MECHATRONIC DESIGN OF AN EXPLOSIVE ORDNANCE DISPOSAL ROBOT

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ABSTRACT

This study concerns with the design of an Explosive Ordnance Disposal (EOD) Robot which is controlled in task space and with the combined sensor system the robot is capable of autonomous navigation. The robot is composed of 4 different gripping apparatus attached to a 4 degree of freedom manipulator arm which is controlled in task space and a mobile platform which provides the mobility of the EOD robot in the operation field. Since the manipulator arm of the robot is controlled in task space apart from the control system of current EOD robots, the explosive ordnance disposal task which requires high precision and dexterity can be accomplished much faster and more accurate.

In addition to improvements in the control system, a combined sensory system named VS-GPS is designed for autonomous navigation of the EOD robot by combining vision system, sonar system and GPS to operate in outdoor fields. In order to achieve the most feasible sensor system, all combinations of most common five conventional sensor systems are evaluated, and VS-GPS is found to be the most effective combined sensor system design.

Design of the EOD robot and sensor system includes the solid modeling of the robot using a computer program, Solidworks®, strength analysis, mathematical modeling of manipulator arm and evaluation of conventional sensor systems for an optimum combination of sensor systems especially for autonomous outdoor navigation of the robot.

ÖZET

Bu araştırma, tutucu kolu iş uzayında kontrol edilen bir bomba imha robotu ve bu robotun otonom yönlendirilmesini sağlayan sensör sisteminin tasarlanmasını kapsamaktadır. Robot, bomba imha işlemini, paletlerle çekişi sağlanan mobil bir platform üzerine yerleştirilmiş, iş uzayında kontrol edilebilen 4 serbestlik dereceli bir tutucu kol ve bu kola takılacak 4 farklı tutma aparatları ile gerçekleştirecektir. Robot kolunun iş uzayında kontrolü sayesinde günümüzde kullanılan bomba imha robotlarının kontrol sistemlerinden farklı olarak, çok daha hassas ve hızlı bir şekilde patlayıcı maddeye müdahale edilmesi mümkün olabilecektir.

Bu robot mekanik tasarım çalışmasına ek olarak VS-GPS olarak adlandırılan ve görüntü, sonar ve GPS sensör ve sistemlerinin kombinasyonu ile oluşturulan bir sensör sistemi sayesinde bomba imha robotunun arazi şartlarında konumunun saptanabilmesi ve yönlendirilebilmesi sağlanacaktır. Optimum özellikteki kombinasyonun sağlanması aşamasında, konvansiyonel sensör sistemleri incelenmiş ve en yaygın 5 sensör tipinin tüm kombinasyonları değerlendirilmiştir, ve VS-GPS en verimli sensör kombinasyonu olarak bulunmuştur.

Bomba imha robotunun tasarlanması, robotun katı modelleme programı (Solidworks®) ile modellenmesini, dayanım hesaplarının yapılmasını, matematik modelinin oluşturulmasını ve kovansiyonel sensör sistemlerinin incelerenerek en uygun kombinasyonun oluşturulması aşamalarını kapsamaktadır.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. The Definition of Explosive Ordnance Disposal (EOD)

The term “Explosive Ordnance Disposal (EOD)” can be defined as the detection, identification, on-site evaluation, rendering, safe recovery, and final disposal of unexploded explosive ordnances. It may also include an explosive ordnance which has become hazardous by damage or deterioration. As a more general term, “Bomb Disposal” may also be alternatively used for the concepts stated above.

1.2. EOD Techniques

Many techniques exist for the neutralization of a bomb or an explosive object where the selection of the technique depends on several variables. The greatest variable is the proximity of the explosive or device to people or critical facilities. Items in open fields are handled much differently than are ones in dense population areas.

The role of the Bomb Technician is to accomplish his task as remotely as possible. Actually laying hands on a bomb is only done in an extremely life-threatening situation, where hazards to people and critical structures can not be stopped.

Once, the technician determines exactly what the explosive or device is, and what state it is currently in, he will formulate a procedure to render it safe. This may include things as simple as replacing safety features, or as difficult as using high-powered explosive-actuated devices to shear, jam, bind, or remove parts of the items' firing train.

Preferably, this will be accomplished remotely, but there are still circumstances when a technician must put himself at grave risk by personally handling the bomb. The technician will often wear a specialized protective suit, consisting of flame and fragmentation-resistant material similar to bulletproof vests. (Figure 1.1). Some suits have advanced features such as internal cooling, amplified hearing, and communications back to the control area (WEB_1, 2005).

Figure 1.1. Protective suit (Source: WEB_1, 2005).

On the rare occasion, the specifications of an explosive or a bomb allow the technician to remove it from the area, a containment vessel is used (WEB_2, 2005). Some of them are shaped like small water tanks and others are like large spheres (Figure 1.2). Using remote methods, the technician places the item in the container and retires to an uninhabited area to complete the neutralization. Because of the instability and complexity of modern bombs, this is rarely done.

After the explosive or bomb has been rendered safe, the technicians will assist in the removal of the item so that the area can be returned to normal.

Figure 1.2. Explosive containment vessel (Source: WEB_2, 2005).

All of these, called a mission or evolution, can take a great deal of time. Because of the construction of devices, a wait time must be taken to ensure that whatever render-safe method was used has worked as intended. While time is usually not on the bomb technician's side, rushing usually ends in disaster.

The bombs or explosives usually are composed of two sections; the explosive part which contains an explosive material and a triggering mechanism to start the reaction which ends up with an explosion. The purpose of EOD operation is disarming or destroying the triggering mechanism before the section containing the explosive material is triggered.

1.3. Definition of EOD Robot

The EOD robot is a mobile robot used in replace of a human in OED operations of searching, detecting and handling of explosive materials. The robotic system consists of a mobile platform equipped with a serial redundant dexterous arm, a gripper and a sensory system which provides the remote controlling abilities. Despite small differences in order to increase versatility, current examples of EOD robots are similar in terms of operating principles.

1.4. The Need for an EOD Robot

The development of synthetic chemicals has increased production of powerful explosives. Most of the time, material with a doubtful origin is manipulated by specially trained bomb squads. However, since the explosive is prepared for the highest damage, complicated and even remotely controlled triggering mechanisms challenge a specialist's talents.

Today's squads wear safety suits in case of an explosion, which minimize the pressure of an explosion and prevent injury to a certain level (Figure1.1). On the other hand, they limit movement capabilities and increase stress. Despite advanced safety precautions, handling of explosive ordnances brings high risks for the operator's life.

The basic reason and justification of the need for an EOD robot is simply the fact that it saves human life in an explosion. The robot can be operated meters away from the danger zone, providing a totally safe place for explosive specialists. In addition, these robots can be used not only for disarming the explosive ordnance but also collecting information about the threatening material and the area before human interference.

1.5. Application Areas

The list of the application areas of an EOD robot can be given as;

- Handling and manipulation of explosives,
- Handling of biologic, biochemical and other hazardous materials,
- Manipulation of suspected packages,
- Neutralizing and disarming unexploded ordnances,
- Determining and disabling landmines,
- And collecting visual information in an unsafe environment.

1.6. Current EOD Robots

Since the EOD robot is not a new concept, many different types of EOD designs are already used in military operations and many prototypes are produced. Their capacities and capabilities vary; however, it is possible to classify the current systems as small size robots and larger size robots. The small size robots are mainly used for inspection and collecting visual information. Their payload capacities are small, under 10 kilos. On the other hand, the second class of robots are larger and relatively stronger. They also have a much higher payload capacities Most of the mobile platforms use tracks for higher traction and some types of robots provide conversion kits between tracks and wheels. In addition to the advantage of higher traction, tracks provide high maneuvering ability and ease of steering.

1.7 Some of the Conventional EOD Robots on the Market

In this section, 5 different commercially available EOD robots and one non-commercial EOD robot are introduced and their strong and weak points are explained.

1.7.1. tEODor™, by "Telerob Fernhantierungstechnik mbH"

The tEODor 2 chain-tracked vehicle is equipped with 2 batteries at 12 volt 85 Ah each, a 6-axle power manipulator with a telescopic lower arm which has a 400-mm telescopic zone and gripper (Figure 1.4). The visual system is composed of a separately selectable pan tilt head as a camera mount for the main camera and two more additional cameras for detailed view. The robot is controlled from a control console by activating each joint separately from the control panel and controlling the motion according to the visual information displayed on the monitor. The whole EOD operation of tEODor depends on joint space control (WEB_3, 2004).

Figure 1.4. tEODor™ (Source: WEB_3, 2004).

1.7.2. Vanguard™ MK2 ROV by Allen -Vanguard Co.

The Vanguard MK2 features an articulated arm and low profile to reach narrow spaces such as under cars (Figure 1.5). The locomotion is provided by independently driven tracks. The manipulator arm which has a 3 degrees of freedom excluding the 2 jaw parallel gripper having 3 degrees of freedom. The manipulator system has a material lifting capacity of 16 kg at retracted position and 7 kg at full extracted position of the arm. Considering the light weight and the size, which allows the robot to fit in a car's trunk, Vanguard MK2 EOD Robot can be classified as a small size robot. The robot is equipped with a 360º pan-tilt-zoom camera and laptop display for remote operation. The arm is controlled in joint space by either touching the keyboard or by a joystick. The narrow width, compared to body and arm length, limits handling capacity when the arm operates sideways (WEB_4, 2004).

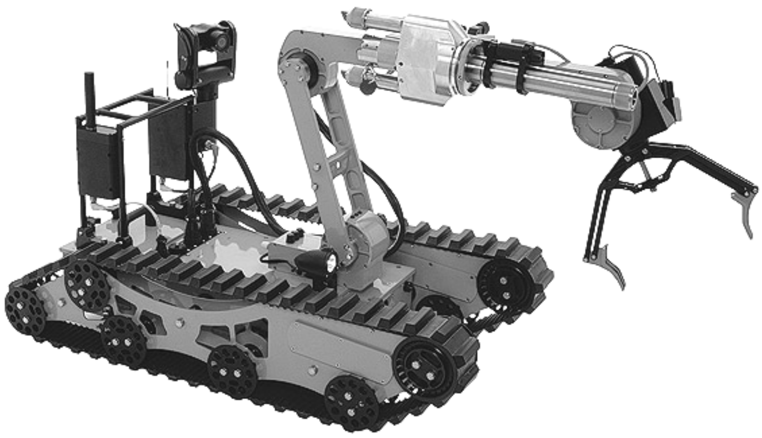

Figure 1.5. Vanguard™ MK-2 (Source: WEB_4, 2005).

1.7.3. MK-5 EOD Robot by ESIT

MK-5 is a heavy duty EOD robot which is offered with either of two arms: one for ordinary operations; the other one for high precision and dexterous operations (Figure 1.6). Depending on the application and the manipulator choice, the number of joints increases up to 7. The robot is driven by wheels or modular tracks which are attached over present wheels. The robot has a parallel 2 jaw gripper for handling explosives and suspected packages. Different end effectors are presented but a quick change system for grippers is not available, so the robot needs to return the control base to change the gripper when different gripper use is required (WEB_5, 2004).

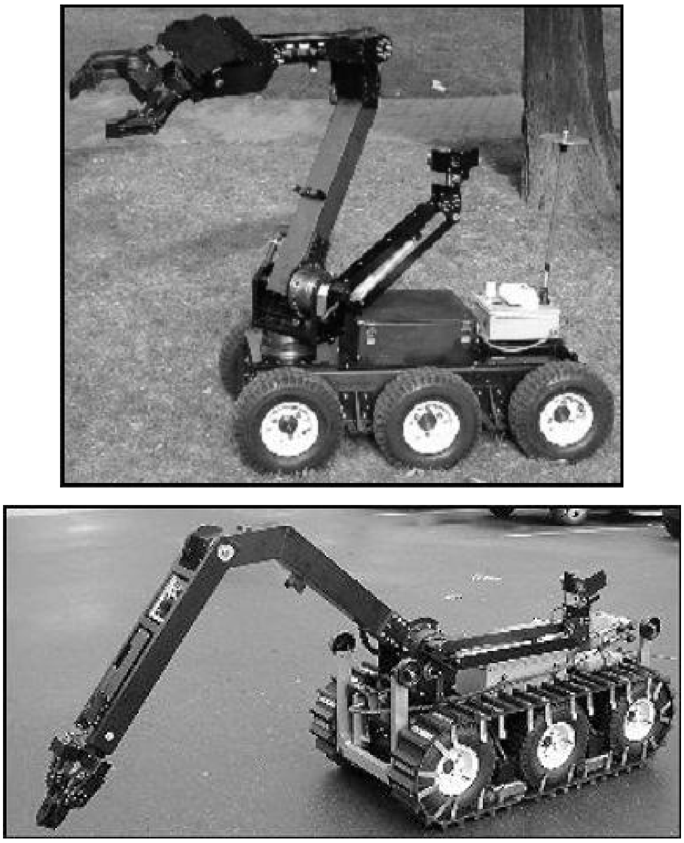

Figure 1.6. ESIT MK-5 (Source: WEB_5, 2004).

1.7.4 Wheelbarrow Super-M by Remotec Inc.

In design principle, Wheelbarrow Robot is very similar to tEODor and MK-5 robots except for its unique articulated track mechanism (Figure 1.7). This mechanism changes the wheel positions, which provides better driving characteristics in rough terrain. Two-way communications and vehicle/camera control can be accomplished through wire cable, fiber optics or RF links. The Wheelbarrow Robot is equipped with multiple television cameras for remote viewing of both the environment and the gripper details. Depending on the end effector type, the manipulator arm has 5-7 degrees of freedom and is actuated by both linear and rotational motors (WEB_6, 2004).

Figure 1.7. Wheelbarrow Super M (Source: WEB_6, 2004).

1.7.5. Robhaz-DT2 Robot

Robhaz DT2 Robot is the only non-commercial robot among the EOD Robots stated above. It presents double tracks at each side which can rotate independent of each other. The passive rotational joint connects the front body with the rear one, providing a good adaptability to rough terrain conditions. In addition, the robot is equipped with a 6 degree of freedom manipulator which is controlled by a haptic joystick. The 6 degree of freedom haptic device eases the manipulators' control in a remarkable grade but can not overcome joint space control problem. Since Robhaz DT2 Robot is not a commercial project, the EOD capabilities and performance are less than the commercial robots previously stated. However, the haptic control unit is a promising method in terms of speed and precision compared to the traditional joint space controlled manipulator mechanisms (Sungchul, K. and Changhyun, C., 2003).

