begin{bmatrix} -q_3 * s_1 & 0 & c_1 \\ q_3 * c_1 & 0 & s_1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

$$X^{\bullet}_{mx1} = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = \begin{bmatrix} X^{\bullet} \\ Y^{\bullet} \\ Z^{\bullet} \\ \phi^{\bullet} \end{bmatrix} = \begin{bmatrix} q_3^{\bullet} * c_1 - q_1^{\bullet} * q_3 * s_1 \\ q_3^{\bullet} * s_1 - q_1^{\bullet} * q_3 * c_1 \\ q_2^{\bullet} \\ q_1^{\bullet} \end{bmatrix}$$

Note: $\theta^{\bullet} = 0, \ \ \psi^{\bullet} = 0$

The inverse kinematics of the position satisfies:

$$q_{nx1} = f^{-1}(X_{mx1}), where: X_{mx1} = f^{-1}(q_{nx1})$$

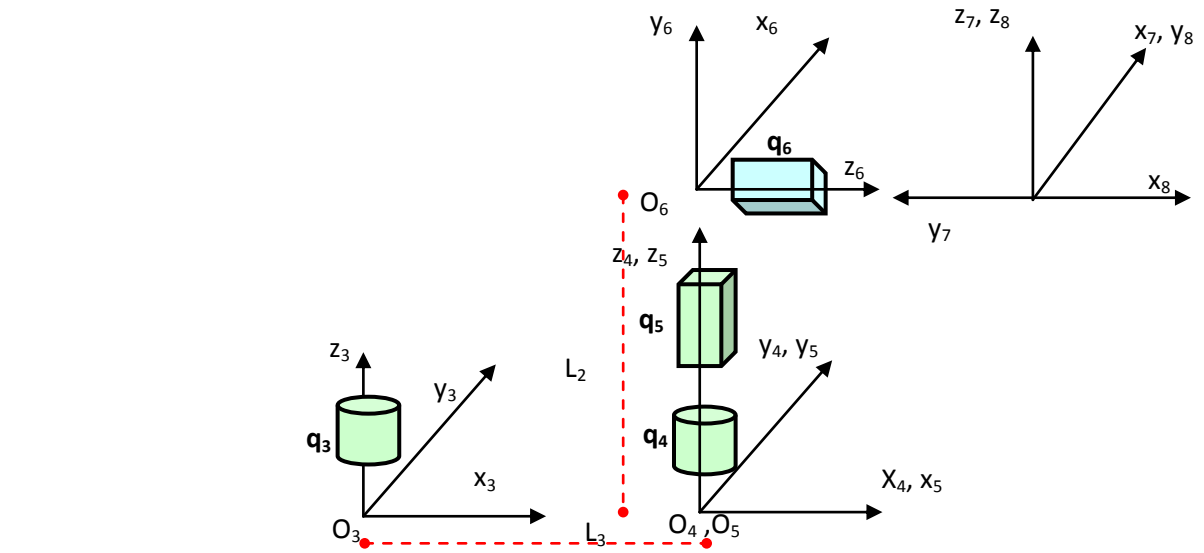
$$IKPM = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} a\tan 2(Y, X) \\ Z \\ \sqrt{X^2 + Y^2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1/c_{\phi} & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ Z \\ \phi \end{bmatrix}$$

The inverse kinematics of the velocity satisfies: $q^{\bullet}_{nx1} = \left[J^t J\right]^{-1}_{nxn} J^t_{nxm} X^{\bullet}_{mx1}$

$$IKVM = q^{\bullet}_{3x1} = (\mathrm{J}^{\mathrm{t}}_{3x4} * \mathrm{J}_{4x3})^{-1} * \mathrm{J}^{\mathrm{t}}_{3x4} * X^{\bullet}$$

$$IKVM = \begin{bmatrix} q_1^{\bullet} \\ q_2^{\bullet} \\ q_3^{\bullet} \end{bmatrix} = \begin{bmatrix} -\dfrac{q_3 s_1}{q_3^2 + 1} & \dfrac{q_3 c_1}{q_3^2 + 1} & 0 & \dfrac{1}{q_3^2 + 1} \\ 0 & 0 & 1 & 0 \\ \mathrm{c1} & \mathrm{s1} & 0 & 0 \end{bmatrix} \begin{bmatrix} X^{\bullet} \\ Y^{\bullet} \\ Z^{\bullet} \\ \phi^{\bullet} \end{bmatrix}$$

4.8.4 Assembled Carriage –Arm (Virtual Robot PPR-RPP)



$$Assume \quad q_3 = q_3^*, \quad q_4 = q_4^*$$
$$q_5 = q_5^* + L_2, \quad q_6 = q_6^*$$
$$where: q_5^* \ is \ the \ actuators \ movement$$

Figure 4.15: Robot Arm-Carriage Modeling (Virtual Robot PPR-RPP)

Table 4.4: PPR-RPP virtual robot D-H parameters

Parameters	Ref-Base	Virtual Robot (PPR-RPP)						End Effector
		Carriage VR (PPR)			Arm (RPP)			
	0	1	2	3	4	5	6	7
a_i	0	0	0	L_3	0	0	0	0
α_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0	0	$\frac{\pi}{2}$	$-\frac{\pi}{2}$	0
θ_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	q_3	q_4	$\frac{\pi}{2}$	0	$-\frac{\pi}{2}$
r_i	0	q_1	q_2	0	0	q_5	q_6	0

Base on figure 4.15 and table 4.4 and by substitution in the HTM eq. 4.1, we can state the elementary HTMs:

$$T_{01}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&0\\0&0&0&1\end{bmatrix},\ T_{12}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_1\\0&0&0&1\end{bmatrix},\ T_{23}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_2\\0&0&0&1\end{bmatrix},$$

$$T_{34}=\begin{bmatrix}c_3&-s_3&0&L_3c_3\\s_3&c_3&0&L_3s_3\\0&0&1&0\\0&0&0&1\end{bmatrix},\ T_{45}=\begin{bmatrix}c_4&-s_4&0&0\\s_4&c_4&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix},T_{56}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_5\\0&0&0&1\end{bmatrix},$$

$$T_{67}=\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&-1&0&q_6\\0&0&0&1\end{bmatrix},\ T_{7,EE}=T_{78}=\begin{bmatrix}0&1&0&0\\-1&0&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix},$$

Sin-Cosines buffers

c3=cos(q3); s3=sin(q3); c4=cos(q4); s4=sin(q4);

c34=cos(q3+q4); s34=sin(q3+q4);

Transformation matrix

$$T_{0,8}=\begin{bmatrix}t_{11}&t_{12}&t_{13}&t_{14}\\t_{21}&t_{22}&t_{23}&t_{24}\\t_{31}&t_{32}&t_{33}&t_{34}\\t_{41}&t_{42}&t_{43}&t_{44}\end{bmatrix}=\begin{bmatrix}c_{34}&-s_{34}&0&q_1+q_6*c_{34}+L_3*c_3\\s_{34}&c_{34}&0&q_2+q_6*s_{34}+L_3*s_3\\0&0&1&q_5\\0&0&0&1\end{bmatrix}$$

<u>By substitution in the</u> Orientation Representation <u>eq. 4.8</u> (yaw-pitch-roll Angles)

sin(θ)=-t31; cos(θ) =(1- sin(θ)* sin(θ))^0.5;

cos(ϕ)=t11/ cos(θ); sin(ϕ)=t21/ cos(θ);

sin(ψ)=t32/ cos(θ); cos(ψ)=t33/ cos(θ);

$$TCP_DKPM=\begin{bmatrix}X\\Y\\Z\\\phi\end{bmatrix}=\begin{bmatrix}q_1+q_6*c_{34}+L_3*c_3\\q_2+q_6*s_{34}+L_3*s_3\\q_5\\a\tan 2(s_{34},c_{34})\end{bmatrix},$$

Note: ψ=0, θ=0

The Jacobean matrix

$$J = \begin{bmatrix} 1 & 0 & -q_6 * s_{34} - L_3 * s_3 & -q_6 * s_{34} & 0 & c_{34} \\ 0 & 1 & q_6 * c_{34} + L_3 * c_3 & q_6 * c_{34} & 0 & s_{34} \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix}$$

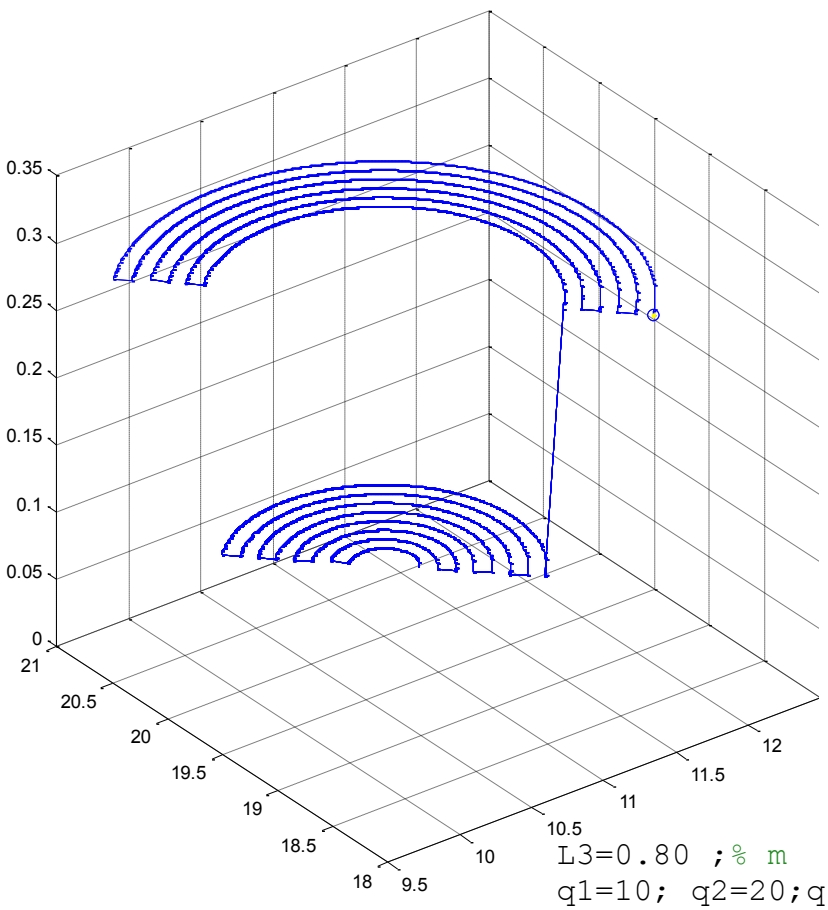
$$TCP_DKVM = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = \begin{bmatrix} X^{\bullet} \\ Y^{\bullet} \\ Z^{\bullet} \\ \phi^{\bullet} \end{bmatrix} = \begin{bmatrix} q_1^{\bullet} - q_3^{\bullet} * (q_6 * s_{34} + L_3 * s_3) + q_6^{\bullet} * c_{34} - q_4^{\bullet} * q_6 * s_{34} \\ q_2^{\bullet} + q_3^{\bullet} * (q_6 * c_{34} + L_3 * c_3) + q_6^{\bullet} * s_{34} + q_4^{\bullet} * q_6 * c_{34} \\ q_5^{\bullet} \\ q_3^{\bullet} + q_4^{\bullet} \end{bmatrix}$$

Note: $\theta^{\bullet} = 0, \quad \psi^{\bullet} = 0$

Also the matrix $\left[J^t_{m\times n} \times J_{m\times n} \right]_{nxn}$ is singular.

DKPM simulation results:




```
L3=0.80 ;% m
q1=10; q2=20;q3=-45;
```

Figure 4.16: PPR-RPP virtual robot DKPM simulation

4.8.5 Assembled Carriage-Arm-Camera Modeling (PPR-RPRR)

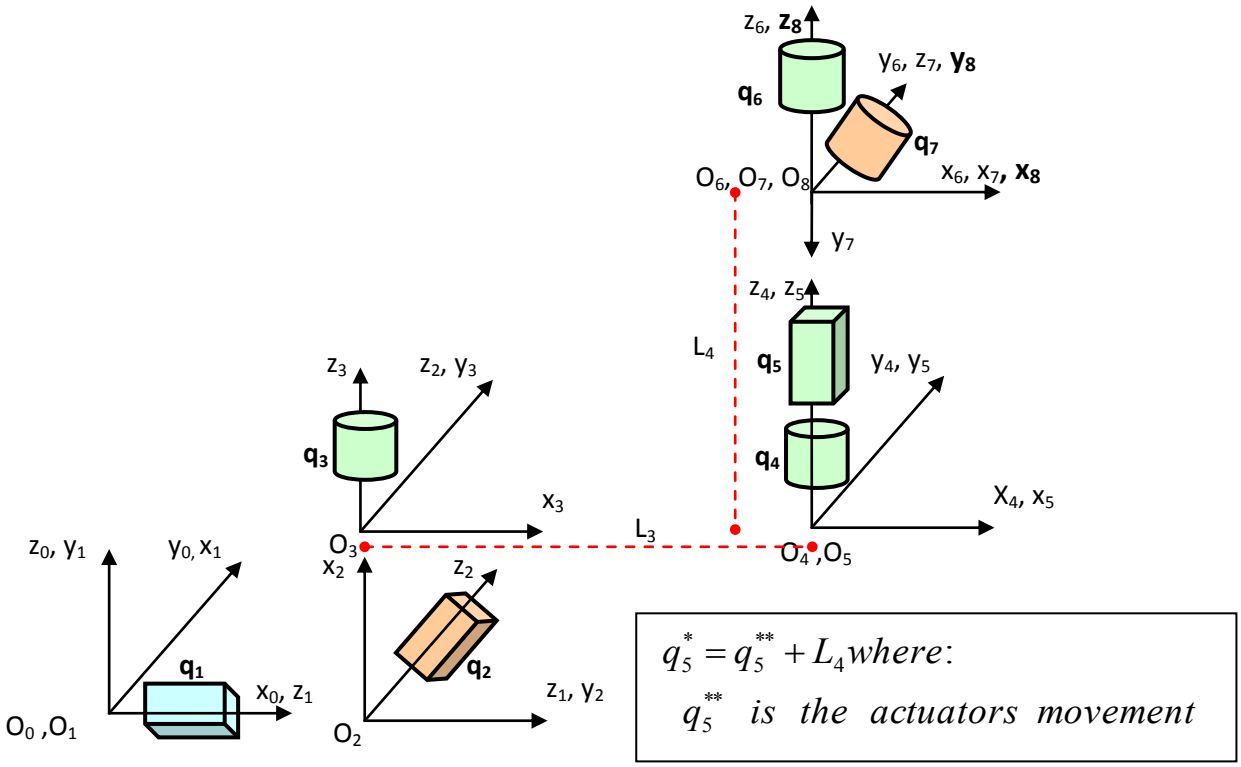


Figure 4.17: Carriage-Arm-Camera Modeling (Virtual Robot PPR-RPRR)

