DESIGN AND MANUFACTURING OF A FIREPROOF FIRE RESCUE ROBOT

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İZMİR

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ABSTRACT

DESIGN AND MANUFACTURING OF A FIREPROOF FIRE RESCUE ROBOT

The aim of this thesis is to design and manufacture fireproof fire rescue robot for extinguishing fire. The robot is designed and manufactured to go in the middle of fire, extinguish it and send images from incident area by using a camera to increase knowledge about fire behavior. This robot makes it possible to extinguish fire without spreading in the shortest time. This will reduce the risk of injury and number of casualties for firefighters as well as for the possible victims. The robot can also decrease the monetary losses which increase considerably as fire duration increases.

For designing the fireproof fire rescue robot three dimensional solid modeling computer program was used. The semi-autonomous robot is powered by two DC electric actuators. It goes on the ground with tracking system which is manufactured by using sprockets and chains. To prevent possible damages that may be incurred by heat, the robot was covered with a ceramic fiber paper that has very low thermal conductivity.

In addition to mechanical design of the fireproof fire rescue robot, two electronic circuits are mounted in order to control actuators and solenoid valve of the extinguisher. Furthermore, in order to control actions of the robot remotely by the operator, two remote controls are used at different frequencies.

As a result of this thesis; a fireproof fire rescue robot is designed and manufactured to be used in fire incidents. Also some ideas were expressed to improve the fireproof fire rescue robot by gained experience throughout the thesis.

ÖZET

ALEVE DAYANIKLI YANGIN SÖNDÜRME ROBOTU DİZAYNI VE İMALATI

Bu tezin amacı yangın söndürmek için yanmaya dayanıklı yangın söndürme robotu tasarlamak ve imalatını yapmaktır. Robot alevlerin arasına girmek, yangını söndürmek ve olay yerinden kamera aracılıyla görüntüler gönderip yangının davranışı hakkında bilgiyi arttırmak üzere tasarlanıp imal edildi. Bu robot sayesinde yangınlar yayılmadan kısa sürede söndürülür. Böylece itfaiyecilerin ve kazazedelerin yaralanma ve yangından etkilenme riski azaltılacaktır. Ayrıca robot sayesinde yangının süresiyle orantılı olarak artan maddi kayıpları azaltacaktır.

Aleve dayanıklı yangın söndürme robotunun tasarımı için üç boyutlu katı modelleme program kullanılmıştır. Yarı otomatik robot iki adet doğru akım motoruyla çalışmaktadır. İlerlemesi dişli ve zincirlerle tırtıllı palet sistemiyle sağlanmaktadır. Isıdan kaynaklanacak sorunlardan robotu korumak için robot ısı iletim katsayısı çok düşük olan seramik fiber kâğıt ile kaplanmıştır.

Aleve dayanıklı yangın söndürme robotunda tasarımına ek olarak motorların ve yansın söndürme tüpünün solenoid valfının kontrolü için iki farklı elektronik devre kullanılmıştır. Bunun dışında robotun hareketlerinin kontrolü için operatörün kullanacağı farklı frekanslarda iki adet de uzaktan kumanda hazırlanmıştır.

Bu tezin sonucu olarak; yangınlarda kullanılacak aleve dayanıklı yangın söndürme robotu tasarımı ve imalatı yapılmıştır. Ayrıca bu tezde yanmaya dayanıklı yangın söndürme robotunu geliştirmek için yapılması gereken değişiklikler hakkında birkaç fikir belirtilmiştir.

To my mother, father and warm hearted sister…

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CHAPTER 1

INTRODUCTION

In Turkey between 2001 and 2005 except forest fires 266.052 fire incidents were happened because of different reasons. Consequently the number of the victim was reached high numbers, 1.613 people and also 70.527 animals. Monetary loss had nearly reached 1.000.000.000 YTL during these five years.

Table 1.1. Number of fire and losses in 5 years

YEAR	**NUMBER OF FIRE**	**MONETARY LOSS ($x\ 10^6$ YTL)**	**NUMBER OF DEATHS**
2001	49.109	54	264
2002	42.367	79	224
2003	56.482	565	505
2004	60.801	99	330
2005	57.293	116	290
TOTAL	266.052	913	1613

To compare these numbers to other countries the table below can be helpful.

Table 1.2. Distribution of fire deaths in different countries
(Source : International Association for the Study of Insurance Economics 2006)

Country	Adjusted Figures (fire deaths)		
	2001	2002	2003
Singapore	10	0	0
Spain	265	230	N/A
Australia	105	135	135
Italy	355	N/A	N/A
Germany	600	N/A	N/A
France	550	N/A	N/A
New Zealand	40	40	40
UK	635	590	625
Slovenia	20	20	25
Czech Republic	105	115	150
Canada	370	N/A	N/A
Poland	510	455	525
Austria	55	40	N/A
Norway	65	65	55
Denmark	75	75	90
Greece	190	145	N/A
Sweden	145	145	140
Ireland	70	60	N/A
USA	6,900	3,700	4,300
Japan	2,250	2,300	2,300
Finland	85	95	105
Hungary	235	195	210

If the forest fires had taken into consideration the numbers given in the Table 1.1 and Table 1.2 would be increased considerably.

There are several reasons for fire incidents. These reasons and their ratios are shown in Figure 1.1.