1.7.6 BISON™ by ABP Precision (Poole) Ltd.

BISON is a four-wheel driven explosive ordnance inspection and disposal robot (Figure 1.8). The robot is electrically driven with a DC motor powering the wheels on each side of the vehicle. Power to the motors is provided from a pair of on-board batteries. The shoulder joint is rotated by a mechanism including linear actuators so the payload capacity is remarkably high. BISON has a relatively simple design and construction compared to the other heavy EOD robots and this fact brings robustness and reliability as an advantage. However, because of the simplicity of design of the manipulator arm, BISON's EOD capabilities in terms of handling and manipulation of explosives are less compared to its rivals which have manipulator arms with a higher degree of freedom. BISON's manipulator is controlled in joint space with a remote control handling unit including LCD display. In addition, the communication with base and remote control is provided by cable (WEB_7, 2004).

Figure 1.8. BISON™ EOD Robot (Source: WEB_7, 2004)

1.7.7 Common Properties of Current EOD Robots

The systems are presented to the market by different arm and end effector designs which have an average of 6-7 degrees of freedom. Considering the range of tasks to be accomplished during operation, one type of end effector design seems insufficient, so two or more alternative grippers are presented by the producer. However, in order to change the end effector, the robot is returned to the base and loses time.

Power to drive the motors and communication with base is provided usually by cable. Some brands optionally offer RF controls and batteries to increase mobility.

When the working conditions are considered, the cable may get stuck or get damaged, causing power or communication loss.

Conventional systems apply to at least two or more cameras for main and detailed view. Commonly, one is placed at the rear part of the vehicle for a wider looking angle and usually includes zoom, while the other placed close to the gripper part for detailed view of the material and task. Both cameras are preferred to have a night vision and infrared option.

However, the biggest problem about current systems is the position control mechanism of arms and end effector. The EOD robots on the market use joint space control in order to position the end effector which complicates the handling of the arm and loses time and versatility. The operator controls the angle of each joint individually, so a number of adjustments are required to reach the exact position and orientation of the end effector. For special tasks where the precision is very important, this control method is insufficient and too slow to accomplish the given task. Moreover, each motor on these robots needs to be operated individually, which brings complexity compared to autonomous mobile robots. A comparison of conventional EOD robots on market is given in Table 1.1.

Table 1.1. Comparison of Conventional EOD Robots on Market.

	tEODor	Vanguard MK2	ESIT MK5	Wheelbarrow Super M	Robhaz DT2	BISON
Manipulator Degree of Freedom	6	7	6	7	4	5
Control Method	Joint Space	Joint Space	Joint Space	N/I	Joint Space (haptic device)	Joint Space
Dimensions (LxWxH)mm	1100x680 x 300	920x440x 410	1170x700x 940	N/I	690x500x 910	1100x740x 1200
Weight	360 kg	55 kg	350 kg	N/I	145 kg	210 kg
Manipulator's lifting capacity	20 kg	5 kg	N/I	N/I	N/I	N/I
Maximum reach of manipulator	1750mm	1320mm	N/I	N/I	N/I	N/I
Speed	3 km/h	1-2 km/h	2-4 km/h	4 km/h	10 km/h	3,6 km/h
Autonomous	N	N	N	N	N	N
Quick change gripper system	N	N	N	N	N	N
Driving mechanism	Tracks	Tracks	Wheels	Tracks	Tracks	Wheels
Visual information	2 cameras	2 cameras	2 cameras	4 cameras	N	3 cameras
Power supply	Battery	Cable (Battery opt.)	Battery	Battery	N/I	Battery
Operation distance	200 m	360 m	N/I	N/I	N/I	1 km
Night vision	Y	Optional	N	Y	N/I	N
Y: Yes, N: No, N/I: No information						

1.8. The Need for Task Space Controlled Operation

Although the concept of an explosive ordnance disposal robot is not an old subject, many commercial samples have been manufactured. Although these have been promising projects for saving human life, the operational difficulties and insufficient motion characteristics while performing precise tasks prevent these robots from effective application. The main reason for such operational insufficiency is the working principle of the manipulator arm.

When the robot is operated in joint space, each of the joints is chosen individually by the operator and actuated remotely from the base, according to the visual information collected by the cameras. When one of the joints is rotated, all of the link system is affected by the rotation of this joint, so all the further joints must be adjusted to keep the original position which they had before the joint rotation. The correction moves cause time and versatility loss. Furthermore since the resolution and accuracy of joint motors differ, the moving the correct joint at the correct rate challenges operator’s talent. The operator focuses on the joints and the motion of the related link instead of concentrating on the explosive ordnance disposal task, which is performed at the tip point of the gripper. In other words, the operator changes the joint angles one by one and repeats this job in an iteration algorithm until the gripper reaches the desired position. Such a control system completely depends on the operator’s talent.

On the other hand, an EOD robot which is controlled in task space is able to perform tasks in a way which is very similar to the control mechanism of a human being and accomplishes difficult tasks faster and more accurate than joint space controlled EOD robots. As a result of a task space controlled motion mechanism, the operator only controls the position of the end point of the manipulator arm where the gripper is attached and the angular and linear change rates at joints to reach that desired position are calculated by computer. Therefore, the operator can concentrate on the position of end point, instead of dealing with relative changes of joints and corresponding links.

1.9. Introduction to Environmental Sensor System Design

An EOD robot, especially when it is operated on unstructured fields, is directly affected by environmental conditions. Therefore, the robot should always be monitored in order to eliminate the problems which can arise. It is a fact that remotely controlled EOD operation requires continuous visual information about robot’s position and condition. In conventional systems, this is provided both by the cameras on the robot and the bare eye of the remote control operator at the base station. However, since the objects have explosive properties the robot deals with, some cases may require that the EOD operators can not be positioned properly due to the safety reasons. For such cases, the robot should be navigated depending only on the visual information provided by the cameras on the robot. If this information is insufficient or corrupted because of thick walls in a building, presence of a sensor system which provides the interaction of the EOD robot with the surrounding environment becomes very important. In addition, the successful design of such a sensor system having sufficient capabilities of positioning and navigating can be used for autonomous movement of mobile platform according to the conditions of the operation area. Apart from the EOD task performed by the manipulator which is completely under direct human interference, the motion of mobile platform can be supported or completely accomplished by a sensor system, in order to design an autonomous EOD robot.

1.9.1. Navigation

Navigation is the science of directing the course of a mobile robot as it traverses the environment (land, sea, or air). Inherent in any navigation scheme is the desire to reach a destination without getting lost or crashing into anything. Navigation involves three tasks: mapping, planning, and driving. A higher-level process, called task planning, specifies the destination and any constraints on the course, such as time. Many problems have to be solved before sophisticated navigation abilities of people will be matched by robots. Most mobile algorithms abort when they encounter situations that make navigation difficult (McKerrow 1991).

Positioning the vehicle is one of the most important steps of navigation. Therefore, the mobile part of the EOD robot, which carries the end effector, should be positioned and navigated properly in order to achieve the given tasks.

The methods of positioning the robot are classified into two groups according to which reference sources are used to receive information about the state of the vehicle. The first one is positioning by using reference points on the field; vision based image processing, laser, radar and sonar. The second method is positioning by absolute coordinates; Global Positioning System (GPS).

The first technique of positioning by reference points on a plane is a vision-based technique, in which the image of environment is captured by a video camera and sent to a computer program where these images are evaluated. The program usually uses colors and contrasts between textures as the reference information in order to determine the distance and direction. Since the process depends on visual information, the nontransparent objects between the camera and the target and dusty weather conditions affect the success of the process (Hague et al. 2000, Jarvis 1996).

In the second technique, a laser sensor and a computer unit are installed on top of the vehicle (or on the end-effector) and a number of passive reflectors are placed at the corners and along the sides of the field. The sensor head transmits a beam of pulsed laser light in different directions as it rotates around an approximately vertical axis, and the beam of laser light spreads out in a vertical direction. Some of the transmitted laser light is reflected by the successively traversed reflectors of which the x, y and z coordinates should be known in a local earth- 3D coordinate system (Sogaard 1999).

The other technique, based on the same principle, uses a radar signal that is reflected from natural forms or artificial reflectors to evaluate and construct a digital map of the field. Therefore, besides positioning the robot, obstacle detection is also provided. The image of the field obtained by radar signals is approximately similar to those obtained from nautical applications. Although the accuracy is not high, the usability of radar over long distances is an advantage of this technique.

Ultrasonic systems use ultrasonic waves for positioning and object detection. In most applications, the sound waves are sent by a rotating emitter, placed on top of the vehicle. The computer measures the distance between the vehicle and an object or a landmark by computing the time of flight of the sound wave. It is also reported that sending a burst of ultrasound instead of a continuous emission and then computing the environment by changes in the frequency and amplitude is also possible. Since the computer uses a frequency spectrum for evaluation, the type of the object can also be recognized up to a level (Harper 2001).

The unique technique of positioning a mobile robot by using absolute or earth-fixed coordinates is called as Global Positioning System (GPS). This device is locked to at least three different satellites for planar positioning and four satellites for the calculation of elevation, and uses triangulation to identify any position on earth. However, the use of GPS in outdoor applications has not shown to be sufficiently accurate for guiding a vehicle over rough terrain until recently, because of the time delay caused by the signal's travel to the satellite and back. Moreover, positioning systems using GPS need assisting devices (gyro, compass or accelerometer) in order to decrease the error (Thuilot et al. 2001). The fact that any of these sensor techniques has advantages and disadvantages in comparison to each other, means that positioning a land vehicle by combining more than one technique will aide in eliminating the disadvantages of each technique. This will provide more accurate sensor systems for all-terrain mobile robots.

1.10. Current Conventional Sensor Systems

1.10.1. Vision System

The vision system consists of a video camera and a computer unit to process the captured images. While this system is locating the position of the robot, it can also measure the position of the objects in the image frame. Therefore, when comparing the image to a pre-defined pattern, the system can recognize the scene or the object itself. Moreover, vision is the only system which can recognize the color of the object.

On the other hand, extracting useful information from images is a difficult task considering that the system has to deal with natural objects under natural lighting conditions. Moreover, high-power computers are required for complicated images. The success of measuring the depth of objects from one frame of image is not sufficient for precise positioning, especially when the blurring due to vibration is considered. Since processing images mainly depends on color and contrast difference in the image frame, the accuracy of vision systems is mixed and usually depends on the application.

1.10.2. Laser System

The laser system depends on the evaluation of reflected laser beams, which are emitted by a unit mounted on the mobile platform. One of the biggest advantages is its simplicity in terms of the principle and the application. In addition, conventional laser systems are very common as measurement devices in industry so this availability means that various types are accessible at a comparatively low cost. Furthermore, the main advantage of this sensor system is that it is not affected by lighting conditions. Nevertheless, laser systems which rely on a vehicle mounted laser have a significant drawback when used on rough terrain. The tilt of the mobile platform of robot may cause the laser beam to miss the targets, unless the beam is diverged vertically. This divergence seriously reduces the practical operating range since the output power is limited by the need for the system to be eye-safe (Hague et al. 2000). Also, a high amount of dust or fog can interfere with the system.

1.10.3. Radar System

Radar is used for measuring the distance of a vehicle to natural and artificial landmarks or objects in an outdoor field. The working principle in robotic applications is very similar to those used in naval applications; radar signals are emitted, and then reflected from the objects. Common radar applications apply some artificial reference landmarks, which are set on fields and define the position of vehicle by triangulation of their distances to the EOD robot (Hague et al. 2000).

One of the most important advantages is that a range of a few hundred meters can be achieved, despite the fact that the beam is being diverged vertically to accommodate a small degree of vehicle tilt. Also, radar systems are less susceptible to climatic disruption than optical sensory systems.

1.10.4. Sonar System

Sonar sensors emit sound waves and measure the time of flight between the sensor and the object. By computing this flight time, the distance can be found easily because of the fact that sound waves move with a constant speed in the air. In most applications sound waves are emitted frequently and the calculations focus on the time it takes the sonic waves to reach a reflective surface and come back to the receiver part of the sensor.

Depending on the type of pulse emission, different types of objects can be recognized by evaluating the frequency spectrum of waves reflected from the object (an experimental system can recognize four different types of trees). As another advantage, common ultrasonic sensors are inexpensive and widely used in industrial applications.

However, these sensors are sensitive to air movement and ambient ultrasonic noise, a great deal of which may be generated by the robotic vehicle itself. Also, data refreshing time is low for high distances because of the pause for time of flight calculations.

1.10.5. Global Positioning System (GPS)

GPS measures distance using the travel time of radio signals from the satellites in the earth's orbit to the GPS device on earth and the position is calculated by a triangulation method. In order to measure accurate travel time and position, the GPS device should be locked to at least four satellites.

Moreover, in order to achieve higher accuracy than that obtained by a regular GPS device advanced systems called Differential GPS (D-GPS) and Real-time Kinematic GPS (RTK-GPS) can be used. These systems use a beacon station on the earth's surface to compare the information received from satellites so that the errors caused by environmental effects can be reduced (Romans et al. 2000). The accuracy increases as the distance between the vehicle and the beacon station decreases.

The need for a number of beacons, which are required for laser and radar systems and the difficulty of positioning them in a precise geometry, is eliminated and centimeter level accuracy is provided with D-GPS or RTK-GPS. These systems are not affected by vibration, sound and vehicle orientation. Also, for advanced devices, it may be assumed that weather conditions will not impair their efficiency.

Since GPS technology requires no reference information from the ground, the problems related to wheel slippage will be overcome easily.

However, time delay caused by signal processing to determine the location and orientation challenges the control system at high field speeds (Wilson 2000). In addition, the system is affected by the presence of buildings, trees or steeply rolling terrain, and interruption in satellite or differential correction signals. Also, since it uses absolute coordinates instead of environmental information, assisting devices are required for accurate measurement in vertical coordinates, which means some extra cost and processing time.

Table 1.2. Comparison of sensor systems capability.

	Vision	Laser	Radar	Sonar	GPS
Pit, cavity, negative height recognition	Y	Y	N	Y	N
Positive height obstacle recognition	Y	Y	Y	Y	N
Affected by rain, fog, dust	Y	Y	N	N	N
Affected by tilting	N	Y	N	N	N
Affected by vibration	Y	N	N	N	N
Affected by sound (noise)	N	N	N	Y	N
Object identification	Y	N	N	Y	N
Precise sensor geometry requirement	N	Y	Y	Y	N
Beacon requirement	N	Y	Y	N	N
Availability on market	Y	Y	N	Y	Y
Distance measurement	N	Y	Y	Y	N

Y: Yes, N: No

Table 1.3. Comparison of sensor systems qualifications.

	VISION	LASER	RADAR	SONAR	GPS
Data refreshing time	1	2	2	2	3
Processing time	1	2	1	2	1
Cost	1	1	2	1	3
Accuracy	2	1	1	2	2
Range	2	3	2	3	1

1: lowest cost, fastest time, high accuracy, highest range;

3: highest cost, slower time, low accuracy, lowest range

1.11. Environmental Sensor System Related Problems

Natural conditions are obviously the most challenging problems encountered in all-terrain mobile robot applications. Because weather conditions can rapidly change and dramatically vary even between two sections of a field, most of the robotic experiments and applications focus on the solution of a limited number of outdoor problems and others assume ideal conditions. The main problems encountered by an all-terrain mobile robot can be summarized as follows.