Table 4.5: PPR-RPRR virtual robot D-H parameters

Parameters	Ref-Base	Virtual Robot (PPR-RPRR) not reduced						End Eff.
		Carriage VR (PPR)			Arm-Camera (RPRR)			
	0	1	2	3	4	5	6	7
a_i	0	0	0	L_3	0	0	0	0
α_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0	0	0	$-\frac{\pi}{2}$	$\frac{\pi}{2}$
θ_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	q_3	q_4	0	q_6	q_7
r_i	0	q_1	q_2	0	0	q_5	0	0

Base on figure 4.17 and table 4.5 and by substitution in the HTM eq. 4.1, we can state the elementary HTMs:

$$T_{01}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&0\\0&0&0&1\end{bmatrix},\ T_{12}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_1\\0&0&0&1\end{bmatrix},\ T_{23}=\begin{bmatrix}0&0&1&0\\1&0&0&0\\0&1&0&q_2\\0&0&0&1\end{bmatrix},$$

$$T_{34}=\begin{bmatrix}c_3&-s_3&0&L_3c_3\\s_3&c_3&0&L_3s_3\\0&0&1&0\\0&0&0&1\end{bmatrix},T_{45}=\begin{bmatrix}c_4&-s_4&0&0\\s_4&c_4&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix},T_{56}=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&q_5\\0&0&0&1\end{bmatrix},$$

$$T_{67}=\begin{bmatrix}c_6&0&-s_6&0\\s_6&0&c_6&0\\0&-1&0&0\\0&0&0&1\end{bmatrix},\ T_{78}=\begin{bmatrix}c_7&0&s_7&0\\s_7&0&-c_7&0\\0&1&0&0\\0&0&0&1\end{bmatrix},$$

Sin-Cosines buffers:

C3=cos(q3);s3=sin(q3); C4=cos(q4);s4=sin(q4);

C346=cos(q3+q4+q6); s346=sin(q3+q4+q6);

C6=cos(q6);s6=sin(q6); C7=cos(q7);s7=sin(q7);

Transformation matrix:

$$T_{0,8}=\begin{bmatrix}t_{11}&t_{12}&t_{13}&t_{14}\\t_{21}&t_{22}&t_{23}&t_{24}\\t_{31}&t_{32}&t_{33}&t_{34}\\t_{41}&t_{42}&t_{43}&t_{44}\end{bmatrix}=\begin{bmatrix}c_{346}*c_7&-s_{346}&c_{346}*s_7&q_1+L_3*c_3\\s_{346}*c_7&c_{346}&s_{346}*s_7&q_2+L_3*s_3\\-s_7&0&c_7&q_5\\0&0&0&1\end{bmatrix}$$

<u>By substitution in the</u> Orientation Representation <u>eq. 4.8</u> (yaw-pitch-roll Angles)

sin(θ)=-t31; cos(θ) =(1- sin(θ)* sin(θ))^0.5;

cos(ϕ)=t11/ cos(θ); sin(ϕ)=t21/ cos(θ);

sin(ψ)=t32/ cos(θ); cos(ψ)=t33/ cos(θ);

$$TCP_DKPM = \begin{bmatrix} X \\ Y \\ Z \\ \phi \\ \theta \end{bmatrix} = \begin{bmatrix} q_1 + L_3 * c_3 \\ q_2 + L_3 * s_3 \\ q_5 \\ a\tan 2(s_{346}, c_{346}) \\ a\tan 2(s_7, c_7 \end{bmatrix},$$

note: ψ =0

The Jacobean matrix:

$$J = \begin{bmatrix} 1 & 0 & -L_3 * s_3 & 0 & 0 & 0 & 0 \\ 0 & 1 & L_3 * c_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$, **Note:** column 4 and 6 is the same.

$$X^{\bullet}_{mx1} = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = \begin{bmatrix} X^{\bullet} \\ Y^{\bullet} \\ Z^{\bullet} \\ \phi^{\bullet} \\ \theta^{\bullet} \\ \psi^{\bullet} \end{bmatrix} = \begin{bmatrix} q_1^{\bullet} - q_3^{\bullet} * L_3 * s_3 \\ q_2^{\bullet} + q_3^{\bullet} * L_3 * c_3 \\ q_5^{\bullet} \\ q_3^{\bullet} + q_4^{\bullet} + q_6^{\bullet} \\ q_7^{\bullet} \\ 0 \end{bmatrix}$$

Note: $\psi^{\bullet} = 0$

Note: The matrix $\left[J^t_{m\times n} \times J_{m\times n}\right]_{nxn}$ is singular.

4.8.6 Assembled Carriage-Arm-Camera Modeling (Virtual Robot PPR-PRRR)

For the Carriage-Arm-Camera, it is needed to modify the modeling in order to solve the problem of the Jacobean matrix similar columns. Because of that problem, we proposed this modeling below.

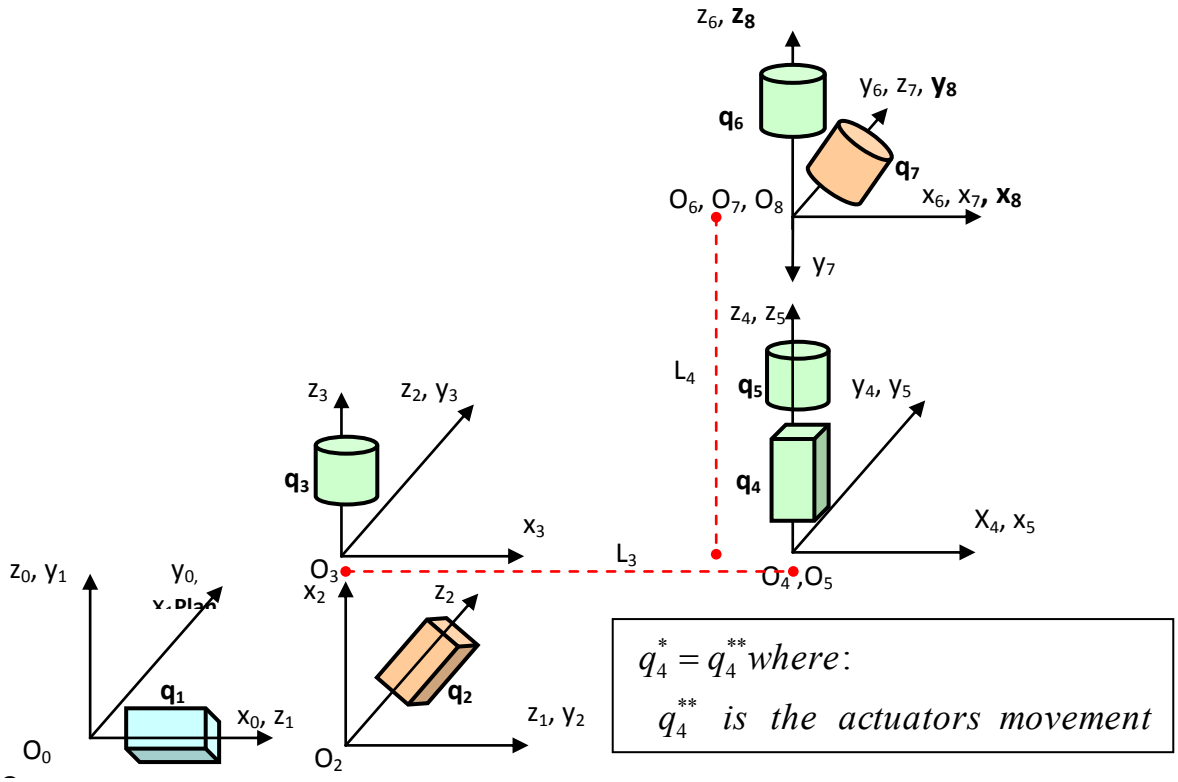


Figure 4.18: Carriage-Arm-Camera Modeling (Virtual Robot PPR-PRRR)

Table 4.6: PPR-PRRR virtual robot D-H parameters

Parameters	Ref-Base	Virtual Robot (PPR-PRRR)						
		Carriage VR (PPR)			Arm-Camera (PRRR)			
	0	1	2	3	4	5	6	7,8
a_i	0	0	0	L_3	0	0	0	0
α_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0	0	0	$-\frac{\pi}{2}$	$\frac{\pi}{2}$
θ_i	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	q_3^*	0	q_5^*	q_6^*	q_7^*
r_i	0	q_1	q_2	0	q_4^*	L_4	0	0

$$
\begin{aligned}
&Assume \quad q_3 = q_3^*, \\
&q_4 = q_4^* = q_4^{**}, \qquad where: \\
&\quad q_4^{**} \ \ is \ \ the \ \ actuators \ \ movement \\
&q_5 = q_5^* + q_6^*, \quad q_6 = q_7^*
\end{aligned}
$$

Table 4.7: PPR-PRR virtual robot D-H parameters

Parameters	Ref-Base	Virtual Robot (PPR-PRR) reduced					
		Carriage VR (PPR)			Arm-Camera (PRR)		
	0	**1**	**2**	**3**	**4**	**5**	**6,7**
$\mathbf{a_i}$	0	0	0	L_3	0	0	0
$\boldsymbol{\alpha_i}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0	0	$-\frac{\pi}{2}$	$\frac{\pi}{2}$
$\boldsymbol{\theta_i}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	q_3	0	q_5	q_6
$\mathbf{r_i}$	0	q_1	q_2	0	q_4	L_4	0

Base on figure 4.18 and tables 4.6, 4.7 and b y substitution in the HTM eq. 4.1, we can state the elementary HTMs:

$$
T_{01} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{12} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & q_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{23} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & q_2 \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

$$
T_{34} = \begin{bmatrix} c_3 & -s_3 & 0 & L_3 c_3 \\ s_3 & c_3 & 0 & L_3 s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, T_{45} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & q_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{56} = \begin{bmatrix} c_5 & 0 & -s_5 & 0 \\ s_5 & 0 & c_5 & 0 \\ 0 & -1 & 0 & L_4 \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

$$
T_{67} = \begin{bmatrix} c_6 & 0 & s_6 & 0 \\ s_6 & 0 & -c_6 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},
$$

Sin-Cosines buffers:

C3=cos(q3); s3=sin(q3); C5=cos(q5); s5=sin(q5); C6=cos(q6); s6=sin(q6);

C35=cos(q3+q5); s35=sin(q3+q5);

Transformation matrix:

$$T_{0,7} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ t_{41} & t_{42} & t_{43} & t_{44} \end{bmatrix} = \begin{bmatrix} c_{35} * c_6 & -s_{35} & c_{35} * s_6 & q_1 + L_3 * c_3 \\ s_{35} * c_6 & c_{35} & s_{35} * s_6 & q_2 + L_3 * s_3 \\ -s_6 & 0 & c_6 & L_4 + q_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

<u>By substitution in the</u> Orientation Representation <u>eq. 4.8</u> (yaw-pitch-roll Angles)

sin(θ)=-t31; cos(θ) =(1- sin(θ)* sin(θ))^0.5;

cos(ϕ)=t11/ cos(θ); sin(ϕ)=t21/ cos(θ);

sin(ψ)=t32/ cos(θ); cos(ψ)=t33/ cos(θ);

$$TCP_DKPM = \begin{bmatrix} X \\ Y \\ Z \\ \phi \\ \theta \\ \\ \end{bmatrix} = \begin{bmatrix} q_1 + L_3 * c_3 \\ q_2 + L_3 * s_3 \\ L_4 + q_4 \\ a\tan 2(s_{35}, c_{35}) \\ a\tan 2(s_6, c_6) \\ \\ \end{bmatrix},$$

Note: ψ=0

The Jacobean matrix:

$$J = \begin{bmatrix} 1 & 0 & -L_3 * s_3 & 0 & 0 & 0 \\ 0 & 1 & L_3 * c_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$X^{\bullet}_{mx1} = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = J_{mxn} q^{\bullet}_{nx1}$$

$$TCP_DKVM = \begin{bmatrix} X^{\bullet} \\ Y^{\bullet} \\ Z^{\bullet} \\ \phi^{\bullet} \\ \theta^{\bullet} \\ \\ \end{bmatrix} = \begin{bmatrix} q^{\bullet}_1 - q^{\bullet}_3 * L_3 * s_3 \\ q^{\bullet}_2 + q^{\bullet}_3 * L_3 * c_3 \\ q^{\bullet}_4 \\ q^{\bullet}_3 + q^{\bullet}_5 \\ q^{\bullet}_6 \\ \\ \end{bmatrix}$$

Note: $\psi^{\bullet} = 0$

The matrix $\left[J^{t}_{m\times n} \times J_{m\times n}\right]_{nxn}$ is singular.

4.9 Summary

This chapter deals with the mathematical modeling of the developed demining mobile robot arm using the virtual robot approach. The modeling is conducted in two levels of complexity: 1st: Spatial platform (carriage): include six joints (three prismatic and three revolute) with virtual links; and 2nd: Planar platform (carriage): include three joints (two prismatic and one revolute) with virtual links. HTMs base on DH parameters for each model are driven and also the DKPM, DKVM and IKVM. Simulations of these models on Matlab environment are done to simulate the direct kinematics and also the inverse kinematic to follow certain path in 2D plan and 3D.