1.11.1. Paddles

Natural pits filled with water because of weather conditions can create obstacles when they are not previously detected. When using conventional type sensors, the water surface is recognized as a flat plane containing no obstructions and in this situation, the vehicle advances and falls into the pit. The problem occurs when the depth of the water may exceed the allowable value for the vehicle to operate (Figure 1.9.)

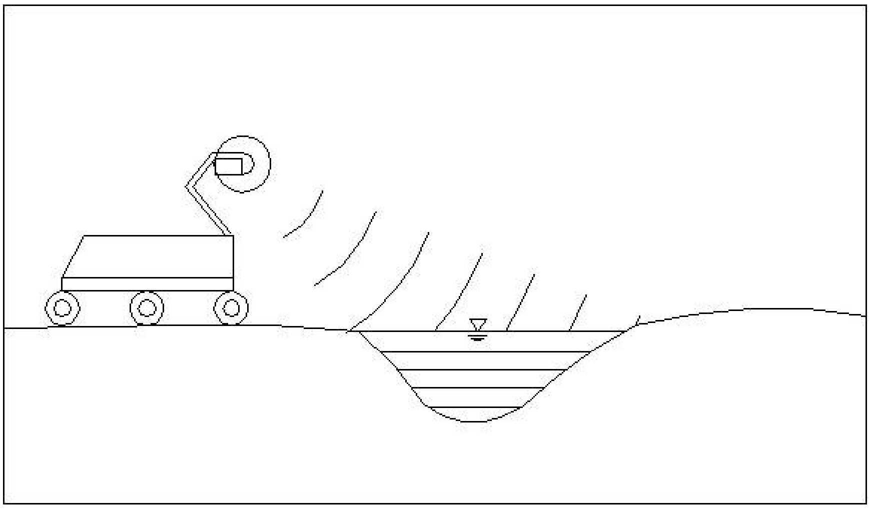

Figure 1.9. Natural pit filled by water on the way of the vehicle.

1.11.2. Shading

Many outdoor tasks including searching, finding and recognizing the target occurs in a complex medium. Some features of the object itself may shade the target, or it may not have a distinct shape and color.

1.11.3. Sensor Tilt

Outdoor fields are unstructured so they have rough surfaces, which cause sudden changes in orientation and altitude. When the sensor is mounted on the vehicle with a specific geometry and direction, change in the vehicle orientation causes change in the geometry of sensors with respect to the ground, which will result in the sensors missing the target which can be either a beacon or an obstacle (Figure 1.10.).

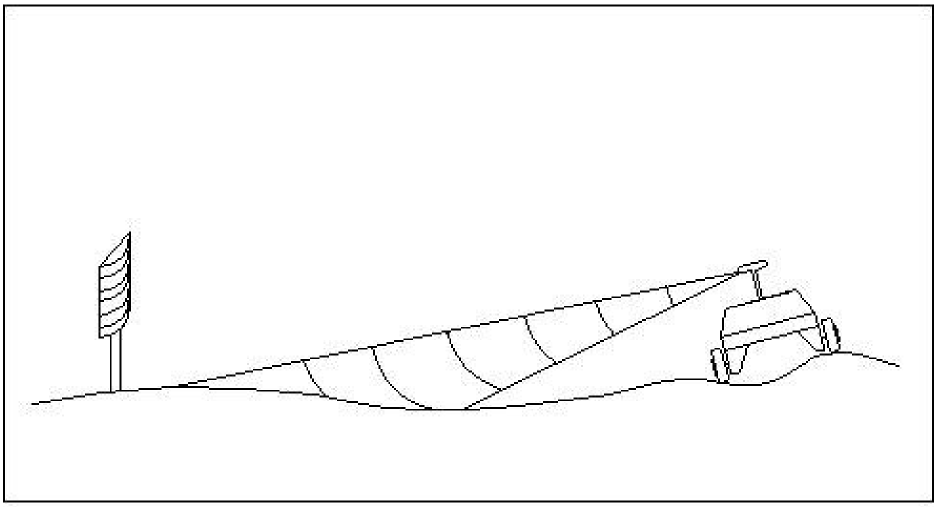

Figure 1.10. Signal is interrupted because of sensor tilting in rough surfaces.

1.11.4. Lighting

The outdoor areas are usually under the effect of natural lighting conditions defined by the position of the sun. However, natural conditions may rapidly change and cause unpredictable situations. For example, a cloud passing over the vehicle on a sunny day affects the vision sensor whose settings are done for daylight conditions.

1.11.5. Weather Conditions

Heavy rain, a thick layer of fog and excessive dust which often behave like a curtain between the sensor and the target, prevent the laser or radar signals from passing. In addition, the systems using visual information are also affected by heavy weather conditions.

1.11.6. Slippery Terrain

The surface of the terrain may be loose or slippery, which causes the odometric sensors to read faulty measurements when the measurement is done by tracking the wheels of the vehicle or a separate sensor wheel.

1.11.7. Vibration

Since the outdoor fields are unstructured and naturally formed, the irregularities in the surface of the field causes vibration which affects the systems using visual information and the result is blurring on the captured image.

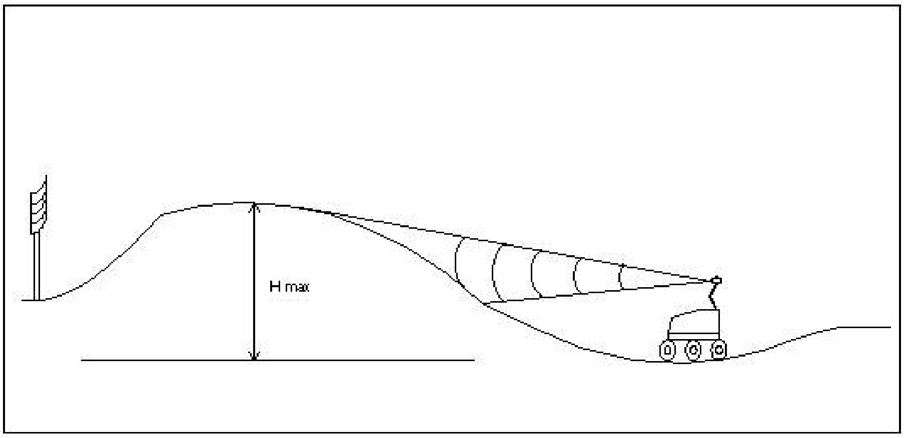

Figure 1.11. Height difference in topography hinders signals to/from the beacon.

1.11.8. Beacons

In some fields, because of the large number of trees or rapid changes in altitude, the communication with the reference points, which defines the position of vehicle with respect to the field, may be interrupted or lost. This is the dilemma created when using sensor systems requiring beacons. For many systems, the maximum height difference of the field should not exceed 2 meters to operate properly (Figure 1.11).

CHAPTER 2

SYSTEM ELEMENTS

The robot is comprised of three main sections which are a mobile platform, a manipulator arm and a gripper (Figure 2.1). The reason for such a classification is that each of these sections is controlled independently during an EOD operation.

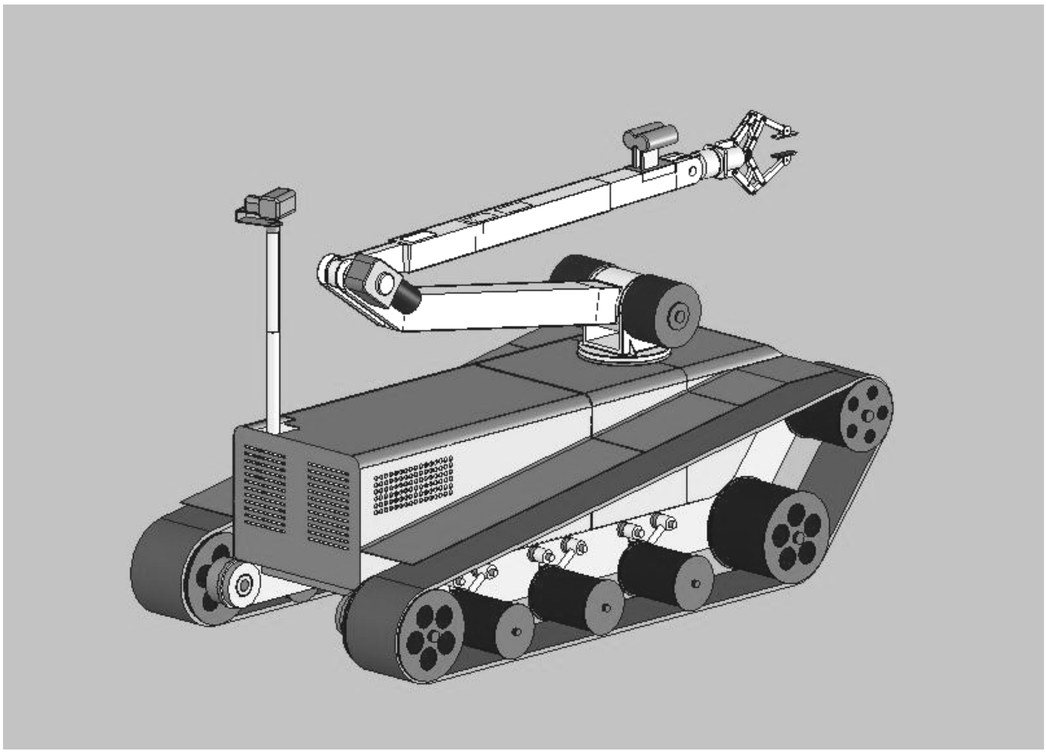

Figure 2.1. The EOD Robot.

2.1. Mobile Platform

This section is the main body of the robot, which is moved on rubber tracks driven by electric powered motors. Since tracks have high traction characteristics on rough terrain compared to wheels, the robot is designed to have tracks. Moreover, the vehicle has high maneuvering ability due to the motion principle of tracks. The 150mm wide rubber tracks are the same as the ones used by conventional light-duty loader vehicles so they can be easily supplied from the market.

The tracks are wound around two 200 mm wheels and one 160mm sprocket wheel which is placed at the front. Three additional wheels including suspensions provide permanent contact with ground and increase traction on rough and slippery terrain (Figure 2.2).

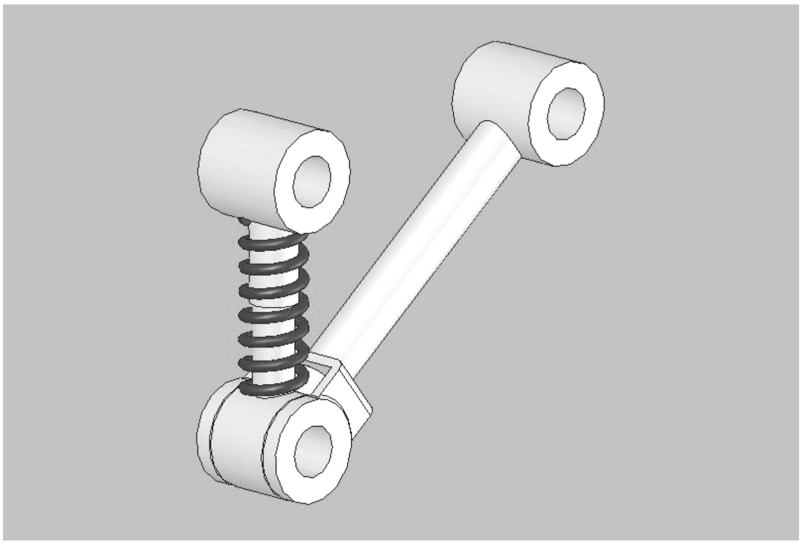

Figure 2.2. Suspension mechanism of assistant wheels.

The sprocket of each track is powered by an independently driven electrical motor providing high maneuvering characteristic at limited volumes (Figure 2.3). Each of the motors has an output torque of 15 Nm which is transmitted to the sprocket wheel by a heavy duty gear box having 1:15 reduction ratio. Being powered by this motor and gearbox configuration, the robot is capable of climbing inclined surfaces of more than 45° and reaching up to a speed of 3 km per hour. Since higher velocity is not necessarily required for EOD tasks, high reduction rate gear boxes are used to provide high output torques from moderate motor powers.

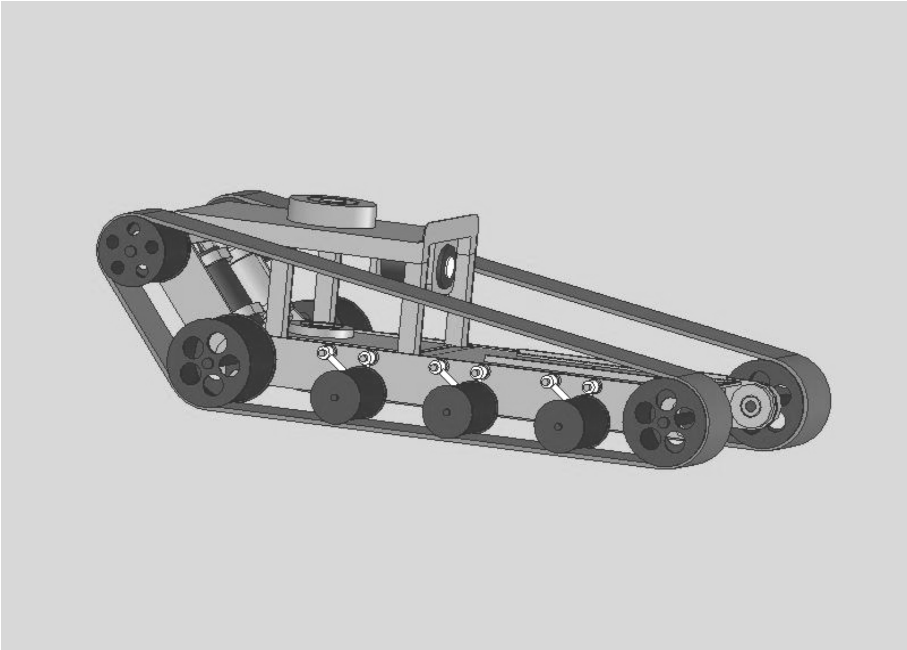

Figure 2.3. Tracks and driving motors.

Obstacles measuring up to 0.28 m in height can be passed without any difficulty. It is also possible to drive up or down stairs and slopes with inclines of up to 40°, as long as the traction between the stairs and the tracks is sufficient. Since the vehicle has a compact size and can climb stairs, the vehicle can pass through doors and operate in buildings and other confined areas.

Most of the body mass of the mobile platform is placed between the tracks keeping the center of gravity as low as possible. As a result of this design, the front and rear downhill gredability is up to 45°; cross-hill gradability is 42° having if the manipulator arm folded (Figure 2.4). The position of batteries on the robot also increases stability when the manipulator arm is fully extracted forward. When the arm is fully extracted forward gripping a load of 10 kg, front downhill greadability is 32º. On the other hand, during an operation with the manipulator fully extracted to sideways, the robot keeps its lateral stability up to the inclination of 33º.

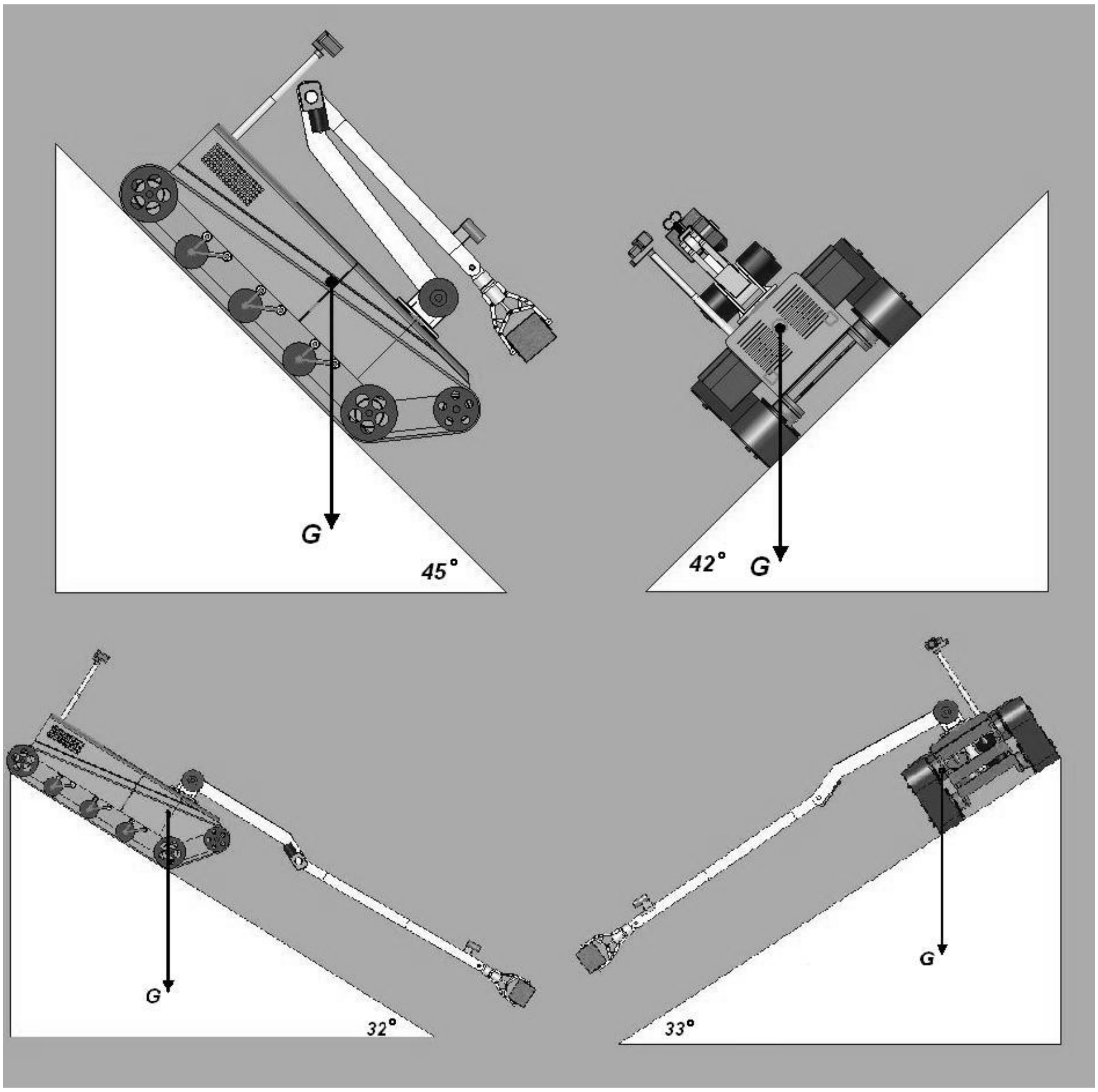

Figure 2.4. Stability of the EOD robot on inclined surfaces.

Besides the drive units and transmission, the main body of the mobile platform contains electronic circuits, laptop, batteries, a tele-operation unit and a vision system. The power needed for electric motors on the robot is supplied by two tractional type conventional gel batteries, which are commonly used for electrical loaders. Batteries can be slid out from the back part of vehicle without removing the body panels avoiding the necessity of moving the arm to a suitable position and lifting the batteries each of which weighs approximately 36 kg (Figure 2.5).

The weather-proof body of the EOD Robot is the result of 2mm-thick sheet metal panels which can be removed easily for quick intervention to internal sections.

The electronic parts such as the remote control unit, the computer and the electronic circuits are also enclosed by separate cases inside the body for maximum protection in rough environmental conditions.

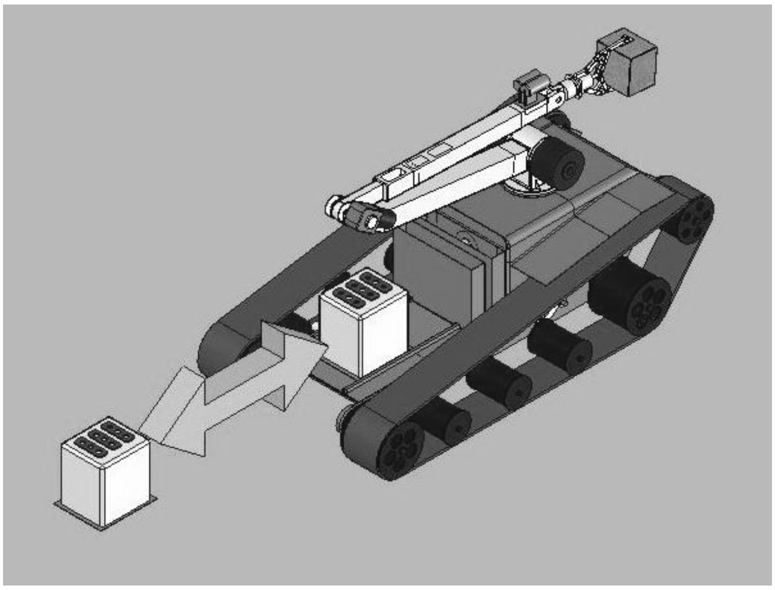

Figure 2.5. Batteries slide out for quick replacement.

2.1.1. Power supply

The power for the electric motors on both the mobile platform and the manipulator sections are supplied by two tractional type gel batteries. Considering an operation time of 2 hours and the unsteady working conditions, heavy-duty type batteries which are chosen similar to the ones commonly used in conventional electrical loaders. According to the power consumption ratings of the motors, the robot is equipped with two batteries each of which has the power supply rate of 500 Ah. The gel type batteries are very suitable for continuous power supply. The robot is included with a charging unit, which eliminates the necessity of removing the batteries.

2.1.2. Cameras

The robot includes two high resolution color cameras; a wide-angle zoom camera mounted on the rear side of the chassis, and a smaller detail camera mounted close to the end effector for a detailed view of the task. The scene of the task space, received from both cameras, is displayed on a laptop monitor at the control base and the images can be switched depending on the requirements of the operation.

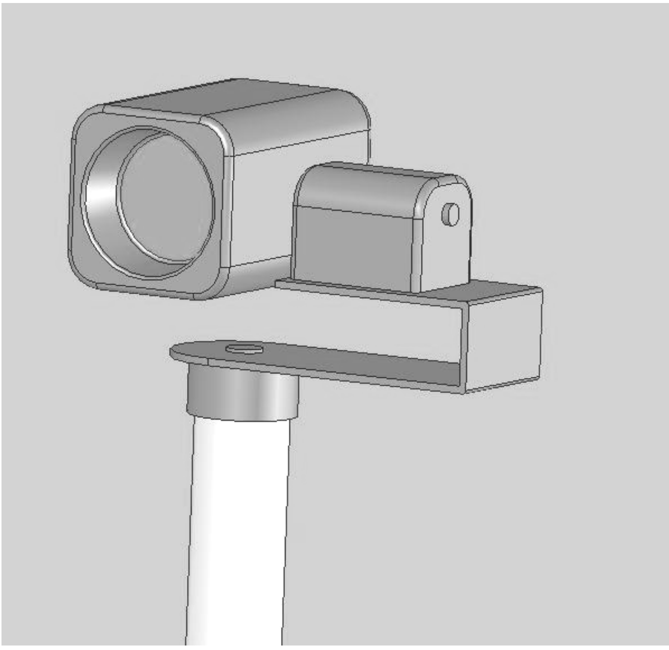

Figure 2.6. Main view camera.

The main camera is mounted on a telescopic turret on the back-side of the chassis for viewing both the mobile platform and manipulator arm (Figure 2.6). The turret has a vertical telescopic stroke of 400 mm and the camera is designed to rotate on a horizontal and vertical plane. This 3 degree of freedom motion characteristic of the main camera provides remarkable versatility during operation. Since the camera is controlled independently from the motion of mobile platform and manipulator, the operator can move the camera to change the looking angle of the target when the visual information is interrupted by an obstacle, which may be even the moving manipulator itself. The main camera is equipped with a night vision system to operate in darkness where the circumstances prohibit the usage of lights. The camera control will also be equipped with a “follow” function so that when the manipulator arm is moved, the camera will follow the gripper.

Details of the EOD process are monitored according to the visual information collected by the detail camera attached to the front section of the manipulator arm (Figure 2.8). The detail camera has a fixed position at the end of the manipulator arm and the viewing angle is directed to the effective task space of the gripper.

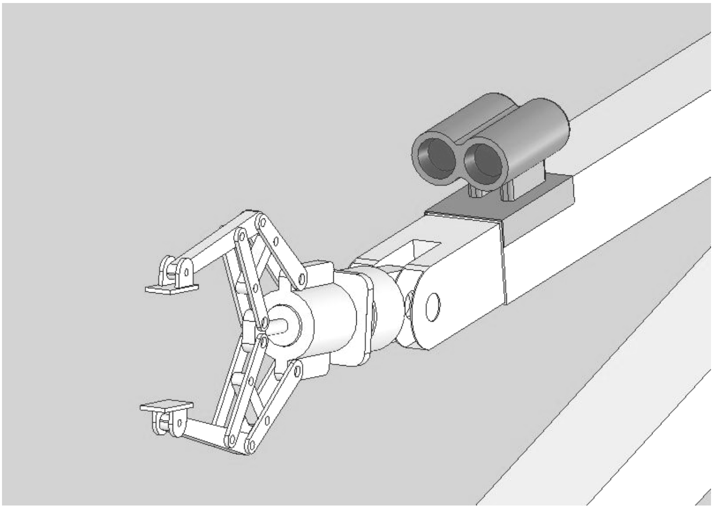

Figure 2.8. Detail camera

2.2. Manipulator Arm

2.2.1 Operation Principle

The manipulator mechanism of the robot can be classified in two sections according to the control mechanism; the arm and the gripper. The manipulator arm is the task space controlled part of the EOD system. The motion of the arm is provided by four electric motors and the angular rotation or linear extension is controlled by optical encoders. Being controlled in task space, the end point of the manipulator arm follows a smooth trajectory. Once the end point of the arm which is also the connection point with the gripper joint is moved to the desired position, the operator actuates the motors on the gripper to accomplish the EOD task. Each motor on the gripper is controlled independently from the other motors on the gripper and also those on the arm.

According to the task space controlled operation principle, the operator just defines the desired position of the end point of the arm by looking at the cameras and then the motion of manipulator arm is controlled by the laptop on board. After the coordinates of the target position are located, the rotation angles of joint motors on the manipulator arm are calculated by the computer and the arm is moved to position the gripper. The motion of the links and joint rotations are controlled by sensors at each joint and errors are compensated by the adaptive control algorithm of the computer program. Moreover, the control system can simply evaluate the priority of joint motions in terms of precision, speed and power consumption in order to work more efficiently.

The reason for limiting the task space controlled operation only to the arm instead of the whole manipulator system is due to the difficulty of controlling a manipulator having a redundant number of joints and also readjustment of control parameters for different gripper types.

2.2.2. Mechanical Properties of Manipulator Arm

The manipulator arm is responsible for precisely locating the end effector to the desired position. The arm has a capacity of handling materials up to 10 kg and a maximum reach of 2 meters at the full extended position (Figure 2.9). This property provides an advantage to the robot in special situations where the mobile platform cannot move further because of its size. For the cases that the explosive material's weight or size is beyond the arm's handling capacity, the robot can pull the material to a safer area. However, in the case that the operation condition allows the robot to manipulate the object from a distance closer than 2 meters, the robot's lifting capacity increases favorably. An illustration for the lifting capacity of the robot according to the object distance is shown in Figure 2.10.