Regarding the velocity, the Jacobean matrix is derived using two methods: The 1st method is by direct partial differentiation and the 2nd method is the indirect (omega matrix), which are implemented using Matlab m files and compared the results to avoid errors.

On Matlab the calculation of cos(pi/2), sin(pi) not exactly equal zero because of the storing precession of pi. So we must consider handling those small values before proceeding in further calculations. This may be done using modified algorithm like cosd, sind for numerical values or by hand if in a symbolic expression, or by writing similar algorithm for symbolic expression.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Landmine detection and removal is a challenging field for researchers. Manual operation is very dangerous, exhaustive and costive (time and money). It is very important to produce assistive mechanisms like Robots to cope with the landmine fields' environment. One of the required design constraints of a robot is its contact pressure with ground in order not to activate the imbedded landmines. In addition, the developed robot must be equipped with Multi-Sensors system to detect the imbedded landmines when scanning the infected areas.

This thesis consists of four main chapters with a literature survey of Egypt Landmine Problem. Based on this survey, a mobile platform with a robot arm basic design requirements are studied and its prototype is developed and manufactured to satisfy these design constraints.

The used mechanical components of this prototype are mainly some scrape and Commercial Off-The-Shelf (COTS) parts available at low costs. Using such parts has significantly reduced the overall cost of the developed robot prototype. The necessary Electrical and Electronic components of developed Printed Circuit Board (PCB) used to drive and control the system DC and Stepper Motors are: Microcontrollers (AVR, PIC), control circuits, and power driver circuits. The robot is equipped with the available sensors in the Egyptian market. MATLAB Graphical User Interface (GUI) is developed to control the developed prototype via a Laptop serial port using USB (USB to serial). Variety of communication techniques and protocols are virtually tested and experimentally verified to measure to what level the design requirements are satisfied.

The kinematic models of the developed robot prototype are obtained using the so called Virtual Robot Approach with the aid of Homogeneous Transformation Matrix (HTM). These models are used to simulate, in MATLAB and SIMULINK the performance of the developed robot prototype when following some desired paths in a virtual infected landmine field. A variety of control algorithms, Fuzzy Logic techniques are considered. The Landmines locations are assumed to be known. The developed robot prototype, which is cheap, needs more sophisticated multi-sensors systems in order to be tested in real landmine fields.

The resulted prototype is only to ensure the possibility to manufacture and remotely control a complete robot from scratch in order to work in very rough terrain. Many thinks still needed such as:

- Enhance the tracks in order to fit in their position while moving and turning.
- Minimize the weight of the robotic system, especially after practice the work life cycle.
- The system hardware/software architecture enrichment is needed to do more tasks.
- Develop better control strategies and complete scenarios for control situation.
- Extend the wireless communication reach through utilizing varieties of communication system like: IR remote extender (60m), Zigbee module (> 100m) , wiFi (> 500m)
- Research in advanced sensors to reach deeper depth.
- Multi-Robot systems in demining

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APPENDIX A: SURVEY PAPER

Ain Shams

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EGYPT LANDMINE PROBLEM:

HISTORY, FACTS, CONSTRAINTS AND DEMINING TECHNIQUES

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ABSTRACT

Egypt is contaminated with Landmines, UneXploded Ordnances (UXO), and Explosive Remnants of War (ERW) which are normally buried under deep layers of sand and mud from World War II. Most of the battles took place in the area between the Quattara Depression and Alamein at the Mediterranean Coast. Other affected areas lie around the city of Marsa Matruh and at Sallum near the Libyan border. In addition, ERW from armed conflicts between Egypt and Israel in 1956, 1967, and 1973 remains to be cleared, especially in the eastern areas (Sinai Peninsula and Red Sea Coast). No reliable figures for the extent of contamination exist. The joint Egypt/UNDP project document of November 2006 referred to 2,680 km^2 of contaminated area, which is almost four times the estimated contaminated area in Afghanistan. Similarly, the number of landmines, UXO and ERW that remain to be cleared can be little more than speculation. The Egyptian army has estimated that 16.7 million explosive items have still to be found, including both antipersonnel landmines (APL) and anti-tank landmines (ATL) and much larger quantities of UXO. This problem has a serious impact on Egypt National Income.

This paper presents the scope of Egypt landmine problem and its available official data as a first step to select the most suitable techniques for safe detection and removal of such landmines. It also addresses some landmine research topics: area reduction techniques, sensors design, detection and removal equipment. The paper is organized in the following main sections:

- Scope of Egypt Landmine Problem
- Egypt Landmine Monitoring Reports
- Survey of Demining Techniques
- NSF Landmine Research
- International Funded Landmine Projects

Keywords: Egypt Landmine Monitoring Report, Demining, Detection, Clearance, Sensors, Robots.

1. INTRODUCTION

Landmines represent a serious danger in a number of regions of the whole world. Many Landmine fields are known, mapped and mostly even fenced-in. Other Landmines, however, no information exist so that they pose the greatest threat. The problem of Landmines at these regions has a serious effect on their national incomes and on the safety of personal living in such regions.

According to the Civil Right Organization, "a Landmine is some object placed on or under the ground or any surface, conceived for exploding by the simple fact of the presence, the proximity or the contact of a person or a vehicle". There are more than 100 countries affected by Landmines, UXO and/or ERW. Approximately 20 countries are heavily-affected, including Angola, Afghanistan, Croatia, Egypt, and Cambodia. More than 12 countries produce Landmines, including Cuba, Egypt, Singapore, and Vietnam; and almost 20 countries or rebel groups use Landmines, including some countries that produce them. As estimated 45-50 million Landmines infest at least 12 million km^2 of land around the world. These Landmines:

- kill or maim a reported 10,000 people annually;
- create millions of refugees and internally displaced persons;
- prevent hundreds of thousands of square kilometers of agricultural land being used;
- deny thousands of kilometers of roads for travel;
- create food scarcities, causing malnutrition and starvation;
- interrupt health care, increasing sickness and disease;
- inflict long-term psychological trauma on Landmine survivors;
- hinder economic development;
- undermine political stability.

Table 1 lists the most important areas around the world infected with Landmines, UXO and/or ERW with their field type.

Table A.1: Estimated Number of Landmines in the Most Infested Countries

Country / region	#Landmines (Million)	Field type (NA= Not available)
Egypt	22	Sandy desert
Angola	10-15	NA
Afghanistan	9-10	Dry, desert, rocky, clay, vegetation, Residential
Cambodia	8-10	Vegetation
Kuwait	5-10	Sandy desert
Yugoslavia	6	NA (without Kosovo)
Bosnia & Sarajevo	NA	Vegetation wild among ruined houses
Lebanon	NA	Rocky high ground
Mozambique	2	NA
Somalia	1	NA
Latin America	0.3-1	NA
Croatia	NA	Vegetation, residential/ industrial, machinery.
Iraq	NA	Semi-arid region
Other countries	6.7-33	NA
Total	70-110	

2. SCOPE OF EGYPT LANDMINE PROBLEM

The Egyptian government cites a figure of 22 million Landmines: 16.7 million affect 268,000 hectares (km^2) in the western desert area and 5.1 million affect 20,000 hectares (km^2) in the eastern areas. Other Egyptian officials have stated that: Only 20-25% of these Landmines are really Landmines, the remainder being other types of UXO and ERW. In the next paragraphs, the available information of Egypt Landmine problem is outlined as follows:

- Egypt Landmine Maps and Time Effect
- Egypt Socio-Economic Effects
- Egypt Landmines Clearance Efforts

- Egypt Landmine Monitoring Reports

2.1 Egypt Landmines Maps, Types and Time Effect:

There are different and inaccurate maps for the Landmines in Egypt as indicated in Figures 1 and 2 with the Maps of Alamein area drawn from memory indicative only of Landmine field records. These Maps are partly misleading because of the limited accuracy of those records. UXO and some Landmines lie scattered across entire area so that the entire area has to be cleared. Table 2 gives the types of landmines used in World War II and Israeli-Egypt (Is-Eg) conflicts.

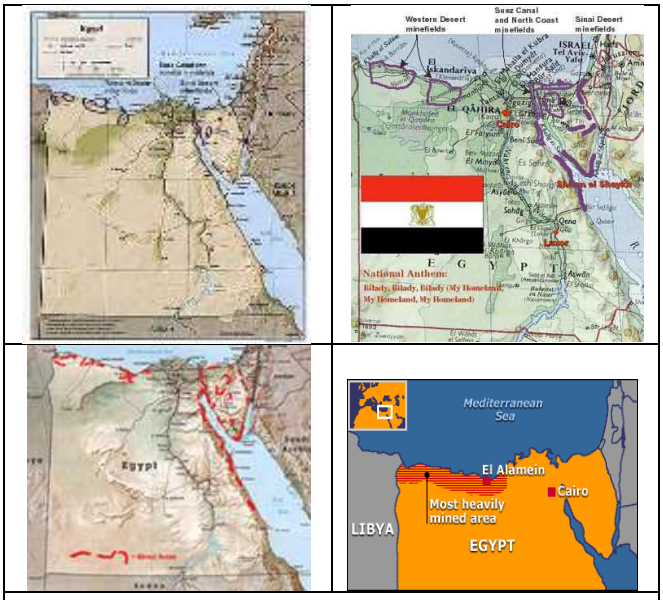

Fig. 1: Egypt Landmines Distribution Maps

Table A.2: Types of Landmines in Egypt

World War II	Is-Eg Conflicts
British: MK5, MK7 **German:** Rieglmine 43, S mines, Tellermine 35, 42, 43 **Italian:** B-2, V-3.	**Israelian:** MOTAPM (Mines Other Than Anti-Personnel Mines) **Egyptian:** M71, TM46, T79 , TS50, MOTAPM
There is also a wide variety of ERW in the infested land of Egypt including air dropped bombs	

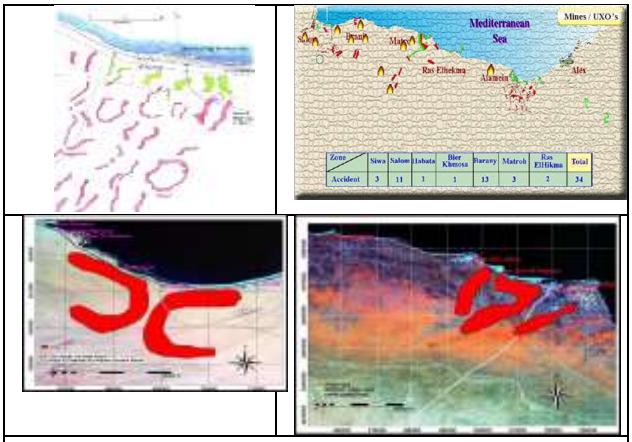

Fig. 2: Alamein Landmines Affected Areas

Maps Data Sources

- North Western Coast Soil Survey and Reports: FAO 1970.
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The time has many unpredictable effects on landmines characteristics especially under sand contaminations. The age of much of these Landmines is up to 66 years. Much of Landmines, UXO and ERW are covered by thick deposits of mud or sand so that conventional detection techniques are often of little value. The military analysts said that storms have increased the depth at which many land mines are buried by eight meters, thus ruling out the use of normal mine-detection methods. The trigger mechanisms on many of the weapons have corroded. Mines that were intended to be set off by the hefty bulk of a tank may be detonated by weight of a baby. Some mines may explode by themselves. All surveys and researches state that the mines status is totally unpredictable especially under sand contaminations.

2.2 Egypt Socio-Economic Effects

There is no national mechanism to record victims of ERW and MOTAPM. Table 3 presents the reported mine/ERW causalities as reported in the Egypt Landmine Monitoring

Reports for the period 1999-2009 (www.icbl.org).

Table A.3: Estimated and reported number of Mine/ERW causalities till 2009

Year	Causality		
	Total	Killed	Injured
Till 1999	8313*	696*	7617*
2000	12	NA	12
2001	11	NA	11
2002	18	5	13
2003	14	NA	14
2004	10	NA	10
2005	16	6	10
2006	22	9	13
2007	25	8	17
2008	40	14	26
2009	22	13	9
Total	8503	751	7752

* Estimated by the Egyptian Official Authorities and Egypt Landmine Monitoring report of the year 1999

The impact of contamination is said to be significant in many Egyptian activities. Landmines, UXO, ERW and MOTAPM prevented the irrigation of land that could have been used for agriculture in affected areas as well the establishment of new communities in the northern coast area. In addition, ERW and MOTAPM have hindered tourist projects on the northern coast and delayed oil and gas extraction from reserves estimated at 4.8 billion barrels of oil and 13.4 trillion cubic feet of gas in the western desert. New kinds of tourism, such as safari and eco-tourism, can encroach on affected areas, increasing the risk of incidents. It is necessary to warn people of potential hazards, but there is a fear of discouraging travel to the country.

The mine/ERW causalities include men, women, boys, girls, children under the age of 18, civilian and military people. Among 50 accidents cases: (16 accidents were reported at suspected areas (32%) and 34 accidents were reported outside the infected areas (68%)). An Egyptian Non-Governmental Organization (NGO) gathered data on ERW and landmine casualties reported similar data.

According to Egypt Landmine monitoring Report 2009 (www.icbl.org), there were 40 new mine/ERW casualties recorded in Egypt in eight governorates from 11 incidents in 2008. Casualties included 28 men, one woman (injured), 11 boys (7 killed and 4 injured), and no girls. ERW caused 33 of the casualties, landmines caused 6, and an unknown device caused one casualty. 3 incidents involving 4 casualties occurred in Matruh Governorate, where the Ministry of International Cooperation (MIC) and UNDP mine action program operates. The other incidents occurred outside the area covered by the mine action project, including 2 incidents in Ismailia, and one incident in each of Albihira, Al Suez, Alqaliobia, Alexandria, North Sinai, and Alsharqia governorates. 2 incidents causing 5 casualties occurred while people were trying to illegally cross the Egypt-Libya border. The vast majority of casualties occurred during activities relating to the scrap metal trade (29 casualties). Other activities at the time of incident included playing with ERW (3), playing/recreation (3), travel (3), agriculture (1), and fishing/hunting (1). Except for the two incidents that occurred at the Egypt-Libya border, none of the casualties witnessed any danger signs or had received risk education, despite some living in or near to mine/ERW-affected areas.