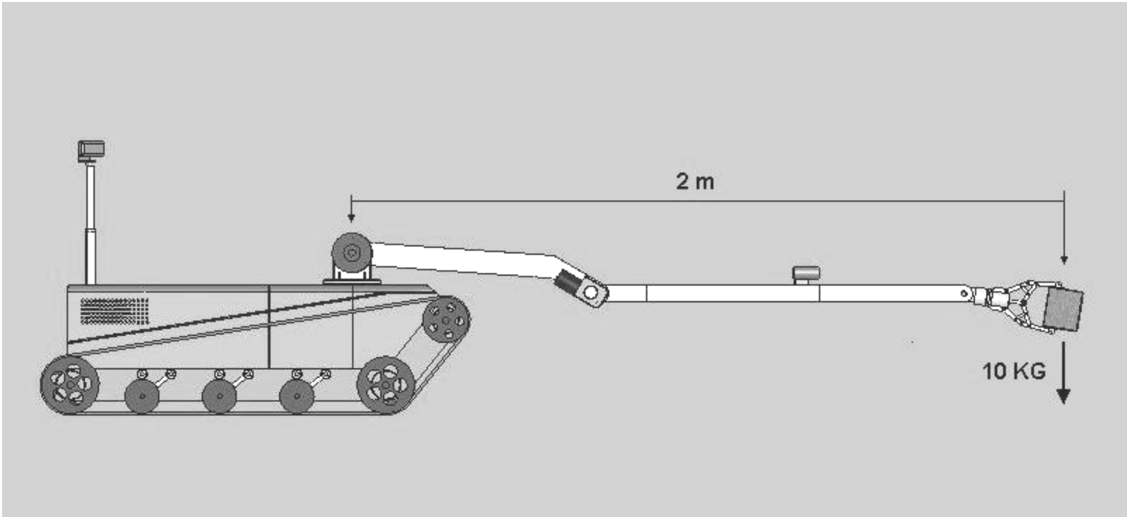

Figure 2.9. Extension capacity of the manipulator arm

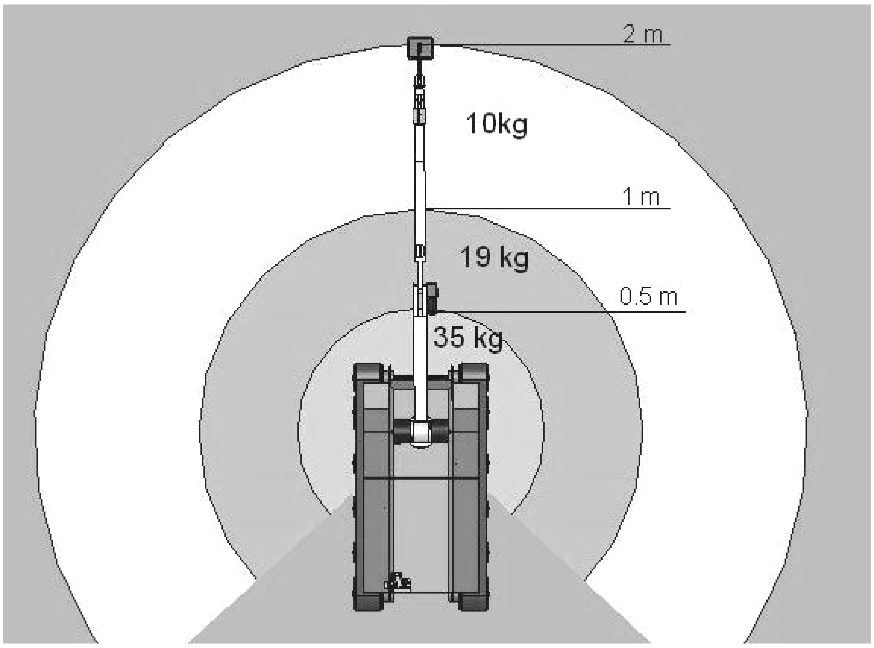

Figure 2.10. Load capacity zones of manipulator

The manipulator arm is composed of 3 main sections; a turret, a back arm and a fore arm. The turret provides the rotation of the arm on a horizontal plane and is designed to sweep 360 degrees. The shoulder joint and related joint motors are also integrated to the turret. The shaft of the turret is attached to the chassis by two thrust bearings. Since the shoulder joint of the back arm link requires the highest torque for the motion of the arm on a vertical plane, this joint is actuated by two identical motors including high ratio reduction-gear boxes.

The extensible telescopic fore arm link is composed of two sections, one of which slides inside the other through a linear joint extending 400 mm. The main purpose of designing a linear joint is to increase the manipulator's versatility in such cases that the EOD operation takes place in a narrow place where there is no sufficient space for the rotational motion of links. This feature provides the user with numerous additional advantages when manipulating objects, such as; the insertion of keys into keyholes, the direct usage of tools during operation (e.g. an electric drill), and an especially long reach in hard-to-access areas (i.e., under a vehicle).

The manipulator arm and the mobile platform are designed to be capable of performing EOD tasks as the manipulator is extracted forward, upward or sideways (Figure 2.13). In addition, depending on the requirement of the EOD operation, the manipulator can operate backwards. When the manipulator arm is not used and during transportation, the arm is folded to take up less space and increase stability. The height of the robot is approximately 700 mm for the folded configuration of the arm, excluding the additional height of the parts of the vision system.

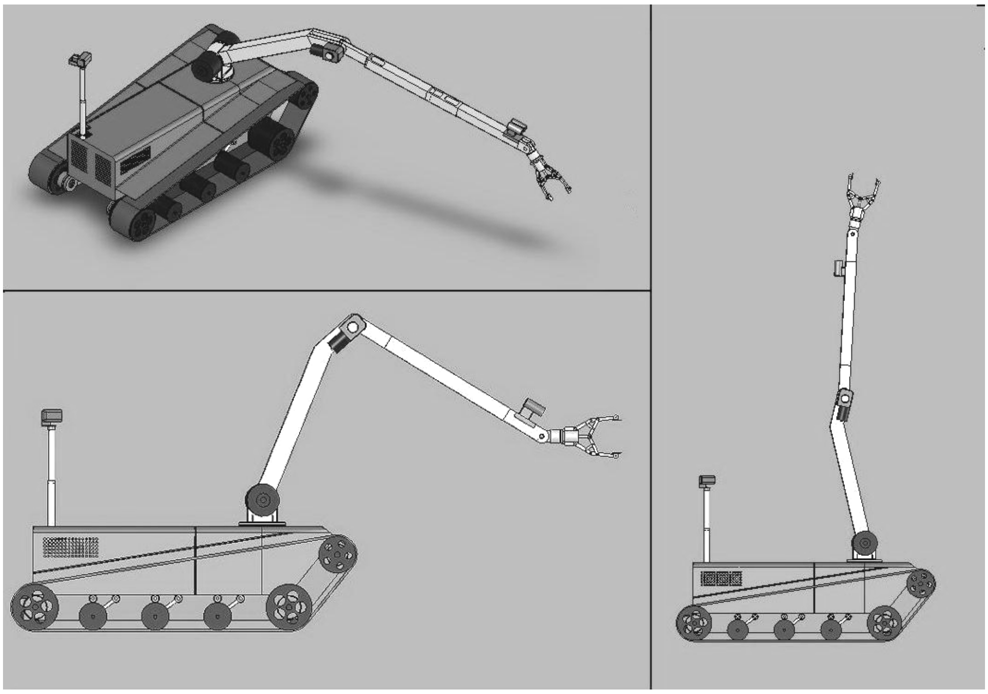

Figure 2.13. Different arm configurations of EOD robot.

A CCD camera is placed on the fore arm, close to the gripper to get a detailed view of the operation scene. Simultaneous usage of this camera and the main camera provides detailed information about the task performed by the arm and the gripper.

2.3 Gripper (End Effector)

The gripper parts are the end effector of the whole system which is designed to accomplish the special EOD tasks. There are 4 types of grippers for different purposes which are attached to the manipulator arm with a multi-purpose changeable joint. The gripper is controlled independently from the manipulator arm, so that the operator does not struggle with the less sensitive, higher powered joint motors of a manipulator arm. The gripper control is activated after the manipulator reaches the desired position.

2.3.1. General Purpose Gripper with 2 Jaws

The robot has a general purpose 2 jaw gripper for basic material handling tasks (Figure 2.14). The gripper is designed to hold 15 cm wide materials with a maximum weight of 10 kg. The gripping force which is supplied by a linear actuator, is transferred and increased by a simple four bar link mechanism, rubber coverings are used in order to increase friction at the touching surface of the tips of the gripper. The gripper has three degrees of freedom and is controlled independently from the control of the arm.

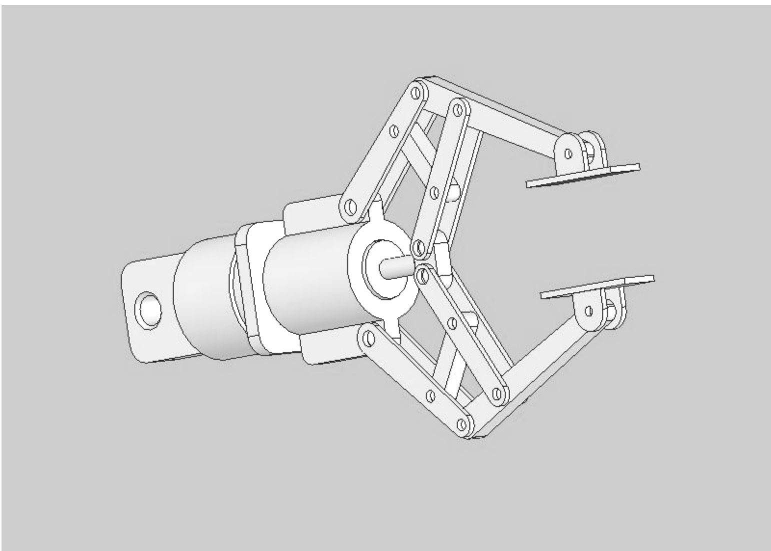

Figure 2.14. General Purpose gripper with 2 jaws.

2.3.2. Cylindrical Object Gripper with 3 Jaws

This type of gripper is designed to handle cylindrical objects (Figure 2.15), since many explosive materials have cylindrical shapes, such as bombs, landmines, and triggering mechanisms of some unexploded ordnances. The 3 jaw gripper can support a cylindrical object from every direction and provide higher friction. The gripper is able to rotate 360 degrees about its own axis which enables unscrewing cylindrical parts such as disintegrating an unexploded bomb's triggering mechanism (Figure 2.16).

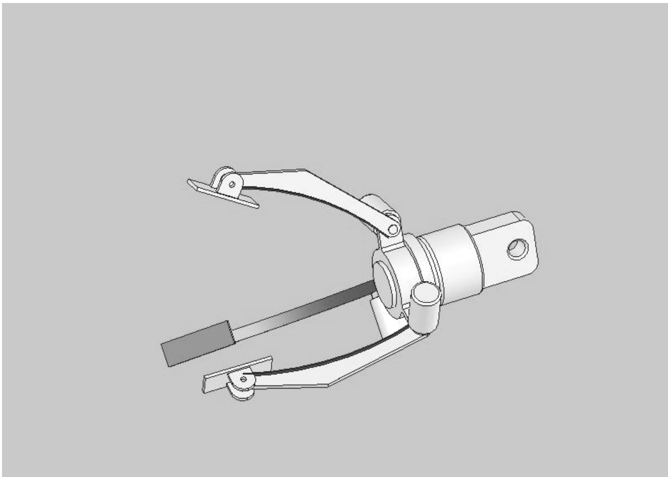

Figure 2.15. Gripper with 3 jaws.

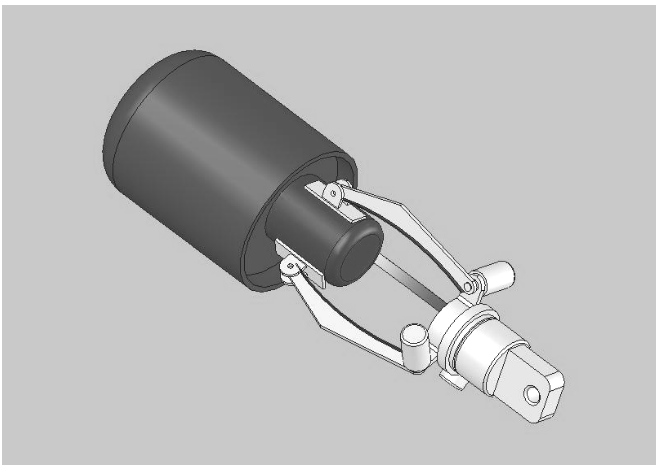

Figure 2.16. Removing the triggering mechanism of an unexploded bomb.

2.3.3. Screwing Apparatus

Most of the explosive mechanisms are placed in a shell in order to minimize the possibility of external intervention as well as the environmental effects. In many cases, bomb technicians use a common screw apparatus to remove the shell which involves taking great risks. In order to eliminate the risk of screw or bolt handling on explosive mechanisms, the EOD robot is equipped with a special end effector which includes different screwdriver heads, so that the screws on the explosive ordnance can be tightened or loosened. The gripper head includes phillips and slotted screwdriver tips and an adjustable wrench for bolts (Figure 2.17).

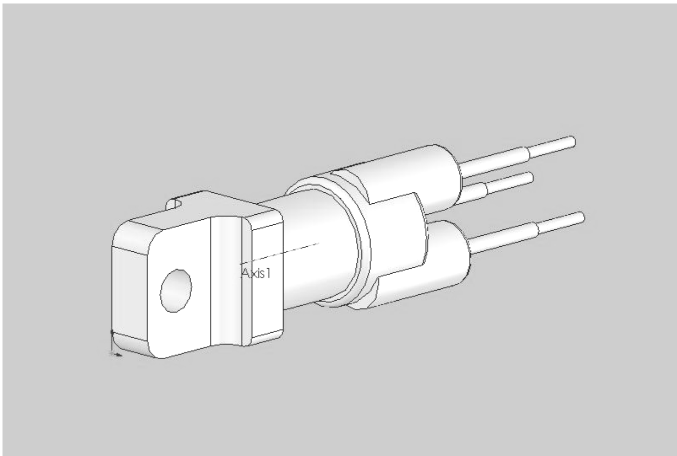

Figure 2.17. Screwing apparatus.

2.3.4. Cutting Apparatus

Depending on the position of the target object, manipulation of the objects can be obstructed by a material such as a wooden box or metal shell. Also, some cases may require that obstructing materials should be removed away in order to clear the operation area. In such cases, the end effector, equipped with a cutting blade which is similar to conventional types, cuts out the obstructing material which is preventing the manipulator from reaching the explosive ordnance (Figure 2.18). The linear motion provided by the telescopic joint on the manipulator arm, is very advantageous when performing the cutting task.

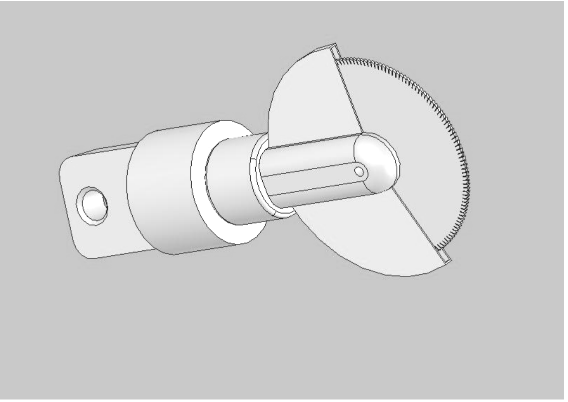

Figure 2.18. Cutting apparatus with a circular blade.

CHAPTER 3

KINEMATIC ANALYSIS OF THE MANIPULATOR ARM

The work space of the arm and calculation of joint parameters for positioning the end effector are provided by kinematic analysis. At this point, there appear to be two types of kinematic analysis; direct kinematics and inverse kinematics. Direct kinematics is simply the method of calculating equations of the end effector position for the given joint parameters. On contrast, by inverse kinematic analysis, the equations of joint parameters are found according to the end effector position (Crane III., 1998).

3.1. Direct Kinematic Analysis of the Manipulator Arm

Although the EOD robot is designed to be controlled in task space, the forward kinematic analysis should be calculated in order to define the link and joint positions and motions which are needed to calculate dynamic analysis of the manipulator arm. Moreover, direct kinematic analysis is applied for obtaining the error between the real position and desired position of the gripper as feedback (Sciavicco, 2003).