Casualties continued in 2009, with 9 boys (8 killed and 1 injured) and the 13 men (5 killed and 8 injured). Activities at the time of the incidents included agriculture (4), fishing/hunting (4), travel (3), playing with ERW (3), playing/recreation (3), and providing security (1); the activities of 4 casualties were unknown. In May 2009, a police officer was injured when he handled a landmine while working at the Egypt-Israel border.

The MIC with UNDP and the local NGO Peace Gardens, conducted a mine/ERW survivor survey from January to May 2008, on the North West Coast (primarily in Matruh governorate). The primary objective of the survey was to verify existing information on survivors collected by the Office of the Governor of Matruh and the Governorate Social Solidarity

Department. Interviews were also conducted to identify previously unknown survivors in cooperation with local authorities. It is estimated that some 80–90% of mine/ERW-affected communities were covered by the survey.

The survey identified 645 mine survivors living on the North West Coast, 94% of them were males and 3% children. It should be noted the survey recorded the age of the person at the time of the survey, not when the mine/ERW incident occurred. Among the injured, 48% suffered upper body injuries, 37% lower body injuries, and 15% other injuries. The number of people injured annually from 2002 to 2004 was found to be 18, but by 2007 the number had decreased to three.

The number of mine/ERW survivors recorded in the survey was considerably lower than the estimate of 8,000 mine/ERW casualties which, according to UNDP is "understood to relate to casualties in the whole country." It should be noted that the Peace Gardens survey included only those injured and those who still lived on the North West Coast at time of survey. A number of survivors particularly from Bedouin communities are assumed to have moved from the area since they were injured by mines/ERW. As a result, the survey does not capture all those injured by mines/ERW in the survey area. The survey did not include military casualties from mines/ERW. The Ministry of Defense estimated that about 700 people, soldiers and civilians, have been killed in mine explosions since 1945.

Landmine Monitor recorded at least 190 mine/ERW casualties (55 killed and 135 injured) in Egypt between 1999 and 2008.

2.3 Egypt Landmines Clearance Efforts

Since 1946, according to the Egyptian Official Authorities, 7 million mines have been cleared from the western desert in the past 15 years and 3 million from the Sinai desert. That leaves at least 20 million others. Egypt has set the year 2017 as the target for finally ridding its sands of land mines, but it is anxious not to left alone in paying for and carrying out this huge task.

The fact that over the years many reference points and landmarks have disappeared by rain and sandstorms added to the complexity of drawing a comprehensive picture of the Landmine situation. The complete marking and fencing of huge areas in the western desert is not considered feasible by the Egyptian Military due to climatic conditions, sandstorms and scrap traders. Next are some other official acts:

- The Government of Egypt has established the National Committee for the Northwest Coast Development and Demining Programs aiming to propose and implement regional developmental programs for the Northwest Coast and its desert back areas up to the year 2017
- Clearance activities severely hampered by having only limited maps, sketches and minefield records. Maps and data sources that have been provided by Germany, Italy and Britain have proven to be inaccurate or incomplete
- All Demining work is handled by a division of the Ministry of Defense in Cairo the Egyptian Military Engineering Organization **(EMEO)**.
- Until recently, all aspects of minefields and Demining are classified. However, the Egyptian government is now pursuing a more open policy, recognizing that information is needed to help secure assistance.

A summary of the 2008 and 2009 Egypt Landmines Monitoring Reports are presented in **Appendix A.1**. These reports include: Mine Ban Treaty status, Stockpile, Contamination, Estimated area of contamination, Demining progress, Mine/ERW casualties, Casualty analysis, Availability of services, Mine action funding, and Key Development in the years 2008 and 2009. The detailed reports can be found on the website: www.icbl.org.

4. SURVEY OF DEMINING TECHNIQUES

There are two main demining categories: Military and Humanitarian Demining. In the military demining, a military force prepares a safe corridor for the troops to move through. Some losses are accepted as an expected part of the conflict. Therefore a flail machine with an 80% clearance success can be used. This sort of clearance operation is not suited to humanitarian demining. In the humanitarian demining, the entire land area must be cleared free of mines to be productive. The United Nations has specified a mine clearance standard of 99.6% for humanitarian Demining. Currently the only way to achieve this is with manual demining methods. The main humanitarian demining technical problems are given in **Appendix A.2** and next are some details about the used Demining techniques.

4.1 Area Reduction Techniques

Demining is the action of removing landmines, booby traps and UXO from an area; those are normally hidden and most often buried and distributed over wide areas. However, not all the wide areas are contaminated. For optimum application of demining; contaminated regions should be detected first, then it is possible to utilize uncontaminated areas for economic and human activities, while contaminated regions are treated for clearance. The process of locating region of interest (ROI) to exclude uncontaminated areas is called Minefield Area Reduction. This technique may be useful to declare the minefields existing inside larger unrecognized area to minimize the overall cost dramatically. Therefore, it is usual to use sensors in two levels; wide view to locate ROI, and detailed view to locate the specific mines. Generally, the reduction is conducted on the basis of collecting more reliable information on the extent of the hazardous area. Clearance data gathered by the GICHD from 15 countries suggests that of suspect areas cleared, less than 3% actually contained mines or other ordnance. The effective area reduction is the phase of demining where the greatest increases in efficiency can be made. Many varied prerequisites have to be observed, such as soil and type of topology, as well as type of contamination. Figure 3 presents the different known area reduction techniques: Mechanical Rollers, Sampling and Imaging. Next are some details about these techniques.

Mechanical Roller: is normally mounted on the front of a minefield intrusive prime mover such as the Minefield Tractor or an armored loading shovel. It is then pushed through the minefield. The roller works by detonating any near-surface or surface pressure-activated mines. It is designed to withstand APL mine blasts only.

Sampling Technique: is a remote explosive sent tracing **(REST).** The sent may be obtained using a pump to draw air containing scent or particles from the soil surface through an absorbent filter. Trained snuffers dogs or rats, or potentially any other natural or artificial odour sensing system may be used for analyzing this sample. **REST** is originally known as the MECHEM Explosives and Drugs Detection System (**MEDDS**).

Imaging Technique: Images taken by Satellite, Balloons or Helicopters may be used to reduce the expected area to be cleared in the next demining phase.

Mechanical Rollers

Sampling (REST)

Imaging:

(http://www.arc.vub.ac.be/images/camcopter.jpg

Fig. 3: Area reduction Techniques

4.2 Landmine Detection Techniques

In addition to metal detectors, biological detection (Fig.4 and Fig. 5) is in use to locate Landmines such as:

- Bacterial sensing of soil
- Transgenic plants for sensing of explosive compounds
- Detection using dogs, rates, bees, rodents, mongoose, and other animals.

Modern anti-personnel mines used today are: relatively small, about 3-20 inches in diameter, made of plastic with very few metal parts and hard to detect. Many companies are currently working in field to test their innovative mine-detection methods such as:

- Supersensitive ground-penetrating radar,
- Infrared emission,
- Thermal neutron activation,
- Energetic photon detection
- Detection by practical applications of certain types of polyurethane foam
- Nuclear Detectors

Next are some details about these types of detection techniques.

Metal Detectors (MD): The operator (human) uses handheld sensors (probe, metal detector, magnometer … etc) and investigates the surface of the required field. Any little mistake can cost his life. False alarm is the main disadvantage of metal detectors. They cannot detect landmines with very low metal content. These metal detectors can be used with non-manual detection techniques.

Bacterial Sensing of Soil: This technique is promising for large areas and provides a tool for direct detection of explosive compounds. The bacteria would be spread over an area from an airborne plate form and would subsequently become luminescent in the presence of explosive compounds in the surface of the soil. The area could be then passively, or actively, observed with an airborne hyper spectral camera. The problems identified with this system have limited its development; since the bacteria need to be activated on site in large quantities, and sophisticated large-area dissemination equipment need to be available. More importantly, once spread over an area of interest the bacteria sense only a thin layer of soil near the surface, where explosive concentration may be quite low. Bacteria are also subject to environmental conditions which may hinder their growth, such as undesirable temperature and UV light.

Fig. 4: Biological detection techniques

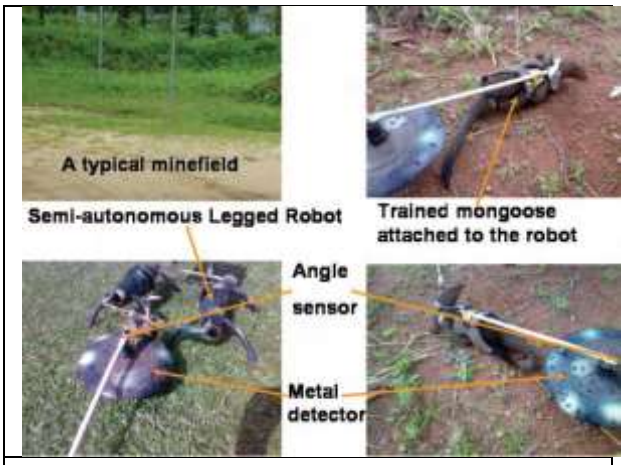

Fig. 5: Robot and animal cooperation

Plants Landmine Detection: Landmines release nitrous oxide that turn these plants turn red. The best studied is the specie mustard Arabidopsis thaliana which has been genetically manipulated for this purpose. However, nitrous oxide can also be released by denitrifying bacteria, resulting in the risk of false positives. Researchers are addressing this problem by making the plant less sensitive. In theory, these plants could either be sown from aircraft or by people walking through demined corridors in

minefields. No studies have yet been conducted with actual landmines, though successful studies have been done in greenhouse environment.

Bacteria Landmine Detection: Scientists have genetically engineered a strain of bacteria to fluoresce under ultraviolet light in the presence of TNT. In tests, the bacteria successfully detected mines when sprayed over simulated minefields in successfully located mines. This method has been found to produce relatively quick results, and could be used over different terrain. Even small amounts of TNT are detected but there are some false positives near plants and water drainage.

Polyurethane Foam Detection: Foam material is being tested on beaches or other battlefields as a sort of "cushion" to keep mines from exploding. When ground troops or vehicles move over them, or in the event that the mines do detonate, as a pressure-wave "absorber", foam will shield troops from destructive effects of explosion.

Nuclear Detection: The concept of detecting explosives through elemental analysis by neutrons to detect nitrogen has been proposed. Majority of explosives are nitrogen rich. The focus has mainly been directed at airport security and hostile trucks although its use for landmine detection has been suggested.

4.3 Landmine Clearance Techniques

Demining clearance operations can be achieved using: Manual Methods, Mine clearance machines, Ground preparation machines, Remotely Operated Vehicles (ROV) and Mine Protected Vehicles (MPV). Next are some Examples (see **Appendix A.3**):

- **Tele-operated Machines:** Light-Flail, Remotely Operated Vehicles (Kentree Limited), Pookie, Vehicle Mounted Detection System (VMDS), and Improved Landmine Remote Detection Vehicle (IL-RDV)
- **Multi Functional Tele-operated:** Robots, Articulated Modular Robotic Mine Scanner (Engineering Service Inc. (ESI)), Enhanced Tele-Operated Ordnance Disposal System (ETODS), (OAO Corporation, Robotics Division), TEMPEST. (Development Technology Workshop (DTW), The Armored Combat Engineer Robot (ACER) MSEA Robotics, Modular Robotic Control System (MRCS) for Mine Detection
- **Demining Service Robots:** Three Wheels Dervish Robot (University of Edinburgh/ UK), Spiral Terrain Autonomous Robot (STAR) (Lawrence Livermore National Laboratory (LLNL), MILmine, FETCH II, Finder, PEMEX-BE (PErsonal Mine EXplorer) (EPFL/Switzerland), Shrimp Robot (EPFL/Switzerland), AMRU and Tridem (I and II) (Belgium HUDEM), WHEELEG (University of CATANIA, Italy), COMET I, II and III: Six legged Robot (Chiba University Japan), Buggy and Legged Robots (TIT in Japan), Mine Hunter Vehicle (MHV), Fuji Heavy Industries (FHI), ARES Wheeled Robot Int. Robot System) (TITAN-IX & Buggy system mounted ALIS), PEACE: An Excavation-Type Demining Robot, Two interchangeable Radar sensor modules and Unmanned Aerial Vehicles (UAV).
- **New Robotic Systems (lizard, warm):** Virtual mock-ups of smart crawling robots for landmine localization in thick vegetation using REST and Robotic modules for steering and peristaltic trust

5. NSF LANDMINE RESEARCH

Research related to Sensors: Recent advances in sensor research have yielded important innovative applications to national security, healthcare, environmental safety, and energy resource management:

(a) Develop new sensor arrays to increase Landmine location/detection capabilities, accurately locate UXO to improve removal activities, and improve data merging solution

(b) Use of sensor data in control and decision making, particularly in relation to the prediction and detection of explosives and related threats,

(c) Detection of explosives and related threats, including improvised explosive devices (IEDs).

Research Related To Prediction: New fundamental research will enable to the recognition of explosives and other threats earlier than current technologies allow, identify and isolate a threat at or before the point of device assembly and placement. Research towards this goal might include:

(a) Algorithms and sensor systems to predict the possible assembly and placement of explosive devices.
(b) Recognition of emplacement patterns, behavioral pattern recognition from video and other innovative sensing systems.
(c) Human intelligence and social network analysis of terrorist networks
(d) Analysis of communications, and knowledge-management systems.

Research Related To Detection: Sensitivity and fine resolution of sensors is important for the detection of explosive devices, since the earlier a threat can be identified, the easier is addressed. Once an explosive device is in place, its rapid detection accelerates its standoff identification and localization. To distinguish real threats in an environment with minimal or no false alarms, signal processing, data fusion, and autonomous system technologies are in use.