For the purpose of calculating the direct kinematic analysis, the robot is thought of as a set of rigid links connected together at various points and the Denavit-Hartenberg Method is used. The Denavit-Hartenberg Method provides a representation of positions of link frames relative to each other by two rotations and two transition matrix transformations. According to this method first, link parameters are defined and the transformation matrices are formed according to these parameters (Table 3.1). The values of position and orientation of the end effector relative to the base frame are calculated by the multiplication of these matrices (McKerrow, 1991).

Table 3.1 Denavit-Hartenberg parameters of the manipulator arm.

	θi	αi	ai	di
Link 1	θ_1	90	0	0
Link 2	θ_2	0	l_2	0
Link 3	θ_3	90	0	l_3
Link 4	0	0	0	l_4

According to the parameters listed in Table3.1., the D-H transformation matrices are found as follows;

$$ {}^{R}A_1 = \begin{bmatrix} Cos\theta_1 & 0 & Sin\theta_1 & 0 \\ Sin\theta_1 & 0 & -Cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.1} $$

$$ {}^{1}A_2 = \begin{bmatrix} Cos\theta_2 & -Sin\theta_2 & 0 & l_2 Cos\theta_2 \\ Sin\theta_2 & Cos\theta_2 & 0 & l_2 Sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2} $$

$$ {}^{2}A_3 = \begin{bmatrix} Cos\theta_3 & 0 & Sin\theta_3 & l_3 Cos\theta_3 \\ Sin\theta_3 & 0 & -Cos\theta_3 & l_3 Sin\theta_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.3} $$

$$ {}^{3}A_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & (\frac{h}{2} - l_4) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.4} $$

where A_1, A_2, A_3 and A_4 are the transformation matrices of frames attached to joints 1, 2, 3 and 4 respectively. The parameters l_2, l_3, refer to lengths of link 2 and link 3, while l_4 *and* h refer to the extension length and the total length of link 4respectively. The position and orientation of the end frame according to the reference frame, which is the center of rotation at the shoulder joint for the EOD robot's manipulator arm can be found by multiplication of these matrices as;

$$
{}^{R}T_4 = \begin{bmatrix}
C\theta_1 C\theta_2\theta_3 - S\theta_2 S\theta_3 & S\theta_1 & C\theta_1 S(\theta_2+\theta_3) & \begin{pmatrix} \frac{1}{2} C\theta_1 (2C\theta_2 l_2 + 2C(\theta_2+\theta_3) l_3 \\ - S(\vartheta_2 + \vartheta_3)(h - 2l_4)) \end{pmatrix} \\
S\theta_3 C\theta_2 C\theta_3 - S\theta_2 S\theta_3 & -C\theta_1 & S\theta_1 S(\theta_2+\theta_3) & \begin{pmatrix} \frac{1}{2} S\theta_1 (2C\theta_2 l_2 + 2C(\theta_2+\theta_3) l_3 \\ - S(\theta_2 + \theta_3)(h - 2l_4)) \end{pmatrix} \\
C\theta_3 S\theta_2 + C\theta_2 S\theta_3 & 0 & -C(\theta_2+\theta_3) & \begin{pmatrix} S\theta_2 l_2 + S(\theta_2+\theta_3) l_3 \\ + \frac{1}{2} C(\theta_2+\theta_3)(h - 2l_4)) \end{pmatrix} \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (3.5)
$$

The representations $C\theta_i$ and $S\theta_i$ refer to $Cos\vartheta_i$ and $Sin\theta_i$ respectively. The 3x3 part of the transformation matrix formed by the elements included in the first 3 rows of the first 3 columns defines the orientation of the end frame while the 3x1 matrix formed by the first three rows of the 4th column defines the position.

3.2. Inverse Kinematic Analysis of Manipulator Arm

Since the EOD robot is controlled in task space, correct evaluation of inverse kinematic analysis has a vital importance in order to compute the correct joint parameters. However; this task becomes complicated as the number of links and joints increase.

The arm consists of three revolute joints and one prismatic joint each having one degree of freedom. The total degrees of freedom of the manipulator arm is 4 for the manipulator arm, excluding the end effector and mobile platform. Considering the platform of the robot stands on a flat horizontal surface, one of the revolute joints moves on a horizontal plane and two of them on a vertical plane.

For the task of positioning an object, a Cartesian coordinate frame is considered, a manipulator with 4 degrees of freedom brings a redundancy problem during the positioning of the end effector. However, considering the versatility provided by this additional linear joint, the control problem caused by this redundancy is justified.

The task space control requires the joint rotation angles according to a desired end effector position. Therefore, an inverse kinematic analysis should be applied. The inverse kinematic analysis task can be defined briefly as obtaining the joint angles for a given position of the end point. During the operation of the robot, the inverse kinematic calculations are performed by the computer on-board.

Since the manipulator arm is composed of 4 serial links and the configuration is relatively simple, a trigonometric approach is applied to complete the inverse kinematic analysis of the manipulator arm (Sponge and Vidyasagar, 1989).

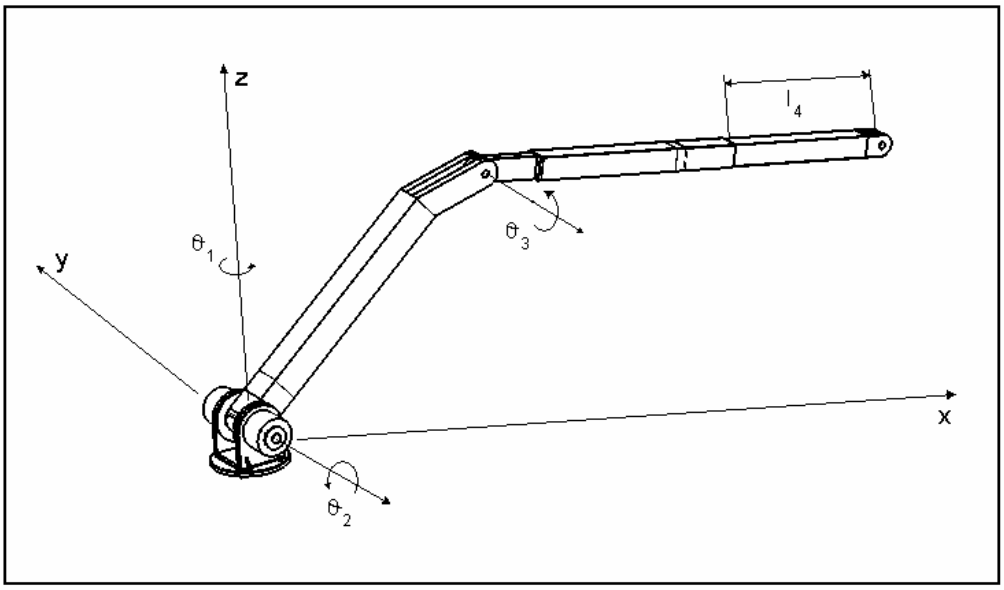

Figure 3.1. The motions of manipulator arm joints.

In order to ease the calculation of θ_1, θ_2 and θ_3 angles and l_4 distance which bring the end point of the arm to the desired position, the angles α, β and $\emptyset$ and distances r_1 and r_2 are introduced (Figure 3.2.).

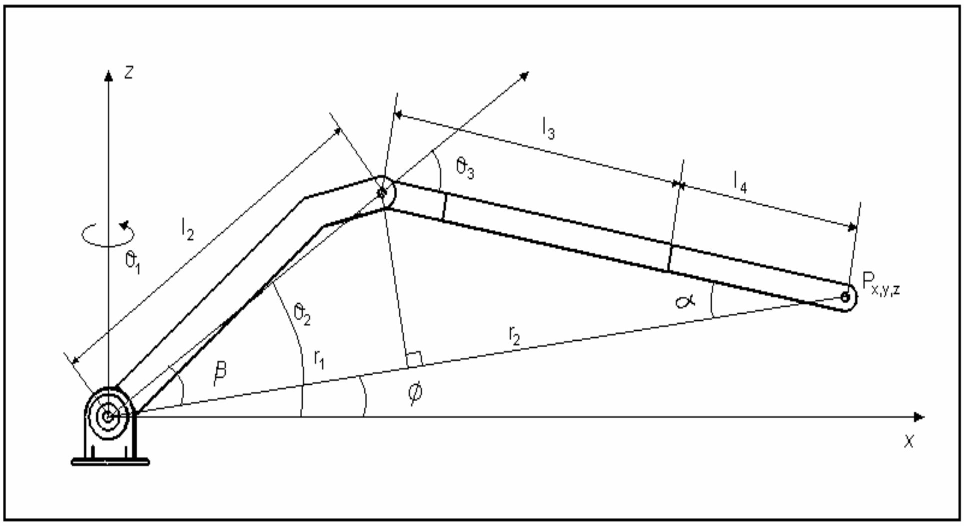

Figure 3.2. The assistant angles and distances used for kinematic analysis

After the kinematic calculations according to the method stated above, the kinematic equations which define the motion of each joint in order to position the end point of the manipulator arm are stated as follows.

$$\theta_1 = \tan^{-1}\left(P_y / ((l_2 x \cos\theta_2 + (l_3 + l_4)\cos\theta_3)^2 - P_y{}^2)^{1/2})\right) \tag{3.6}$$

$$\theta_2 = \phi + \beta \tag{3.7}$$

$$\theta_3 = \phi - \alpha \tag{3.8}$$

$$l_4 = (P_{xy} - l_2 x \cos\theta_2 - l_3 x \cos\theta_3) / \cos\theta_3 \tag{3.9}$$

The variables θ_1, θ_2, θ_3 and l_4 show the joint parameters. The variables l_2 and l_3 show the link lengths and P_{xy} refers to the projection of the end point of the arm in the xy plane, while P_y refers to the projection of P_{xy} on y axis.

The other assistant parameters α, β and $\varnothing$ are defined as follows.

$$\alpha = \tan^{-1} \pm \left(((l_3 + l_4)^2 - r_2^2)^{1/2} / (l_3 + l_4)\right) \tag{3.10}$$

$$\beta = \sin^{-1}(\sin\alpha . l_2 / l_1) \tag{3.11}$$

$$\phi = \tan^{-1}(P_{x,y} / P_z) \tag{3.12}$$

where P_z defines the projection of end point of manipulator arm on the z axis.

The "±" symbol which belongs to α angle shown above in the assisting angle equation states that for any position of the end point of the manipulator arm apart from singularity points, there appear to be 2 different solutions as the length l_4 is maintained.

The assistant parameters r_1, r_2 which are used to calculate the assisting angles, are formulated as follows.

$$r_2 = \frac{({P_{xy}}^2 + P_z + l_2^2 - (l_3 + l_4)^2)^2}{2({P_{xy}}^2 + P_z)} - (l_2^2 - (l_3 + l_4)^2)^{1/2} \tag{3.13}$$

$$r_1 = \left(\frac{({P_{xy}}^2 + P_z + l_2^2 - (l_3 + l_4)^2)^2}{2({P_{xy}}^2 + P_z)} - (l_2^2 - (l_3 + l_4)^2)^{1/2} \right) - ({P_{xy}}^2 + P_z^2)^{1/2} \tag{3.14}$$

CHAPTER 4

DYNAMIC ANALYSIS OF THE MANIPULATOR ARM

In order to control the manipulator arm of the EOD robot in task space, the dynamic analysis of the arm should be calculated and the generalized force equations should be obtained according to the robot configuration. The dynamic analysis in this study is accomplished by Lagrange formulation method.

The Lagrangian formulation describes the dynamic behavior of a robot in terms of the work done by, and energy stored in the system. The arm is treated as a black box that has an energy balance. The constraint forces are eliminated during the formulation of the equations. As with Lagrangian dynamics, the closed-form equations can be derived in any coordinate system.

According to Lagrange method, kinetic energies of all the links of the manipulator arm are summed and the difference between the potential energies is calculated.

In this method, first the kinetic energy of each link is calculated depending on the center of gravity of the link, and later the difference between the sum of the kinetic energy and the sum of the potential energy of the links are calculated. This difference discribes the Lagrangian of the system. By taking the derivative of the Lagrangian depending on the time change of the joint velocities and joint position and calculating the difference yields the generalized force needs to be applied to each joint.

$$F_n = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_n}\right) - \left(\frac{\partial L}{\partial q_n}\right) \tag{4.1}$$

In equation (4.1), F_n refers to the generalized force while n and L refer to joint number and Lagrangian value, respectively (Sponge, 1989; McKerrow, 1991).

$$L(q_n, \dot{q}_n) = K - U \tag{4.2}$$

In order to compute the kinetic energies, the linear and angular velocities of links of the manipulator arm should be calculated. Angular velocities can be defined as the rate of change of the angle of joints in time. In other words, the angular velocity is the rotation of output shaft of the related joint motor. The angular velocities of revolute joints are stated below;

$$ {}^{1}w_0 = \begin{bmatrix} 0 \\ \dot{\theta}_1 \\ 0 \end{bmatrix} = \dot{\theta}_1 \tag{4.3} $$

$$ {}^{2}w_0 = {}^{2}w_0 + {}^{2}R_1\,{}^{1}w_0 = \begin{bmatrix} Sin\theta_2\dot{\theta}_1 \\ Cos\theta_2\dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \tag{4.4} $$

$$ {}^{3}w_0 = {}^{3}w_2 + {}^{2}R_1\,{}^{2}w_0 = \begin{bmatrix} Sin\theta_2\dot{\theta}_1 \\ Cos\theta_2\dot{\theta}_1 \\ \dot{\theta}_2 + \dot{\theta}_3 \end{bmatrix} \tag{4.5} $$

Since, the 4th joint is linear, angular velocity of link 4 is same as the link 3;

$$ {}^{4}w_0 = \begin{bmatrix} Sin\theta_2\dot{\theta}_1 \\ Cos\theta_2\dot{\theta}_1 \\ \dot{\theta}_2 + \dot{\theta}_3 \end{bmatrix} \tag{4.6} $$

Linear velocities of the links are found by calculating the positions of the link frames according to the reference frame which is calculated by Denavit-Hartenberg transformation matrices, and then the derivative of the resulting matrix is computed according to the joint angle parameters. Eventually, the linear velocities are calculated as follows;

$$ {}^{0}V_1 = 0 \tag{4.7} $$

$$
{}^{0}V_2 = \begin{bmatrix} -Cos\theta_2 Sin\theta_1 l_2 \dot{\theta}_1 - Cos\theta_1 Sin\theta_2 l_2 \dot{\theta}_2 \\ Cos\theta_2 Cos\theta_1 l_2 \dot{\theta}_1 - Sin\theta_1 Sin\theta_2 l_2 \dot{\theta}_2 \\ Cos\theta_1 l_2 \dot{\theta}_2 \end{bmatrix} \tag{4.8}
$$

$$
{}^{0}V_3 = \begin{bmatrix} -C\theta_1\dot{\theta}_3 S(\theta_2+\theta_3)l_3 - \dot{\theta}_1 S\theta_1 C\theta_2 l_2 + C(\theta_2+\theta_3)l_3) - C\theta_1\dot{\theta}_2 S\theta_2 l_2 + S(\theta_2+\theta_3)l_3 \\ -S\theta_1\dot{\theta}_3 S(\theta_2+\theta_3)l_3 - \dot{\theta}_1 C\theta_1 C\theta_2 l_2 + C(\theta_2+\theta_3)l_3) - S\theta_1\dot{\theta}_2 S\theta_2 l_2 + S(\theta_2+\theta_3)l_3 \\ \dot{\theta}_3 C(\theta_2+\theta_3)l_3 + \dot{\theta}_2 C\theta_2 l_2 + C(\theta_2+\theta_3)l_3 \end{bmatrix} \tag{4.9}
$$

$$
{}^{0}V_4 = \begin{bmatrix} \frac{1}{2}(C\theta_1 \dot{l}_4 S\theta_{23} l_3 - C\theta_1\dot{\theta}_3(2S\theta_{23}l_3 + C_{23}(h-2l_4)) - C\theta_1\dot{\theta}_2(2S\theta_2 l_2 + 2S\theta_{23}l_3 \\ + C\theta_{23}(h-2l_4)) + \dot{\theta}_1 S\theta_1(-2C\theta_2 l_2 - 2C\theta_{23}l_3 + S\theta_{23}(h-2l_4))) \\ \frac{1}{2}(S\theta_1 \dot{l}_4 S\theta_{23} l_3 - S\theta_1\dot{\theta}_3(2S\theta_{23}l_3 + C_{23}(h-2l_4)) - S\theta_1\dot{\theta}_2(2S\theta_2 l_2 + 2S\theta_{23}l_3 \\ + C\theta_{23}(h-2l_4)) + \dot{\theta}_1 C\theta_1(2C\theta_2 l_2 + 2C\theta_{23}l_3 - S\theta_{23}(h-2l_4))) \\ -C\theta_{23}\dot{l}_4 + \dot{\theta}_3(C\theta_{23}l_3 - \frac{1}{2}S\theta_{23}(h-2l_4)) + \dot{\theta}_2(C\theta_2 l_2 + C\theta_{23}l_3 - \frac{1}{2}S\theta_{23}(h-2l_4)) \end{bmatrix} \tag{4.10}
$$

When the calculated velocities are applied to the kinetic energy formula;

$$
K_n = \frac{1}{2} m_n V_n{}^2 + \frac{1}{2} I_n w_n{}^2 \tag{4.11}
$$

kinetic energies of links are calculated as follows;

$$
K_1 = \frac{1}{2} I_1 \dot{\theta}^2 \tag{4.12}
$$

$$
K_2 = \frac{1}{2} m_2(((Cos^2\theta_2(\dot{\theta}_1{}^2 + \dot{\theta}_2^2)l_2^2)) + \frac{1}{2} I_2(\dot{\theta}_1^2 + \dot{\theta}_2^2) \tag{4.13}
$$

$$K_3 = \frac{1}{2} m_3 (((\dot{\theta}_3^2 l_3^2 + \dot{\theta}_1^2 (Cos\theta_2 l_2 + Cos\theta_{23} l_3)^2 + \dot{\theta}_2^2 (l_2^2 + 2Cos\theta_3 l_2 l_3 + l_3^2)))) + \frac{1}{2} I_3 ((\dot{\theta}_1^2 + (\dot{\theta}_2 + \dot{\theta}_3)^2) \tag{4.14}$$

$$K_4 = \frac{1}{2} m_4 \{ (\frac{1}{8} (8\dot{l}_4^2 + 2(\dot{\theta}_3^2 (4l_3^2 + (h-2l_4)^2) + \dot{\theta}_2^2 (4l_2^2 + 4l_3^2) + l_2 (8Cos\theta_3 l_3 - 4Sin\theta_3 (h-2l_4)) + (h-2l_4)^2)) + \dot{\theta}_1^2 (8Cos\theta_2^2 l_2^2 + 2(-2Cos\theta_{23} l_3 + Sin\theta_{23} l_3 (h-2l_4))^2 + 8Cos\theta_2 l_2 (2Cos\theta_{23} l_3 + Sin\theta_{23} (hCos(2\theta_1) + 2l_4))))) \} \tag{4.15}$$

and the potential energies of linkages are calculated as follows;

$$U_1 = 0 \tag{4.16}$$

$$U_2 = l_2 Sin\theta_2 m_2 g \tag{4.17}$$

$$U_3 = (l_2 Sin\theta_2 + l_3 Sin\theta_3) m_3 g \tag{4.18}$$

$$U_4 = (l_2 Sin\theta_2 + (l_3 + (l_4 - \frac{h}{2})) Sin\theta_3) m_4 g \tag{4.19}$$

Then, the Lagrange equation is formed according to the kinetic and potential energy equations;

$$
\begin{aligned}
L &= \frac{1}{2}I_1\dot{\theta}^2 + \frac{1}{2}m_2(((Cos^2\theta_2\dot{\theta}_1^2 + \dot{\theta}_2^2)l_2^2)) + \frac{1}{2}I_2((\dot{\theta}_1^2 + \dot{\theta}_2^2) \\
&+ \frac{1}{2}m_3(((\dot{\theta}_3^2 l_3^2 + \dot{\theta}_1^2(Cos\theta_2 l_2 + Cos\theta_{23}l_3)^2) + \dot{\theta}_2^2(l_2^2 + 2Cos\theta_3 l_2 l_3 + l_3^2)))) \\
&+ \frac{1}{2}I_3((\dot{\theta}_1^2 + (\dot{\theta}_2 + \dot{\theta}_3)^2) + \frac{1}{2}m_4((\frac{1}{8}(8\dot{l}_4^2 + 2(\dot{\theta}_3^2(4l_3^2 + (h-2l_4)^2) \\
&+ \dot{\theta}_2^2(4l_2^2 + 4l_3^2 + l_2(8Cos\theta_3 l_3 - 4Sin\theta_3(h-2l_4)) + (h-2l_4)^2)) + \dot{\theta}_1^2(8Cos^2\theta_2 l_2^2 \\
&+ 2(-2Cos\theta_{23}l_3 + Sin\theta_{23}(h-2l_4))^2 + 8Cos\theta_2 l_2(2Cos\theta_{23}l_3 \\
&+ Sin\theta_{23}(hCos2\theta_1 + 2l_4))))))\frac{1}{2}I_4((\dot{\theta}_1^2 + (\dot{\theta}_2 + \dot{\theta}_3)^2 - l_2 Sin\theta_2 m_2 g \\
&- (l_2 Sin\theta_2 + l_3 Sin\theta_3)m_3 g - (l_2 Sin\theta_2 + (l_3 + (l_4 - \frac{h}{2}))Sin\theta_3)m_4 g
\end{aligned}
\tag{4.20}
$$

By using the Lagrangian calculated in equation (4.20), the generalized forces for each joint are found as;

$$
\begin{aligned}
\tau_1 &= \ddot{\theta}_1 I_4 + \frac{1}{4}hm_4(\ddot{\theta}_1 Sin\theta_{23} + \dot{\theta}_1 2Cos\theta_{23}Sin_{23}(\dot{\theta}_2 + \dot{\theta}_3)) + l_2^2 m_4(-2Sin\theta_2\dot{\theta}_2 Cos\theta_2\dot{\theta}_1 \\
&+ Cos^2\theta_2\ddot{\theta}_1) - hl_3 m_4((-Sin\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_1 + \ddot{\theta}_1 Cos\theta_{23})Sin\theta_{23}) + Cos^2\theta_{23}\dot{\theta}_1(\dot{\theta}_2 + \dot{\theta}_3)) \\
&+ 2l_2 l_3 m_4((-Sin\theta_2\dot{\theta}_2 Cos\theta_{23} - Cos\theta_2 Sin\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_1 + Cos\theta_2 Cos\theta_{23}\ddot{\theta}_1) \\
&+ l_3^2 m_4(-2Sin\theta_{23}Cos\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_1 + \ddot{\theta}_1 Cos^2\theta_{23}) + hm_4((\ddot{\theta}_1 Sin^2\theta_{23} + 2\dot{\theta}_1 Cos\theta_{23}Sin\theta_{23} \\
&(\dot{\theta}_2 + \dot{\theta}_3)l_4) + (\dot{\theta}_1 Sin^2\theta_{23}\dot{l}_4) + hl_2 m_4(((-2Sin(2\theta_1)\dot{\theta}_1 Cos\theta_2 - Cos(2\theta_1)Sin\theta_2\dot{\theta}_2)\dot{\theta}_1 Sin\theta_{23}) \\
&+ Cos(2\theta_1)Cos\theta_2(\ddot{\theta}_1 Sin\theta_{23} + Cos\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_1))) + 2l_2 m_4(((-Sin\theta_2\dot{\theta}_2 Sin_{23} \\
&+ Cos\theta_2 Cos\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3))\dot{\theta}_1 l_4) + ((\ddot{\theta}_1 l_4 + \dot{l}_4\dot{\theta}_1)Cos\theta_2 Sin\theta_{23})) + 2l_3 m_4(((-Sin\theta_{23} \\
&(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_1 + \ddot{\theta}_1 Cos\theta_{23})Sin_{23}l_4) + ((Cos\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3)l_4 + \dot{l}_4 Sin_{23})Cos\theta_{23}\dot{\theta}_1)) \\
&+ m_4(((\ddot{\theta}_1 Sin^2\theta_{23} + 2\dot{\theta}_1 Cos\theta_{23}Sin\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3))l_4{}^2) + \dot{\theta}_1 Sin^2\theta_{23}2l_4\dot{l}_4) + \ddot{\theta}_1 I_2 + (-2Sin\theta_2 \\
&Cos\theta_2\dot{\theta}_2\dot{\theta}_1 + Cos^2\theta_2\ddot{\theta}_1)l_2^2 m_3 + l_2 l_3 m_3 2((-Sin\theta_2\dot{\theta}_2 Cos\theta_{23} - Sin\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3)Cos\theta_2) \\
&+ Cos\theta_2 Cos\theta_{23}\ddot{\theta}_1) + (-2Cos\theta_{23}Sin\theta_{23}(\dot{\theta}_2 + \dot{\theta}_3)\dot{\theta}_1 + Cos^2\theta_{23}\ddot{\theta}_1)l_3^2 m_3 + \dot{\theta}_1 I_2 + Cos^2\theta_2 \\
&\dot{\theta}_1 l_2^2 m_2 + I_1\ddot{\theta}_1 + hSin(2\theta_1)Cos\theta_2\dot{\theta}_1{}^2 Sin_{23}l_2 m_4
\end{aligned}
$$

$$\tau_2 = I_4\ddot{\theta}_2 + I_4\ddot{\theta}_3 + \frac{h^2}{4}\ddot{\theta}_2 m_4 + \ddot{\theta}_2 l_2^2 m_4 + 2l_2 l_3 m_4(-Sin\theta_3\dot{\theta}_3 + \ddot{\theta}_2 Cos\theta_3) + \ddot{\theta}_2 l_3^2 m_4$$
$$- m_4 h(\ddot{\theta}_2 l_4 + \dot{l}_4\dot{\theta}_2) + 2m_4 l_2(((\ddot{\theta}_2 Sin\theta_3 + Cos\theta_3\dot{\theta}_2\dot{\theta}_3)l_4) + \dot{l}_4(\dot{\theta}_2 Sin\theta_3)$$
$$+ m_4(\ddot{\theta}_2 l_4^2 + 2l_4\dot{l}_4\dot{\theta}_2) + I_3\ddot{\theta}_2 + \ddot{\theta}_3 I_3 + I_2^2 m_3\ddot{\theta}_2 + 2l_2 l_3 m_3(-Sin\theta_3\dot{\theta}_2\dot{\theta}_3 + \ddot{\theta}_2 Cos\theta_3)$$
$$+ I_3^2 m_3\ddot{\theta}_2 - Cos\theta_2 Sin\theta_2\dot{\theta}_1^2 l_2^2 m_2 - \{\frac{1}{4}h^2\dot{\theta}_1^2 Cos\theta_{23} Sin\theta_{23} m_4 + \frac{1}{2}hCos\theta_1\dot{\theta}_1^2 l_2 m_4$$
$$(-Sin\theta_2 Sin\theta_{23} + Cos\theta_2 Cos\theta_{23}) - Cos\theta_2 Sin\theta_2\dot{\theta}_1^2 l_2^2 m_4 + \frac{1}{2}h\dot{\theta}_1^2 l_3 m_4(Cos^2\theta_{23} - Sin^2\theta_{23})$$
$$+ \dot{\theta}_1^2 l_2 l_3 m_4(-Sin\theta_2 Sin\theta_{23} + Cos\theta_2 Cos\theta_{23}) - Sin\theta_{23} Cos\theta_{23}\dot{\theta}_1^2 l_3 m_4 + h\dot{\theta}_1^2 Cos\theta_{23} Sin\theta_{23} l_4 m_4$$
$$l_2 l_4 m_4\dot{\theta}_1^2(-Sin\theta_2 Sin\theta_{23} + Cos\theta_2 Cos\theta_{23}) + \dot{\theta}_1^2 l_4 l_3 m_4(-Sin\theta_{23} Sin\theta_{23} + Cos\theta_{23} Cos\theta_{23})$$
$$+ \dot{\theta}_1^2 l_4^2 m_4 Cos\theta_{23} Sin\theta_{23} - Cos\theta_2 Sin\theta_2 l_2^2 m_3\dot{\theta}_1^2 - \dot{\theta}_1^2 l_2 l_3 m_3(Sin\theta_2 Cos\theta_{23} + Cos\theta_2 Sin\theta_{23})$$
$$- Sin\theta_{23} Cos\theta_{23}\dot{\theta}_1^2 l_3^2 m_3 - Cos\theta_2 Sin\theta_2\dot{\theta}_1^2 l_2^2 m_2\} - \{l_2(m_4 + m_2 + m_3)Cos\theta_2 g\}$$

$$\tau_3 = \ddot{\theta}_2 I_4 + \frac{1}{4}h^2 m_4\ddot{\theta}_3 + (2l_4\dot{l}_4\dot{\theta}_3 + \ddot{\theta}_3 l_4^2)m_4 + \ddot{\theta}_2 I_3 + \ddot{\theta}_3 I_3 + l_3^2 m_3\ddot{\theta}_3$$
$$- \{\frac{1}{4}h^2\dot{\theta}_1^2 Cos\theta_{23} Sin\theta_{23} m_4 - \frac{1}{2}h\dot{\theta}_2^2 Cos\theta_3 l_2 m_4 + \frac{1}{2}hCos(2\theta_1)Cos\theta_2\dot{\theta}_1^2 Cos\theta_{23} l_2 m_4$$
$$+ \frac{1}{2}h\dot{\theta}_1^2 l_3 m_4(-Sin^2\theta_{23} + Cos^2\theta_{23}) - Cos\theta_2 Sin\theta_{23}\dot{\theta}_1^2 l_2 l_3 m_4 - Sin\theta_3\dot{\theta}_2^2 l_2 l_3 m_4 - Sin\theta_{23}$$
$$Cos\theta_{23}\dot{\theta}_1^2 l_3^2 m_4 - h\dot{\theta}_1^2 Cos\theta_{23} Sin\theta_{23} l_4 m_4 + \dot{\theta}_2^2 l_2 l_4 m_4 Cos\theta_3 + Cos\theta_2\dot{\theta}_1^2 Cos\theta_{23} l_2 l_4 m_4$$
$$+ \dot{\theta}_1^2 l_3 l_4 m_4(-Sin^2\theta_{23} + Cos^2\theta_{23}) + \dot{\theta}_1^2 Cos\theta_{23} Sin\theta_{23} l^2 4 m_4\} - \{l_3 Cos\theta_3 m_3 g$$
$$+ Cos\theta_3 m_4 g(l_3 + (l_4 - \frac{h}{2}))$$

$$\tau_4 = \ddot{l}_4 m_4 - \frac{1}{2}m_4((\dot{\theta}_1^2 S_1^2 C_2^2)(2l_4 + 2l_3 + 2l_2 - h) + \dot{\theta}_1^2 C_1^2 C_{23}^2 + \dot{\theta}_2^2 S_1^2 S_{23}^2 + \dot{\theta}_2^2 C_{23}^2 + \dot{\theta}_2^2 S_1^2 S_{23}^2$$
$$+ \dot{\theta}_3^2 C_1^2 S_{23}^2 + \dot{\theta}_3^2 S_1^2 S_{23}^2 + \dot{\theta}_3^2 C_{23}^2)(2l_4 + 2l_3 - h) + (2\dot{\theta}_1 C_1^2 l_2 C_2 C_{23} + 2\dot{\theta}_2^2 C_2 l_2 C_{23} +$$
$$2\dot{\theta}_2^2 S_1^2 l_2 S_2 S_{23}))(Sin\theta_3 m_4 g)$$