6. INTERNATIONAL FUNDED LANDMINE PROJECTS

Many organizations are working on Landmine field Area Reduction to develop their own techniques. Two examples of Governmental and commercial organizations are presented here. The 1st project (http://www.arc.vub.ac.be/) is carried out by 7 European organizations and partially funded by the European Commission. The parties are: CROMAC (Croatian Mine Action Center), Croatia, FOI (SDRA: Swedish Defense Research Agency), Sweden, GEOSPACE Satellitenbilddaten GmbH, Austria, GTD (Ingenieria de Sistemas y Software Industrial), Spain, IMEC (Ineruniversity MicroElectronic Center), Belgium, Schiebel GmbH, Austria and TNO (Netherland's Organization for Applied Scientific Research), Netherlands. The 2nd project (www.mineclearing.com) is carried out by Mine Clearing Company Corp

7. COMMENTS AND CONCLUSIONS

The exploration, localization, mapping, and removal of Landmines in infested areas are complicated problems. Many questions are still raised about the most efficient technique for Landmines detection and removal as well about the most efficient sensor(s). The answers of these questions will be useful to develop safer, faster and cost effective Anti-Personal and Anti-Tank Landmines (APL & ATL) clearance. This will save human lives and will have a very positive impact on the Egyptian National Income.

This paper presents the scope of Egypt Landmine problem and its available official data as a first step to select the most suitable techniques for safe detection and removal of such landmines. The paper also addresses some Landmine research topics: Area reduction techniques, sensors, and detection and removal equipment. One of the possible solution to this problem is the use of a multi-function remotely operated robot equipped with metal detectors (MD), ground penetration radar (GPR) and/or radioactive or foam materials for localizing, marking and clearance of landmines.

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Appendix A
Egypt Landmine Monitoring Reports (2008 & 2009) (www.icbl.org)

	2008	2009
Mine Ban Treaty Status	Not a State Party	Not a State Party
Production, Transfer and Stockpile	Unknown, but thought to be substantial	Egypt has stated that it stopped production of antipersonnel mines in 1988 and export in 1984
Contamination	Antipersonnel and anti-vehicle mines, UXO	Antipersonnel and anti-vehicle mines, UXO and ERW
Estimated area of Contamination	2,680km^2, to be significantly reduced by technical survey	2,680km^2, to be significantly reduced by technical survey
Demining progress	None	The "Support to the North West Coast Development Plan and Mine Action Project" between Egypt and UNDP was signed in November 2006 and, following an extension, was due to run until December 2009
Mine/ERW casualties	Total: 25 (2006: 22) Mines: 10 (2006: 8) ERW: 14 (2006: 8) Unknown: 1 (2006: 6)	Total: 40 (2007: 25) Mines: 6 (2007: 10) ERW: 33 (2007: 14) Unknown: 1 (2007: 1)

	2008	2009
Casualty analysis	Killed: 8 (2006: 9) Injured: 17 (2006: 13)	Killed: 14 (2007: 8) Injured: 26 (2007: 17)
Risk Education capacity	Inadequate	Risk Education was included in the joint UNDP/Egypt project signed in November 2006, yet little has been implemented. In July 2008, the Chair of the State Information Service stated that a three-month Risk Education campaign in Matruh, Alexandria, Suez, Al-Arish, northern and southern Sinai, and Ismailia governorates would take place, but no activities had taken place as of July 2009
Availability of services	Unchanged-inadequate	Unchanged—inadequate
Mine action funding	$500,000 (2006: none)	$918,244 (2007: $500,000)
Key developments	In mid-August 2008, it was announced that Demining would begin before the end of the month.	From 7 February 2009 until 31 July 2009, Demining operations were reported to have cleared 210,214 items of UXO and 13720 mines from 14474 acres (58.6 km^2). It is not possible to verify these figures, which seem high given the available resources

Appendix B

Difficulties in Humanitarian Demining

(All photos Prof. J. Trevelyan)

Complications and Description	
1- Landmines locations are usually unknown: because they are very cheap, it is easy to build weapons, so they have been largely used in different types of conflict, by military or civilians.	
2- Landmines are often discovered by accidents: Associations like the Red Cross when they have to provide support for mine victims.	
4- Maps indicating the locations are useful in few cases: as demining operations do not start until years after the minefield was laid and during this time the conditions of the affected lands can drastically change.	
5- Mines that have been in place for years: Can be corroded, waterlogged or impregnated with mud or dirt, and then behave quite unpredictably.	
6- Floods and heavy rains: may cause mines to move from the original place to another or to move deeper into the ground.	
7- Mines placed near buildings: may lie deep under fallen rubble with more mines laid on top	
8- Stakes supporting fragmentation mines: may fall over and may rot, leaving the fragmentation mines half buried lying on their sides.	
9- Tripwires may run through: the branches of the scrub may pull the pins from the fragmentation mine as the branches sway in the wind.	
10- The vegetation grown in many years after the landmines were laid: an obstacle to demining operations.	

border between Croatia and Republika Serbska within (present and 8 years later)

11- Type of terrain: Plenty of metal fragments represent an obstacle for the use of metal detector. Uneven rocky terrains add complications to the mine removing operation.	Photo: MCPA, Afghanistan
13- Mines buried in a sandy desert: can easy move deeper when the wind blows the sand.	Western Desert, near Al Alamein
14- Mine age implies high sensitivity of mines: In Western Desert and Sinai Peninsula, age of most of the explosive materials is up to 65 years. (high sensitivity)	
15- The climate is extremely unpleasant for deminers: Temperatures up to 55˚ C are common. The conditions are either dusty and sandy or muddy (salty mud and swamps) along the coast: sometimes both. The muddy areas and marshes are particularly difficult to deal with as it is often impossible to stand in the mud.	
16- Mines status are not expected as well: Array of mines as those German mines in the World War II. Waiting for press in order to be activated. Already pressed under certain weight of contaminations and waiting for release in order to be activated.	

Appendix C

Demining Machines and Robots

(a) Armtrac 25. (Armtrac Ltd., United Kingdom)
(b) Bozena 4 (WAY Industry J.S. Co, Slovak Republic)
(c) Mini-flail. (US Department of Defense)
(d) Diana 44T (Hontsav S.R.O., Slovak Republic)
(e) Minecat 140. (Norwegian Demining Consortium)
(f) The MV-4. (DOK-ING d.o.o., Croatia)

1- Light-Flail

(a) The wheeled Hobo.
(b) The wheeled Hobo.
(c) the tracked Hobot.
(d) The Brat.
(e) Thrasher.

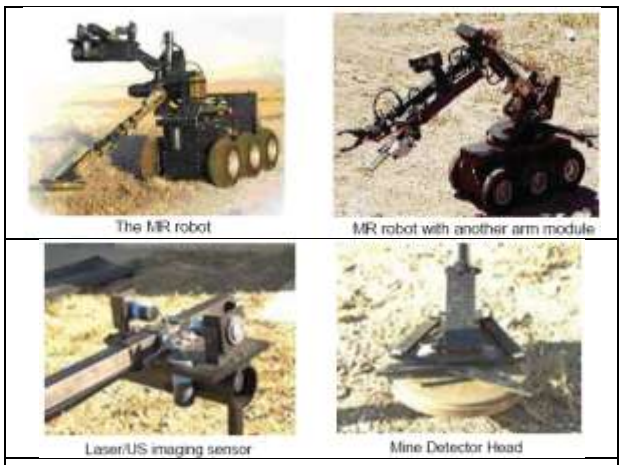
2- ROV

1st phase | 2nd phase

3- Pookie

4- VMDS

5- IL-RDV



6- AMM Scanner

7- ETODS

8- TEMPEST

9- ACER (MSEA Robotics)

10- MRCS

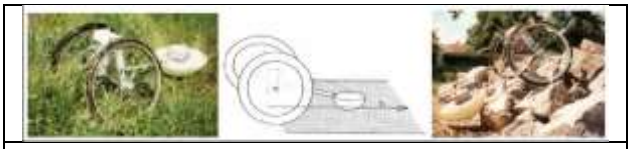
11- Three Wheels Dervish Robot

12- STAR

13- MIL mine

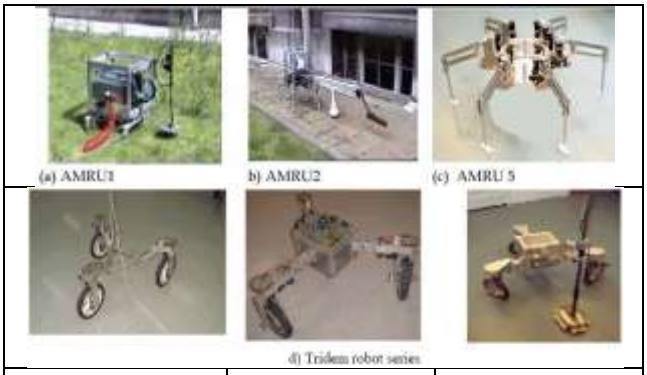
14- FETCH II

15- Finder



16- PEMEX-BE

17- Shrimp Robot



18- AMRU | 19-Tridem-I | 20-Tridem-II

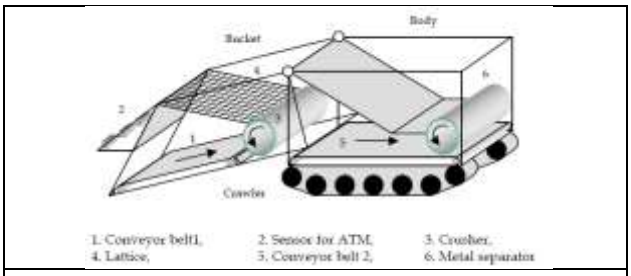
21- WHEELEG, COMET I, II and III & Six Legged Robots

22-a Buggy and Legged Robots

22-b Buggy and Legged Robots

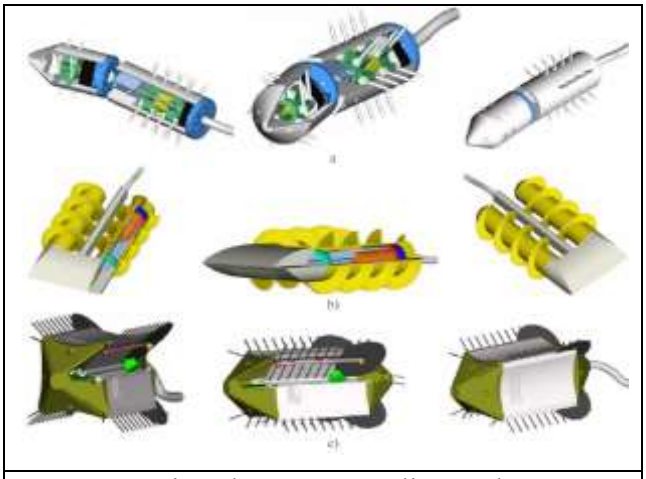
23- MHV

24- ARES Wheeled Robot

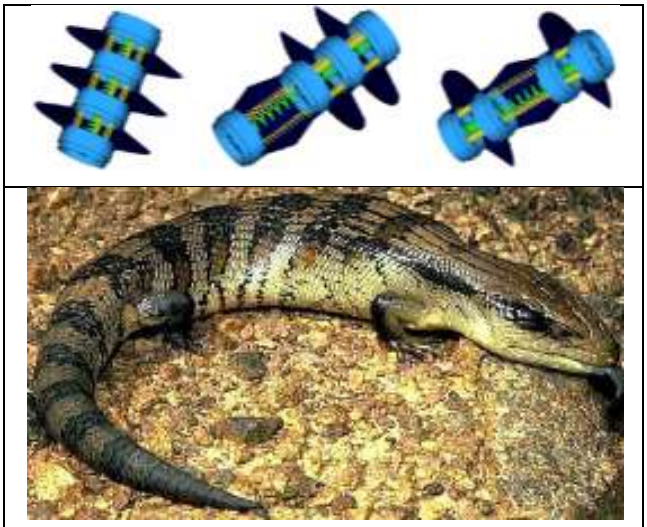


25- PEACE

26- UAV



27- Virtual Smart Crawling Robots



28- Robotic modules for steering and peristaltic trust

APPENDIX B:

TABLES OF AVAILABLE SENSORS INFORMATION ANALYSIS AND SELECTION

This part is based on two studies on sensors comparisons. The 1st is done by Prof. Yvan Baudoin [57], and the second is done by Cristian Keller [20]. They build their tables using linguistic. We select the sensors based on the data processing with fuzzy logic concepts.

Using the 1st study and the fuzzy grading table 2.2 we calculated the table B.1 which applies a fuzzy logic values (grades) to replace the linguistic value assigned for each linguistic variable: Maturity, Cost, Speed, and Effectiveness. Formula: **S1 = ∑grade**

Using the 2nd study and the fuzzy grading table 2.3 we calculated the table B.2 which applies a fuzzy logic values (grades) to replace the linguistic value assigned for each linguistic variable: kind of terrain, speed, false alarms rate, cost and complexity, maximum depth, kind of mines. formula: $\mathbf{S2 = N_y*2+N_b*1+N_r*(-1)}$ where N_y (number of very good occurrences, yellow), N_b (number of good occurrences, blue), N_r (number of bad occurrences, red)

The aggregation of the fuzzy grading of the two studies: In this fuzzy grads of the sensors are aggregated and the five sensors with highest score are selected table B.3. formula: **T=S1*17+S2*10 ,**where S1: study1 grades, S2: study2 grades, T: Aggregation of S1, S2 grades.