CHAPTER 5

TASK SPACE CONTROL OF MANIPULATOR ARM

The desired motion of the robot is defined in task space. The relationship between the joint parameters q and the tip point of the manipulator arm is stated as

$$x = f(q) \tag{5.1}$$

and the first and second derivatives of this equation are calculated as follows,

$$\dot{x} = J(\dot{q}) \tag{5.2}$$

$$\ddot{x} = J\ddot{q} + \dot{J}\dot{q} \tag{5.3}$$

where $J = (df / dq)$ shows the Jacobian matrix. The error in task space and an assistive error function is defined as

$$e = x_d - x, \quad s = \begin{bmatrix} e \\ \dot{e} \end{bmatrix}^T$$

and controller input is selected as,

$$\tau = D(q)b + C(q, \dot{q})\dot{q} + G(q) \tag{5.4}$$

where $b = w \dfrac{h_1 + h_2}{\dot{e}^T Jw}$, if $\dot{e}^T Jw \neq 0$ w is any vector, $w \in R^n$, $h_1 = \dot{e}^T (e + \ddot{x}d - \dot{J}\dot{q})$, and $h_2 = (1/2)\alpha s^T s$ where $\alpha > 0$.

Proof: Assume that a Lyapunov-like function is selected as in equation (5.5),

$$V = \frac{1}{2} s^T s \tag{5.5}$$

Deriving in time domain and using control and robot dynamic equations,

$$\dot{V} = e^T \dot{e} + \dot{e}^T \ddot{e} \tag{5.6}$$

$$= e^T \dot{e} + \dot{e}^T (\ddot{x}_d - \dot{J}\dot{q}) - \dot{e}^T J\ddot{q} \tag{5.7}$$

$$= \dot{e}^T (e + \ddot{x}_d - \dot{J}\dot{q}) - \dot{e}^T Jb \tag{5.8}$$

$$= h_1 - \dot{e}^T Jw \frac{h_1 + h_2}{\dot{e}^T Jw} \tag{5.9}$$

$$= -\alpha V \ . \tag{5.10}$$

By selecting positive definite Lyapunov-like function V and showing that the time derivative of this function $\dot{V}$ is negative semi definite, it has been proved that e and s are limited (Ogata, 1996; Kuo, 1982, Feng, 1993) and

$$\lim_{t \to \infty} e(t) = 0 \, . \tag{5.11}$$

CHAPTER 6

SENSOR SYSTEM DESIGN

6.1. Combined Sensory System Design

Considering the conventional systems, there are five different sensor systems for an EOD robot system. Four of these use relative information and GPS is the only system that uses absolute coordinates on earth. Individually, these methods are insufficient against various outdoor conditions. In order to overcome this problem, robotics applies sensor combinations for perfection of the system. However, complexity brings cost in the form of time and money. In order to design the best combination of sensor systems, combinations of the five different types of sensors (separate, dual, ternary, quaternary and one with all of the sensor systems) are evaluated. Theoretically, there are 31 sensor combinations of the five different sensor systems studied (Table 6.1.). When the capabilities of these systems in one combination are summed, none of the sensors are adequately perfect when applied individually.

On the other hand, the only combination, which includes all sensor types, obviously seems to handle all outdoor problems stated. However, this combination brings high cost and requires powerful computers in order to process more sensor input. Since it includes all sensor types, there are some disadvantages which reduce the system's performance and feasibility. Eventually, a solution including fewer sensors but having the same capability is more desirable.

Combining different sensor systems in order to eliminate errors and provide accurate and smooth drive has been applied to autonomous vehicles.
However, all-terrain mobile robotics is a relatively new subject, the existing prototypes, which include more than two sensors, were prepared for "on-road" conditions. Nevertheless, the following examples are stated in order to give an idea about what has been done previously.

For the first example, D-GPS, laser scanner, radar and vision systems are combined for an "Autonomously Guided Vehicle" project. However, this is an "on-road" vehicle, where the number of difficulties existing in outdoor fields is not taken into account. This system presents a stereo vision sensor, which recognizes and tracks lane boundaries.

It simultaneously computes the three-dimensional geometry of the lane and the position of the vehicle relative to this lane. A combination of D-GPS with inertial sensors and a digital map determines the position and direction of the vehicle as well as the road geometry. The inertial sensors are employed for continuous determination of the ego position and orientation via integration while the DGPS signal compensates for the integrational drift. A front radar sensor with a small viewing angle but long range is mounted on the front bumper and two laser scanners are mounted at the left and right on the front bumper. Each of the sensors covers a wide viewing angle of 270° to the left front and right front, respectively. The sensors overlap in the most important front view in 180°. Different sensor technologies are combined in order to reduce the probability of encountering gross errors by the sensor outputs (Stiller et al. 2000).

The second project comprises an ultrasonic sensor, video camera and an external laser tracking device, whose reflector is mounted on the vehicle instead of the ground and the laser scanner is on the ground. The color CCD-Camera is used for visual recognition of roads, landmarks and beacons. The laser range finder is used for obstacle detection and the ultrasonic sensor is used for proximity sensing.

The position control of all-terrain mobile robots mostly includes Kalman filtering in order to eliminate high frequency noise. The Kalman filter includes a number of parameters, which are used to optimize the filter depending on the dynamic characteristics of the mobile robot. This approach relies on tracking the position of the mobile robot over time. The filtering eliminates the necessity of locating the vehicle according to the starting position and the vehicle is located by an estimate of the last known position.

In our research the VS-GPS concept is introduced. The combination of vision, sonar and GPS seems to be the optimum solution for a mobile EOD robot sensory system, considered all-terrain conditions.

Since this combination of sensors does not require beacons due to the high data refreshing frequency of the vision system and because it contains accurate position finding ability of GPS and the object recognition properties of vision and sonar systems, this system is the most reliable combination of sensor systems. A vision system has the advantage of high detail processing and its presence is needed in many different outdoor tasks.

Using a video camera in multiple processes results in simplicity of the control system and reduction of costs. However, distance measurement and recognizing pits challenges the vision systems and these problems can be easily handled by sonar sensors.

In addition, special analysis of reflected sound waves gives some information about the characteristics of the target. This ability of sonar may assist the vision system in the case that the information provided by the camera is insufficient due to weather or lightning conditions. Moreover, the information received from the sonar system can also be used to justify the information provided by vision system. For the cases where the robot encounters a deep pit, the sonar system can be used to measure the depth of the water in order to determine whether or not it is advisable for the robot to progress. Blurring due to the vibration of the robot vehicle, which is the main disadvantage of vision system, can be overcome by a suspension mechanism mounted between the vehicle's body and video camera.

In some outdoor tasks, dual sensor combinations including the vision system may be sufficient depending on the requirements of the task to be accomplished. Despite some inadequacies, the vision system is needed in such a combination for its ability of detailed identification of the target and the surrounding area. For instance, assuming that the field is almost flat, relatively smooth and does not include trees or obstacles to impede the signals or beams, radar or laser sensors combined with a video camera may be used for obstacle detection, positioning and also navigation of the robot. Therefore, the cost of GPS can be eliminated; on the other hand, difficulty of correct positioning of beacons arises.

CHAPTER 7

CONCLUSIONS

This thesis study concerns the mechatronic design of an explosive ordnance disposal robot. The robot is designed to replace human explosive specialists and perform EOD tasks providing completely safe conditions for human life. Apart from conventional joint space controlled EOD robots, which are currently used for EOD operations; the EOD robot in this study is designed to be controlled in task space. The versatility provided by the task space control of 4 degrees of freedom serial manipulator arm brings precision and speed during EOD operation. Therefore, the operator can concentrate on the task rather than adjusting the joint angles to bring the end effector to the required position. By using this control technique, a higher percentage of accomplishment in EOD operations can be achieved compared to the current level.

Moreover, the design introduces a target following system by main camera where the three joint of camera turret mechanism is rotated by computer to follow the position of the end effector, providing a better view of the EOD task. The mechanical design includes the solid modeling and static analysis and mathematic modeling of the robot's manipulator arm by kinematic and dynamic analysis and developing a control algorithm for task space control.

A quick gripper change joint is conceptually design for manipulator arm of the robot so the need for returning to the base in order to substitute different grippers designed for different EOD tasks. This specification of the EOD robot saves time and power by avoiding the necessity of the travel between the base and the operation area.

In addition, sensor systems for outdoor problems related to applications of autonomous all-terrain mobile robots are evaluated and feasible sensor combinations are determined. This research showed that none of the sensor systems is individually sufficient to handle all of the outdoor terrain difficulties. Considering all the common outdoor problems the ternary sensor system consisting of vision, sonar and GPS (VS-GPS) seems ideal for a variety of all-terrain tasks. The centimeter level accurate positioning can be achieved by a Real-Time Kinematic GPS while image processing can be done by a CCD video camera integrated vision system and distance calculations and obstacle detection can be performed via the sonar sensors.

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APPENDIX A

SOLID MODELING OF THE EOD ROBOT

The design of all mechanical parts of the EOD robot is accomplished by the 3 dimensional modeling software SolidWorks®. The software applies parametric modeling principle; therefore the designed model is open for development.

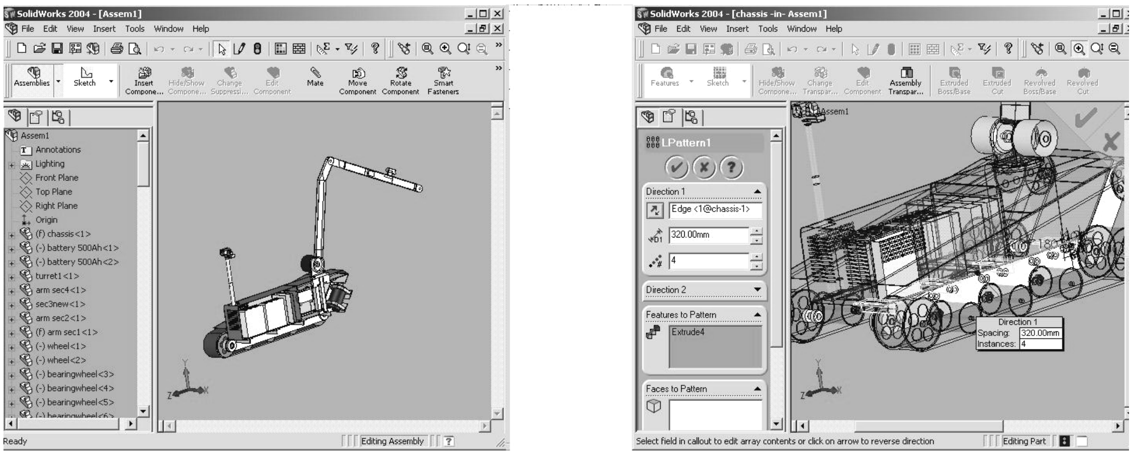

Figure A.1.

APPENDIX B

STRENGTH ANALYSIS

The static analysis and strength calculations are computed by CosmoXpress plug-in tool of SolidWorks®. The components of EOD robot are analyzed and modified when required. The software also determines the weak points of the structure, shows the deformed shape under excessive load and calculates the minimum factor of safety number for a given load.

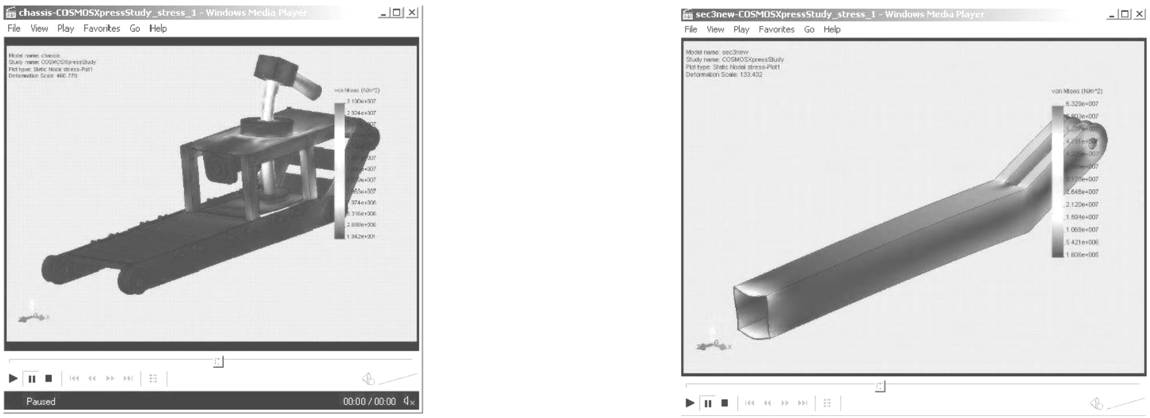

Figure B.1.