Table B.1: The first study: Sensors comparison analysis using fuzzy logic,(The columns with superscript (1) are from the reference [57])

#	Sensor Family(1)	Sensor(1)	Maturity(1)	Grade --/6	Cost(1)	Grade --/6	Speed(1)	Grade --/6	Effectiveness(1)	Grade --/6	Total Grade
1	Electro-optic	LIDAR	R&D	**1**	Very High	**1**	Medium	**3**	Low	**1**	**6**
2	Electro-optic	Terahertz	R&D	**1**	Very High	**1**	Medium	**3**	Low	**1**	**6**
3	Electro-optic	Multi & hyper spectral	R&D	**1**	High	**2**	Medium	**3**	Medium	**2**	**8**
4	Electro-optic	SLDV	R&D	**1**	Very High	**1**	Medium	**3**	Medium to high	**3**	**8**
5	Nuclear & Chemical	X-Ray backscattering	R&D Prototype	**2**	High	**2**	Medium	**3**	Low	**1**	**8**
6	Nuclear & Chemical	Chemical detectors	R&D	**1**	High	**2**	Medium	**3**	Unknown	**2**	**8**
7	Electro-optic	Infrared Polar	R&D Prototype	**2**	High	**2**	Medium	**3**	Medium	**2**	**9**
8	Biosensors	Artificial nose	R&D	**1**	Medium to high	**3**	Medium	**3**	Medium	**2**	**9**
9	Nuclear & Chemical	TNA	R&D Prototype	**2**	High	**2**	Medium	**3**	Medium	**2**	**9**
10	Prodders & Acoustic	Seismic & acoustic	R&D	**1**	High	**2**	Medium	**3**	High(in wet soil)	**4**	**10**
11	Electro-magnetic	Electr Imp Tom	R&D	**1**	Low to medium	**5**	Low to medium	**2**	Unknown	**2**	**10**
12	Electro-magnetic	Electrography	R&D	**1**	Low to medium	**5**	Low to medium	**2**	Unknown	**2**	**10**
13	Nuclear & Chemical	NQR	R&D Prototype	**2**	Medium to high	**3**	Medium	**3**	Medium	**2**	**10**

#	Sensor Family[1]	Sensor[1]	Maturity[1]	Grade --/6	Cost[1]	Grade --/6	Speed[1]	Grade --/6	Effectiveness[1]	Grade --/6	Total Grade
14	Nuclear & Chemical	X-Ray fluo	R&D Prototype	**2**	High	**2**	Medium to high	**4**	Medium	**2**	**10**
15	Electro-magnetic	MWR\	In develop.	**4**	Medium to high	**3**	Low to medium	**2**	Medium	**2**	**11**
16	Nuclear & Chemical	FNA	R&D	**1**	Very High	**1**	Medium	**3**	Very High	**6**	**11**
17	Electro-optic	Infrared	OK	**6**	High	**2**	Medium	**3**	Medium	**2**	**13**
18	Prodders & Acoustic	Smart Prodder	In Use, In develop.	**4**	Low to medium	**5**	Very low	**1**	High	**5**	**15**
19	Electro-magnetic	GPR	In Use	**5**	Medium to high	**3**	Low to medium	**2**	High	**5**	**15**
20	Electro-optic	Visible	OK	**6**	Low to medium	**5**	Medium	**3**	Low	**1**	**15**
21	Biosensors	Rodents	In develop.	**4**	Medium	**4**	Medium to high	**4**	Medium to high	**3**	**15**
22	Biosensors	Dog	Ok	**6**	Medium to high	**3**	Medium to high	**4**	Medium to high	**3**	**16**
23	Prodders & Acoustic	Prodder	In Use	**5**	Low	**6**	Very low	**1**	High	**5**	**17**
24	Electro-magnetic	EMI devices	In Use	**5**	Low to medium	**5**	Low to medium	**2**	High	**5**	**17**
25	Electro-magnetic	Magnetometer	In Use	**5**	Low to medium	**5**	Low to medium	**2**	High	**5**	**17**
26	Electro-magnetic	Gradiometer	In Use	**5**	Low to medium	**5**	Low to medium	**2**	High	**5**	**17**

Table B.2: The second study: Sensors comparison analysis using fuzzy logic (The columns with superscript (2) are from the reference: [20].)

No.	Class(2)	Sub class(2)	Terrain(2)	Speed(2)	False alarms rate(2)	Cost& complexity(2)	Depth(2)	Kind of mines(2)	Con's(2)	Pro's(2)	Grading	Grading values
1	**Chemical sniffers**	Alive sniffers (dogs)	All	--	--	Medium	Deep	All	Tired quickly, approximate, sensitivity to environmental condition	High sensitivity	4*2+2*1=	**10**
2	**Ground penetrating Radar (GPR)**	--	All	High	High	Medium	Chang-eable	All	--	Many studies	4*2+2*1+1*-1 =	**9**
3	**Induction coil**	Metal Detector	All	High	High	Low	Deep	Metallic	--	Reliable	4*2+2*1+1*-1 =	**9**
4	**Magnetometers**	Fluxgate	--	High	High	Low	Deep	All	--	Reliable, low energy consumption	4*2+1*1+1*-1 =	**8**
5	**Magnetometers**	Proton precession	--	High	High	Low	Deep	All	Slower	More sensitivity	4*2+1*1+1*-1 =	**8**
6	**Brute force**	Mechanical	Roads, level lands	High	N.A.	Low	--	All	Requires heavy and large vehicles	--	3*2+1*1 =	**7**
7	**Manual Prodding**	--	All	Low	High	Low	Deep	All	Dangerous	Very accurate	5*2+3*-1 =	**7**

No.	Class(2)	Sub class(2)	Terrain(2)	Speed(2)	False alarms rate(2)	Cost& complexity(2)	Depth(2)	Kind of	Con's(2)	Pro's(2)	Grading	Grading values
8	**Magnetometers**	Optically pumped	--	High	High	--	Deep	All	More expensive	More sensitivity	3*2+1*1+1*-1 =	**6**
9	**Induction coil**	Imaging	All	High	High	--	Deep	Metallic	Heavy	Reliable	3*2+2*1+2*-1 =	**6**
10	**Brute force**	Explosive	--	High	N.A.	Low	--	All	Limited applications, displaces some kinds of mines rather than exploding them	--	3*2+1*-1 =	**5**
11	**Chemical sniffers**	Antibodies	All	--	--	High	Deep	--	Sensing devices must be replaced periodically	High sensitivity	3*2+1*-1=	**5**
12	**Nuclear Quadrupole Resonance (NQR)**	--	--	Low	Low	High	--	All	Affected by electro-magnetic pollution	Very reliable	3*2+2*-1=	**4**
13	**Ion mobility spectrometers**	--	--	High	--	--	--	--	Low sensitivity	Compact	1*2+1*1+1*-1 =	**2**
14	**Passive millimeter wave detection**	--	Only for dry soil	--	--	High	Chang-eable	Metallic	--	--	0*2+3*1+1*-1 =	**2**
15	**Chemical sniffers**	Artificial noses	All	Low	--	High	--	--	Low sensitivity, large	--	1*2+2*-1 =	**0**
16	**Optical methods (multispectral)**	--	Only for some terrains	--	--	High	--	--	Sensitivity to environmental condition	--	1*1+1*-1 =	**0**

Table B.3: The aggregation of the two studies and sensors selection

No.	Class	Sub class	from Study 1 S1 /10	From Study 2 S2 /17	Aggregation S1*17+S2*10		Remarks
1	**Chemical sniffers**	Alive sniffers (dogs)	10	16	**330**	**best 1**	**Selected**
2	**Magnetometers**	Fluxgate	8	17	**306**	**best 2**	**Selected**
3	**Magnetometers**	Proton precession	8	17	**306**	**best 3**	**Selected**
4	**Ground penetrating Radar (GPR)**	--	9	15	**303**	**best 4**	**Selected**
5	**Induction coil**	Metal Detector	9	14, relative	**293**	**best 5**	**Selected**
6	**Manual Prodding**	--	7	17	**289**	**best 6**	--
7	**Brute force**	Mechanical	7	12, relative	**239**	**best 7**	--

APPENDIX C:

TABLES OF AVAILABLE SENSORS WITH COST ESTIMATES

This appendix contains 8 tables giving more detailed information about different types of sensors.

These tables gives are:

1. Metal Detectors
2. UXO Detectors
3. Magnometor Detectors
4. Dual Sensor and GPR Systems
5. Vehicle-Mounted Detectors
6. Free internet search outside the Geneva Humanitarian Demining Organization PEE Reports
7. Detectors in use in Egypt (from PEE-Cat-2009)
8. The selected Sensors (Based on the comparison specially the depth of detection)

This appendix is based on the information from **REF: PEE-CAT-2009.**

Table C.1: METAL DETECTORS					Weight with full equipment	in production / in use	Depth			ERW	Price
Country	Brand	Model	Version	Technology			Low-Metal content mines	Antitank Plastic	Antitank Ferrous cased		
CHINA	BGIF	GTL115-2	01 | 2005	Metal mine detector | pulse induction	4.9-11 kg	In production /worldwide	0.8 - 12 cm	12 cm	70 - 75 cm	Depending on their size, material and the local interference	US$ 1,400
ITALY	CEIA	MIL-D1	3.4	Electromagnetic induction | CW (Continuous Wave)	7 - 12.5 kg	13,000, worldwide	Optimized according to the mines and soils				--
GERMANY	EBINGER	EBEX® 421 GC (stands for Ground Compensation)	11 | 2002	Metal detector | pulse induction	3.8 | 8.5 kg	approx 2000 worldwide	Depending on their size, material and the local interference				US$ 2,000 - US$ 3,000
	EBINGER	EBEX® PBD (stands for Pulse Bipolar Dynamic)	11 | 1996	Metal detector | pulse induction	2 - 8.5 kg	approx 5000 worldwide	Depending on their size, material and the local interference				US$ 2,000 - US$ 3,000
	EBINGER	EBEX® 420 H	01 | 2002	Metal detector | sine wave	2- 5 kg	approx 2000 worldwide	Depending on their size, material and the local interference				US$ 1,000 - US$ 2,000
	FOERSTER	MINEX 2FD	4.530	Continuous - wave EMI with two parallel frequencies in combination with gradiometric receiving coil system	5.7 - 8 kg	in production prev- version in 30 countries worldwide.	Type 72A | approx. 18 cm	TM 62M | up to 60 cm			--

Table C.1: METAL DETECTORS (Cont'd)					Weight with full equipment	in production / in use	Depth			ERW	Price
Country	Brand	Model	Version	Technology			Low-Metal content mines	Antitank Plastic	Antitank Ferrous cased		
CZECH REPUBIC	All-metal, non-motion discriminative metal detector	EXPLORER TM-D	TM-D	Pulse | Induction electromagnetic method	13 kg	App. 300 pieces with military, police and field -Europe, Asia, North America	Several cm with circular 13 cm coil	50 cm to 200 cm depending on coil used			1,600 - 3,500 USD for 100 x 100 cm square coil
AUSTRALIA	MINELAB	F1A4	Version 8	Pulse induction | multi-period-sensing	4 - 8 kg	10,000 plus - 50+ countries	Type 72 at 15-19 cm	Metal mine at 1.0 m		500 lb bomb at 1.8 m	US$ 1,000 - US$ 2,000
	MINELAB	F3	F3L, F3S & UXO configurations	Pulse induction | multi-period-sensing-bipolar	6.5 - 10.5 kg	5,000 plus - 25+ countries	Type 72 at 15-19 cm	Metal mine at 1.0 m		500 lb bomb at 1.8 m	US$ 2,000 - US$ 3,000
AUSTRIA	SCHIEBEL	AN-19/2 Mine Detecting Set	Mod 7	Electromagnetic pulse induction	2.2 - 6.02 kg	more than40,000 worldwide	72A – 18 cm | M14 – 14 cm	nearly all types at operational threat depth	1 m;	NATO std 7.62 at 40 cm, AK 47 at 30+ cm; all larger items 1 m	US$ 2,000 - US$ 3,000
	SCHIEBEL	ATMIDTM All Terrain Mine Detector	--	Electromagnetic pulse induction and continuous wave induction	2.2-6.36 kg	more than 900 worldwide	72A – 20 cm | M14 – 16 cm	nearly all types at operational threat depth	1 m;	NATO std 7.62 at 40 cm, all larger items 1 m	US$ 2,000 - US$ 3,000
	SCHIEBEL	MIMID™ Miniature Mine Detector	--	Electromagnetic pulse induction	0.64 - 2 kg	More than 1,500 worldwide	72 A - 14 cm; M14 – 12 cm	at threat depth	Metallic mines down to 80 cm	NATO std 7.62 at 32 cm Larger items 80 cm	US$ 3,000 - US$ 4,000

Table C.1: METAL DETECTORS (Cont'd)					Weight with full equipment	in production / in use	Depth	Price
Country	Brand	Model	Version	Technology				
GERMANY	VALLON	VMC1	--	Metal detector | Pulse induction	0.3 - 5 kg	In production - used worldwide other: VMH3CS | VMM3 | VMH3| VMC1 | VMXC1 | VMXC1-3	Depending on their size, material and the local interference	Upon request
	VALLON	VMH3	--	Metal detector | Pulse induction	1 - 4.8 kg		Depending on their size, material and the local interference	Upon request
	VALLON	VMH3CS	--	Metal detector | Pulse induction	0.9 - 8kg		Depending on their size, material and the local interference	Upon request
GERMANY	VALLON	VMM3	--	Metal detector | Pulse induction	5.6 -11kg		Depending on their size, material and the local interference	Upon request
	VALLON	VMW1	--	Metal detector | Pulse induction	2.3 -5.4 kg		Depending on their size, material and the local interference	Upon request
	VALLON	MW1630B	--	Metal detector | Pulse induction	5.6 -11.6kg		Depending on their size, material and the local interference	Upon request

Table C.2: UXO DETECTORS							Depth				
Country	Brand	Model	Version	Technology	Weight with full equipment	In production / in use	Low-metal-content mines	Antitank Plastic	Antitank Ferrous cased	ERW	Price
ITALY	CEIA	MIL-D1 / DS	6.0	Electromagnetic induction | CW (Continuous Wave)	7.8 -14 kg	in production, Cambodia, Laos, Sudan, Denmark, Egypt, France, Italy, Switzerland, USA, Yemen	Optimized according to the mines and UXOs and soils				--
GERMANY	EBINGER	UPEX® 740M-V and UPEX® MM (vehicle)	--	AEM-PI		50, Angola, Cambodia, Eritrea, Mozambique, Sudan	Not suitable	Designed for		Designed for	More than US$ 5,000
	VALLON	VMXC1	--	Metal detector | Pulse induction Metal discrimination	0.3 - 9 kg	in production, VMH3 | VMH3CS | VMC1 | VMM3 | VMX3, worldwide	Depending on their size, material and the local interference as well as implemented firmware				Upon request
	VALLON	VMX3	--	Metal detector | Pulse induction	3.5 - 9.1 kg		Designed for UXO, only with metal content, Depending on their size, material and the local interference				Upon request

Table C.3: MAGNOMETER DETECTORS						In production / in use	Depth				Price
Country	Brand	Model	Version	Technology	Weight with full equipment		Low-metal-content mines	Antitank Plastic	Antitank Ferrous cased	ERW	
CHINA	BGIF	CCT-2	01 | 2005	Difference magnetometer working on fluxgate principle	6.2 - 12.5 kg	In production, worldwide	Depending on their size, material and the local interference				Not given
GERMANY	EBINGER	MAGNEX® 120 LW magnometer	05 | 2001	Difference magnometer using fluxgate principle	3 - 4.2 kg	1,200 - worldwide	--	Depending on their size, material and the local interference			4,000-5,000 US$
	FOERSTER	FEREX 4.032	API, DLG,DLG Kartograph	Metal detector working by fluxgate magnetometers	4 - 9 kg	In production	No	Full metal case (ferromagnetic)		Hand grenade; 500 lbs bomb (Mk 82);	Upon request
	FOERSTER	FEREX DATALINE 4.800	STD, STD-F, GPS, GPS-F, BM	The sw calculates ferromagnetic objects by: magnetic data taken in a plane applies mathematical, iterative computation methods which refer to the magnetic moment of a spherical body.(best possible approximations of the real-life situation),don't accept any liability.		Worldwide (countries see FEREX 4.032 data logger)	--	--	--	--	Upon request
U.S.A.	GEOMETRICS	G-858	Man carry and towable version (back pack & non-magnetic cart versions are available)	Self oscillating split-beam cesium vapor magnetometer (non-radioactive)	9.5-29.5 kg	> 2,000 sensors | > 500 of model G-858 US & Hawaii, Japan, China, Europe, Cambodia, Vietnam	Depends on the size and the material of the object being detected, typically 2 kg at 3 m				Approximately $ 18K
U.S.A.	SCHONSTEDT	GA-52 CX	--	Fluxgate - Patented heliflux sensor	0.3 - 1.5 kg	> 90,000 worldwide	Target dependent, from a few cm to several meters				< US$ 1,000
U.S.A.	SCHONSTEDT	GA-72 CD-ML	--	Fluxgate - Patented heliflux sensor	0.3 - 1.5 kg	> 2,000 worldwide	Target dependent, from a few cm to several meters				1,000 - 2,000 US$

Table C.3: MAGNOMETOR DETECTORS(Cont'd)							**Depth**				
Country	**Brand**	**Model**	**Version**	**Technology**	**Weight with full equipment**	**In production / in use**	Low-metal-content mines	Antitank Plastic	Antitank Ferrous cased	ERW	**Price**
GERMANY	VALLON	EL 1302-D2	D2	Difference magnetometer using fluxgate principle	6.3 -12 kg	EL 1302D2 | EL 1303D2 | VET2 | VXC1 | VMXC1 VMXC1-3 - worldwide	No	Depending on their size, material and the local interference			Upon request
		EL 1303-D2	--		9.5 - 20 kg		No	Depending on their size, material and the local interference			Upon request
		VET2	--		16.3 - 22 kg		No	Depending on their size, material and the local interference			Upon request
		VXC1	--		1 - 8.4 kg		No	Depending on their size, material and the local interference			Upon request
		VXV4	Vehicle Mounted	--	Customer's	--	Not	(please specify) Depends on the construction			Upon request
			MultiSensor System(customized solutions)	--	requirements	--	applicable, UXO detector	--			--

Table C.4: DUAL SENSOR AND GPR SYSTEMS							Depth				
Country	Brand	Model	Version	Technology	Weight with full equip.	in production / in use	Low-metal-content mines	Antitank Plastic	Antitank Ferrous cased	ERW	Price
JAPAN	TOHOKU Univ.	ALIS	ALIS-PG/ALIS-VNA	Continuous wave (CW) Electromagnetic induction (EMI) & ground-penetrating radar (GPR)	5 - 15 kg	Development (final phase)	Optimized according to the mines and soils				on request
JAPAN	TOHOKU Univ.	ALIS-EMI	1	Electromagnetic induction (EMI)	0.5 kg (PC)	In production	Optimized according to the mines and soils				on request
RUSSIA	TR-GEO	TR-GEO-04, MIRADOR	MIRADOR 2009	Ultra-short video pulses of electromagnetic waves	1 - 6 kg	Development - TR-GEO-03; MIRADOR; TR-GEO-04 Roads in Russia	Moving of sensor head (antenna unit) by an operator manually above the ground at a height 5-10 cm along a line 0.5-1.5 m. Imaging of 2-D profile on the monitor after scanning Objects (dielectric, metallic) with size (diameter) 5-7 cm at a depths: 0.1 m in moist or clayey soils 0.5-0.7 m in dry sandy soil				US$ 10,000
U.S.A	CYTERRA	AN/PSS-14 (HSTAMIDS) / AMD-14 (Humanitarian demining model) MD: similar to MINELAB F3	--	MD, GPR	AN/PSS-14: 20 kg | AMD-14: 20 kg	Development - AN/PSS-14 more than 2,000	AN/PSS-14 & AMD-14: Will detect mines presenting an operational threat (PD, PFA:a)).			--	More than US$ 5,000
GERMANY	VALLON	VMR2	--	Metal detector with ground penetrating radar	4-14 kg	In production	Depending on their size, material and local interference			--	Upon request

Table C.5: VEHICLE-MOUNTED DETECTORS							Depth				
Country	Brand	Model	Version	Technology	Weight with full equip.	in production / in use	Low-metal-content mines	Antitank Plastic	Antitank Ferrous cased	ERW	Price
GERMANY	FOERSTER	FOERSTER MULTICAT	Standard vehicle for 4 or 8 probe scanning	Metal detector working by fluxgate magnetometers	145 kg	In production	No	Full metal case (ferromagnetic)		Hand grenade; 500 lbs bomb (Mk 82); 1,000 lb bomb	Upon request
AUSTRALIA	MINELAB	STMR ARRAY	2.0	Pulse induction | multi-period-sensing-bipolar	32 kg	In production | development Africa, Middle East, US	PMN2 55 cm | IO 22 cm	ATMC > 160 cm		500 lb bomb > 1.8 m	> US$ 5,000
AUSTRIA	Schiebel Elektronische Geräte GmbH	VAMIDS™ Vehicular Array Mine Detection System	2.0	Pulse mode, flexible array	20 kg per meter array	In production	72A - 18 cm | M14 - 14 cm	nearly all types at operational threat depth	1 m;	NATO std 7.62 at 40 cm, AK 47 at 30+ cm all larger items 1 m	3,000 - 4,000 US$ with training
GERMANY	VALLON	VMV8	Vehicle mounted metal detector	Metal detector | Pulse induction	160kg	In production, worldwide	Not recommended	Depending on their size, material and the local interference			Upon request
	VALLON	VMXV	Vehicle mounted multi sensor system (customized solutions)	Metal detector (EMI) and/or difference magnetometer (fluxgate)		In production, Worldwide land and/or underwater	Depends on the construction				Upon request

Table C.6: Free internet search outside the PEE							Depth				
Country	Brand	Model	Version	Technology	Weight with full equip.	in production / in use	Low-metal-content mines	Antitank Plastic	Antitank Ferrous cased	ERW	Price
Germany	OKM	eXp 5000	--	GPR	--	--	Penetration Depth Operating Mode Magnetometer about 2 meters Penetration Depth Operating Mode Ground Scan about 25 meters Penetration Depth Operating Mode Discrimination about 25 meters Penetration Depth Operating Mode Metal Detector about 2 meters Penetration Depth Operating Mode Live Scan about 25 meters				$26,770
	OKM	eXp 5000_Pro	--	GPR	--	--					$64,995
	OKM	Future I-160	--	electromagnetic pulse method	--	--	Maximal Penetration Depth (Horizontal Probe) about 18 meters Maximal Penetration Depth (Vertical Probe) about 3 meters				$35,998

Note: OKM Products have been intensively Tested and Certified by one of the leading Physicist and technical experts in Germany to locate all metallic objects and cavities in the ground http://www.kellycodetectors.com

Table C.7 Detectors in use in Egypt (from PEE-Cat-2009)

Country	Brand	Model	Testing executed in Cairo university
ITALY	CEIA	CEIA-MIL-D1	Experimental Cairo Testing and Evaluation of Mine and UXO Detectors: Faculty of Engineering, Cairo University, Giza, Egypt; 2008.
GERMANY	FOERSTER	MINEX 2FD 4.530	--
GERMANY	Vallon	VMH3CS	--
ITALY	CEIA	CEIA MIL D1/DS	Experimental Cairo Testing and Evaluation of Mine and UXO Detectors: Faculty of Engineering, Cairo University, Giza, Egypt; 2008.
GERMANY	Ebinger	Ebinger UPEX 740 M	--
GERMANY	FOERSTER	FEREX 4.032 DLG (data logger)	A. M. El-Nadi, Experimental Cairo Testing and Evaluation of Mine and UXO Detectors, by Faculty of Engineering, Cairo University, Giza, Egypt, published 2007
JAPAN	TOHOKU Univ.	ALIS	--

Table C.8: The selected Sensors					Weight with full equipment	In production / in use	Depth				
							Low-metal-content mines	Antitank		ERW	
Country	Brand	Model	Version	Technology				Plastic	Ferrous cased		Price
MAGNOMETOR DETECTORS (from PEE-Cat-2009)											
U.S.A.	GEOMET-RICS	G-858	Man carry and towable version (back pack and non-magnetic cart versions are available)	Self oscillating split-beam cesium vapor magnetometer (non-radioactive)	9.5-29.5 kg	> 2,000 sensors | > 500 of model G-858 US and Hawaii, Japan, China, Europe, Cambodia, Vietnam	Depends on the size and the material of the object being detected, typically 2 kg at 3 m				Approximately $ 18K
Free internet search outside the Geneva Humanitarian Demining Organization PEE Reports											
Germany	OKM	Future I-160	--	electromagnetic pulse method	--	--	Maximal Penetration Depth (Horizontal Probe) about 18 meters Maximal Penetration Depth (Vertical Probe) about 3 meters				$35,998

Note: OKM Products have been intensively Tested and Certified by one of the leading Physicist and technical experts in Germany to locate all metallic objects and cavities in the ground http://www.kellycodetectors.com

APPENDIX D:

AVAILABLE ROBOTS IN THE MARKET

#	Robot Photo	Short specification	Company/ R&D Center	Cost
1	Knight	**Height:** 1016 mm **Width:** 705 mm **Length:** 1359 mm **Weight :** 250 kg **Multi-tool**	Foster www.foster-miller.com	300,000 USD
2	ATV	ATV: The new remote controlled/semi autonomous all-terrain miniature vehicle pulling a trailer with detectors, including a Vallon GmbH UXO or Mine detector. It is scalable, so that Vallon Data mapping software, GPS, Mine marking tools, front plows, IED disrupters, etc.. can be added to increase value and functionality.	Foster	110,000 USD
3	TALON	**Height:** 1300 mm (Arm Extended) **Width:** 572 mm **Length:** 1300 mm (horiz. reach) **Weight :** 22 to 64 kg	Foster	Not available

#	Robot Photo (continued)	Short specification	Company/ R&D Center	Cost
4	**MAXXPLUS**	Multi-tool Unmanned Ground Vehicle (UGV), tracked, tele-operated, platform + arm + changeable tools and actuators: ACTIVE: Mulcher (used for cutting vegetation), Rotor, PASSIVE: material handler, fork	MgM Mine Clearance NGO - R&D	250,000 USD
5	Buggy Robot	Not available	TIT in Japan	Not available
6	Andros Robot	Not available	Pacific Northwest National Laboratory's (PNNL's) http://www.bragg.army.mil/eod/	Not available

APPENDIX E:

MARKET SURVEY VERSUS ROBOT PARTS LIST AND SPECIFICATION

#	Components	Market locations	Remarks
1	Motors : Stepper / DC / AC	Elsayeda Eisha, Al-gomaa Market, beside Elkahlawi mosque, and Elmagzar Elaly.	Very cheap, very wide types of scrape, relatively, hard to find something
2		Shoubra, Elsa7el, copiers scrape market, ex: Elramly.	normal cost, more organized, relatively, easy to find something. (more suitable for researcher)
3		Elgomhoria st.,	high cost, more organized, relatively, hard to find something (if not technician or expert with this area)
4	Metal sections, wires, tires, bolts, ...	Elsabteiah	Medium cost, variety of type, model and applications
5	wires, tires, bolts, joints...	Elrowe3y	Medium cost, variety of type, model and applications
6	microcontrollers, transistors, …, etc.	Grash Elbostan street Hosam Abdelsahfie	Low cost,
7	resistors, capacitors, …, etc.	Albeer	Low cost,
8	resistors, capacitors, …, etc.	Elgammal	high cost,
9	microcontrollers, kits,…, etc.	Radio Elamer	high cost,
10	microcontrollers, transistor, metal detector, ultrasonic sensor…, etc.	Elnekhely	high cost,
11	microcontrollers, transistor, …, etc.	RAM	high cost,

Robot Specification

Vehicle Dimensions
Height: 1.80 m
Height (arm extended): 2.25 m
Width: 1.15 m
Length: 1.15 m
Horizontal reach: 1.6 m
Below grade reach: 0.5 m
Ground clearance: 7 cm

Weight
70 to 90 kg (estimated, Mission profile dependent)

Maneuverable Speed
Forward: 0.496 m/s
Backrward: 0.491 m/s

Maneuverability Control
Using Laptop through matlab GUI

Operator Control Unit (OCU) Dimensions
Laptop Fujitsu – Processor: Intel(R) Core(TM)2 Duo 2.53 GHz
with Windows 7 and Matlab

Robot Rechargeable Battery
Two Lead Acid, 12 A-hr, 12 Vdc,

Cameras
Wirless camera

Human interface and Communication Ports
GUI with matlab to command the actuators through the laptop ports to the control circuit 1 then the RF module.
RS 232 ports or USB (using USB2Serial)

Sensors
• Metal Detector
• Ultrasonic Sensor

APPENDIX F:

COMPUTATIONAL METHODS OF ROBOT ARM JACOBIAN MATRIX

Direct: need computation of partial derivative of DKPM

Indirect: doesn't need computation of partial derivative of DKPM, as follows.

For any revolute joint

$$T_{i,i+1}(q_i) = \begin{bmatrix} Cq_i & -C\alpha_i Sq_i & S\alpha_i Sq_i & a_i Cq_i \\ Sq_i & C\alpha_i Cq_i & -S\alpha_i Cq_i & a_i Sq_i \\ 0 & S\alpha_i & C\alpha_i & r_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \begin{bmatrix} -Sq_i & -C\alpha_i Cq_i & S\alpha_i Cq_i & -a_i Sq_i \\ Cq_i & -C\alpha_i Sq_i & S\alpha_i Sq_i & a_i Cq_i \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \overline{Q}\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\frac{\partial T_{i,i+1}(q_i)}{\partial q_i}$$

Revolute joint $\sigma_i = 0, \overline{\sigma}_i = 1$

For any prismatic joint

$$T_{i,i+1}(q_i) = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & C\alpha_i & -S\alpha_i & 0 \\ 0 & S\alpha_i & C\alpha_i & q_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = Q\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}\frac{\partial T_{i,i+1}(q_i)}{\partial q_i}$$

Prismatic joint $\sigma_i = 1, \overline{\sigma}_i = 0$

$$\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = Q_i T_{i,i+1}(q_i) \quad , \quad Q_i = \overline{\sigma}_i \overline{Q} + \sigma_i Q$$

The HTM $\{T_{1,n+1}\}$ between the base coordinate frame and $(n+1)^{th}$ frame is given by:

$$T_{1,n+1} = T_{12}(q_1)\, T_{23}(q_2)\, T_{34}(q_3) \ldots T_{n,n+1}(q_n)$$

The partial differentiation of the matrix w.r.t q_i is given by:

$$\frac{\partial T_{1,n+1}}{\partial q_i} = T_{1,i}(q_1, q_2, \ldots, q_{i-1}) Q_i T_{i,n+1}(q_i, q_{i+1}, \ldots, q_n) = T_{1,i} Q_i T_{i,1} \quad T_{1,n+1}$$

$$T_{1,i} = \begin{bmatrix} R_{1,i} & P_{1,i} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} X_{1i} & Y_{1i} & Z_{1i} & P_{1i} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad , \quad T_{i,1} = T_{1,i}^{-1} = \begin{bmatrix} R_{1,i}^t & -R_{1,i}^t P_{1,i} \\ 0 & 1 \end{bmatrix}$$

Differential operator $T_{1,i} Q_i T_{i,1} = \begin{bmatrix} \Omega_i \\ 0 \end{bmatrix}_{4X4}$

For any vector A=[a_1 a_2 a_3] the associate matrix $\hat{A} = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & a_1 \\ -a_2 & a_1 & 0 \end{bmatrix}$

Let Z=[0 0 1]^t, $Q = \begin{bmatrix} 0 & Z \\ 0 & 0 \end{bmatrix}_{4X4}$, $\overline{Q} = \begin{bmatrix} \hat{Z} & 0 \\ 0 & 0 \end{bmatrix}_{4X4}$

Computation of Ω_i depends on the joint type revolute or prismatic

Case1: Revolute joint

$$T_{1,i}Q_iT_{i,1} = \begin{bmatrix} R_{1,i} & P_{1,i} \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \hat{Z} & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} R_{i,1} & P_{i,1} \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} R_{1,i}\hat{Z} & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} R_{1,i}^t & -R_{1,i}^tP_{1,i} \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} R_{1,i}\hat{Z}R_{1,i}^t & -R_{1,i}\hat{Z}R_{1,i}^tP_{1,i} \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \hat{Z}_{1,i} & -\hat{Z}_{1,i}P_{1,i} \\ 0 & 0 \end{bmatrix}$$

$$\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \begin{bmatrix} -Sq_i & -C\alpha_iCq_i & S\alpha_iCq_i & -a_iSq_i \\ Cq_i & -C\alpha_iSq_i & S\alpha_iSq_i & a_iCq_i \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \overline{Q}\frac{\partial T_{i,i+1}(q_i)}{\partial q_i} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\frac{\partial T_{i,i+1}(q_i)}{\partial q_i}$$

Revolute joint $\sigma_i = 0, \overline{\sigma}_i = 1$

Case2: Prismatic joint

$$T_{1,i}Q_iT_{i,1} = \begin{bmatrix} R_{1,i} & P_{1,i} \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 0 & Z \\ 0 & 0 \end{bmatrix}\begin{bmatrix} R_{i,1} & P_{i,1} \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & R_{1,i}Z \\ 0 & 0 \end{bmatrix}\begin{bmatrix} R_{1,i}^t & -R_{1,i}^tP_{1,i} \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & R_{1,i}Z \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & -Z_{1,i} \\ 0 & 0 \end{bmatrix}$$

Prismatic joint $\sigma_i = 1, \overline{\sigma}_i = 0$

Where $\Omega_i = \overline{\sigma}_i\overline{\Omega} + \sigma_i\Omega$, $\overline{\Omega} = [\hat{Z}_{1,i} \quad -\hat{Z}_{1,i}P_{1,i}]$, $\Omega = [0 \quad Z_{1,i}]$,

$$\frac{\partial T_{1,n+1}}{\partial q_i} = \begin{cases} \begin{bmatrix} \Omega_i \\ 0 \end{bmatrix} T_{i,n+1} & for \quad i \le n \\ 0 & for \quad i > n \end{cases}$$

Also:

$$R_v = I\begin{bmatrix} 0 \\ 0 \\ \alpha^{\bullet} \end{bmatrix} + rot(z,\alpha)\begin{bmatrix} 0 \\ \beta^{\bullet} \\ 0 \end{bmatrix} + rot(z,\alpha)rot(y,\beta)\begin{bmatrix} \gamma^{\bullet} \\ 0 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ \alpha^{\bullet} \end{bmatrix} + \begin{bmatrix} C\alpha & -S\alpha & 0 \\ S\alpha & C\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ \beta^{\bullet} \\ 0 \end{bmatrix} + \begin{bmatrix} C\alpha & -S\alpha & 0 \\ S\alpha & C\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} C\beta & 0 & S\beta \\ 0 & 1 & 0 \\ -S\beta & 0 & C\beta \end{bmatrix}\begin{bmatrix} \gamma^{\bullet} \\ 0 \\ 0 \end{bmatrix}$$

$$R_v = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\alpha^{\bullet} + \begin{bmatrix} -S\alpha \\ C\alpha \\ 0 \end{bmatrix}\beta^{\bullet} + \begin{bmatrix} C\alpha C\beta \\ S\alpha C\beta \\ -S\beta \end{bmatrix}\gamma^{\bullet}$$

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} 0 & -S\alpha & C\alpha C\beta \\ 0 & C\alpha & S\alpha C\beta \\ 1 & 0 & -S\beta \end{bmatrix}\begin{bmatrix} \alpha^{\bullet} \\ \beta^{\bullet} \\ \gamma^{\bullet} \end{bmatrix}$$

$$\begin{bmatrix} \alpha^{\bullet} \\ \beta^{\bullet} \\ \gamma^{\bullet} \end{bmatrix} = \begin{bmatrix} Cos\alpha \tan\beta & Sin\alpha \tan\beta & 1 \\ -\sin\alpha & Cos\alpha & 0 \\ Cos\alpha / Cos\beta & Sin\alpha / Cos\beta & 0 \end{bmatrix}\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

ملخص الرسالة

يعتبر مجال الكشف وإزالة الألغام الأرضية تحديا كبيراً للباحثين. ففي عمليات إزالة الألغام ، وتحديداً مرحلة تخفيض المساحة مهمه جداً في المناطق المصابة بالألغام الأرضية والمتفجرات من مخلفات الحرب (ERW) والذخائر غير المنفجرة (UXO). هذه المرحلة لها أثر كبير على تكلفة عمليات إزالة الغطاء النباتي وكذلك إعداد الأرض لغيرها من عمليات إزالة الألغام. التشغيل اليدوي خطير جدا ومجهد ومكلف (من حيث الوقت والمال). ومن المهم جدا إنتاج آليات للمساعدة مثل الروبوتات للتعامل مع بيئة حقول الألغام. أحد قيود تصميم الروبوت المطلوبة هو الضغط على مساحة تلامس مع الأرض حتى لا تنشط الألغام الأرضية المطمورة. وبالإضافة إلى ذلك يجب أن يكون الروبوت مجهز بنظام متعدد المجسات للكشف عن الألغام الأرضية المطمورة عند مسح المناطق المصابة.

وهذه الرسالة تتألف من أربعة فصول رئيسية .ففى الفصل الأول والملاحق تم عمل دراسة استقصائية لمشكلة الألغام الأرضية فى مصر. وفي الفصل الثانى ، تحديد المتطلبات الأساسية للروبوت المتحرك والقائمة على الدراسة الإستقصائية.

في الفصل الثالث ، تم تطوير نموذج أولي لمنصة متنقلة مع ذراع الالي لتلبية قيود التصميم. المكونات الميكانيكية المستخدمة فى هذا النموذج هي أساسا بعض الخردة والمكونات المتوفرة بالأسواق والمتاحة بتكاليف منخفضة. استخدام مكونات من هذا القبيل وفر كثيرا من الوقت والتكلفة العامة. تم إستخدام المكونات الكهربائية والالكترونية (اللوحات الإلكترونية المطبوعة (PCB)) للتشغيل وللتحكم فى محركات التيار المستمر ومحركات الخطوة، وهي Microcontrollers: (AVR ، PIC) ، دوائر التحكم ، ودوائر التشغيل. وقد تم تجهيز الروبوت بأجهزة الاستشعار المتاحة في السوق. وتم إعداد برنامج (Matlab: GUI) لقيادة النموذج الحقيقي بواسطة كمبيوتر محمول من خلال Serial Port أو USB2Serial. تم اختبار مجموعة متنوعة من تقنيات الاتصال والبروتوكولات والتحقق منها تجريبيا وعمليا لقياس مستوى تحقق متطلبات التصميم. في الفصل الرابع ، تم الحصول على النماذج الرياضية الحركية للروبوت المراد تصنيعة باستخدام طريقة Virtual Robot بإستخدام (HTM). واستخدمت هذه النماذج ، في Matlab وSimulink لمحاكاة أداء النموذج عند تنفيذ بعض المسارات المطلوبة في حقل إفتراضى من الألغام الأرضية. وتم توظيف مجموعة متنوعة من الخوارزميات للتحكم ، وتقنيات المنطق النسبى المتدرج (Fuzzy Logic). ويفترض أن مواقع الألغام الأرضية معروفا. النموذج الروبوت المنتجة رخيصة الثمن ، يحتاج الى المزيد من النظم المتعددة أجهزة الاستشعار المتطورة من أجل إختبارها في حقول الألغام الحقيقية.

مهنـــــــدس: حسين فؤاد محمد على

تاريخ الميلاد: 1977/03/23

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تاريخ التسجيل: 2004/10/01

تاريخ المنح: / /

القســـــــم: هندسة التصميم الميكانيكى والإنتاج

الدرجـــــة: ماجستير

المشـرفون: أ.د. سعيد محمد مجاهد

الممتحنون: أ.د. أحمد أبو اسماعيل (الأستاذ بهندسة أسيوط)

أ.د. محمد السيد العربى

أ.د. سعيد محمد مجاهد

عنوان الرسالة:

" متطلبات وقيود تصميم نموذج روبوت مبدئي لتطهير الألغام مع إيجاد نماذجه الكينماتيكية ومحاكاته مع التطبيق العملي"

الكلمات الدالة:- تطهير الألغام - طرق الكشف عن الألغام - روبوت - ميكاترونيكس

ملخص الرسالة: يعتبر مجال الكشف وإزالة الألغام الأرضية تحديا كبيراً للباحثين. ففي عمليات إزالة الألغام ، وتحديداً مرحلة تخفيض المساحة مهمه جداً في المناطق المصابة بالألغام الأرضية والمتفجرات من مخلفات الحرب (ERW) والذخائر غير المنفجرة (UXO). هذه المرحلة لها أثر كبير على تكلفة عمليات إزالة الغطاء النباتي وكذلك إعداد الأرض لغيرها من عمليات إزالة الألغام. التشغيل اليدوي خطير جدا ومجهد ومكلف (من حيث الوقت والمال). ومن المهم جدا إنتاج آليات للمساعدة مثل الروبوتات للتعامل مع بيئة حقول الألغام. أحد قيود تصميم الروبوت المطلوبة هو الضغط على مساحة تلامس مع الأرض حتى لا تنشط الألغام الأرضية المطمورة. وبالإضافة إلى ذلك يجب أن يكون الروبوت مجهز بنظام متعدد المجسات للكشف عن الألغام الأرضية المطمورة عند مسح المناطق المصابة.

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متطلبات وقيود تصميم نموذج روبوت مبدئي لتطهير الألغام
مع إيجاد نماذجه الكينماتيكية ومحاكاته مع التطبيق العملي

إعــداد

مهندس/ **حسين فؤاد محمد على**

رسالة مقدمة إلى كلية الهندسة، جامعة القاهرة
كجزء من متطلبات الحصول على درجة الماجستير
فى التصميم الميكانيكى والإنتاج

يعتمد من لجنة الممتحنين:

الأستاذ الدكتور/ **أحمد أبو اسماعيل** عضو اللجنة

الأستاذ الدكتور/ **محمد السيد العربى** عضو اللجنة

الأستاذ الدكتور/ **سعيد محمد مجاهد** المشرف الرئيسى

كلية الهندسة، جامعة القاهرة
الجيزة، جمهورية مصر العربية
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تحت إشــراف

الأستاذ الدكتور/ سعيد محمد مجاهد
قسم **هندسة** التصميم الميكانيكى والإنتاج
كلية الهندسة جامعة القاهرة

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فى التصميم الميكانيكى والإنتاج

كلية الهندسة، جامعة القاهرة
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