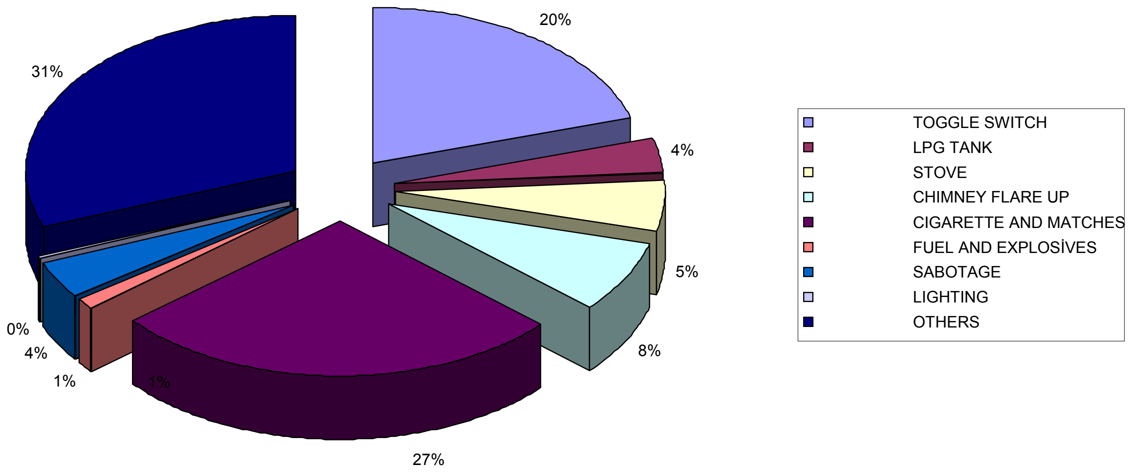


Figure 1.1. Amount of fires with respect to their causes

Thought of making a fire rescue robot comes from extinguishing fire without loss of life with the minimum damage. The fire rescue robot is a mobile robot which is used in fire incidents replace of firemen to extinguish and decrease the damage caused by fire. When fire rescue robots put together with fire fighters fire fighting will become safer and more effective.

There are different approaches about fire rescue robots all over the world. Except small differences these examples of fire rescue robots are similar in terms of operation principles.

Firefighting robots decrease the need of firefighters in dangerous situations. If the robots replace or support firefighters in missions, the difficulty which firefighters encounter is reduced and the robot technology makes possible to rescue much more victims. The vehicles can reach positions that firefighters cannot, such as petrochemical complexes and huge warehouses fire. Day after day with improving technology the number of fire departments around the world which use firefighting robots increase.

Japanese fire departments are on leading edge in using firefighting robot which is mostly remote controlled.

Some fire fighting robots are equipped with a manipulator, which can remove obstacles and handle drums. For small, low-down and narrow spaces small fire fighting robot which moves on crawlers is used. This robot is small, its dimensions are 120 m in depth, 0.74 m in width, and 0.45 m in height, and the mass is 180 kg. The robot (Japanese 1) is able to move by reactive force of water stream for case where power supply cable does not function. (Amano 2002)

Another robot is equipped with a manipulator, two TV cameras, thermal camera, and so on. The manipulator has 6 degrees of freedom, and the robot moves with four crawlers. It is controlled by a wired system. A different type of robot a diesel engine and the maximum speed of it is 10 km/h. Its dimensions are 3,97m x 1,90m x 2,38m and have a weight of 5000kg. The vehicle has a master-slave manipulator, and is driven hydraulically, having four degrees of freedom. Four types of end effectors are attachable to the manipulator: a small gripper, a large gripper, a bucket, and a gripper for rescue. This fire fighting robot (Japanese 2) can handle 280kg. The robot is carried by a fire engine, which is equipped with a fire pump. The robot moves with a double pair of crawlers, which are a characteristic of the robot. The robot has 3 cameras, except these cameras this robot has a thermal camera also it has a sensory system which is formed by a radiation detector, a combustible gas detector and a toxic gas detector. (Amano 2002)

Another fire department has a remote-control monitor nozzle robot, which is mounted on a chemical fire pumper. Its camera turns following the monitor nozzle. Its (Japanese 3) dimensions are 1.59 m length, 0.89111 m width, and 0.80 m height, and its mass is 750 kg. Also a reconnaissance robot with an innovative, simple design is constructed. The robot looks like a radio-controlled car with a camera and detectors. It is based on an electric wheelchair, and is loaded with a camera, infrared camera, gas detector, and so on. It weighs about 58 kg. The robot does not need to go up and down the stairs, which would require many mechanisms and make the robot large, heavy and expensive.

Some other fire departments also have remote-control monitor nozzle vehicles, which move with a pair of crawlers. Most of them are large and heavy, and are useful in large, open spaces, but they cannot work easily in a complicated room. After they spray water once, the robots cannot move because of the weight of the water in the hoses that are connected to the robot and the hose connections are detached by remote control. (Amano 2002)

The ROBOGAT is a fireproof special cart running on a monorail fixed under the vault or to the wall of the tunnel, in the zone of the external section through the outlines. It is used in tunnel fires where the capability of interference of firemen in tunnels is very limited because of the extreme environmental conditions (high temperature, intense smoke, gas emissions, traffic, rails and other obstructions) which delay or block the action of men and machines. (Celento, et al. 2004)

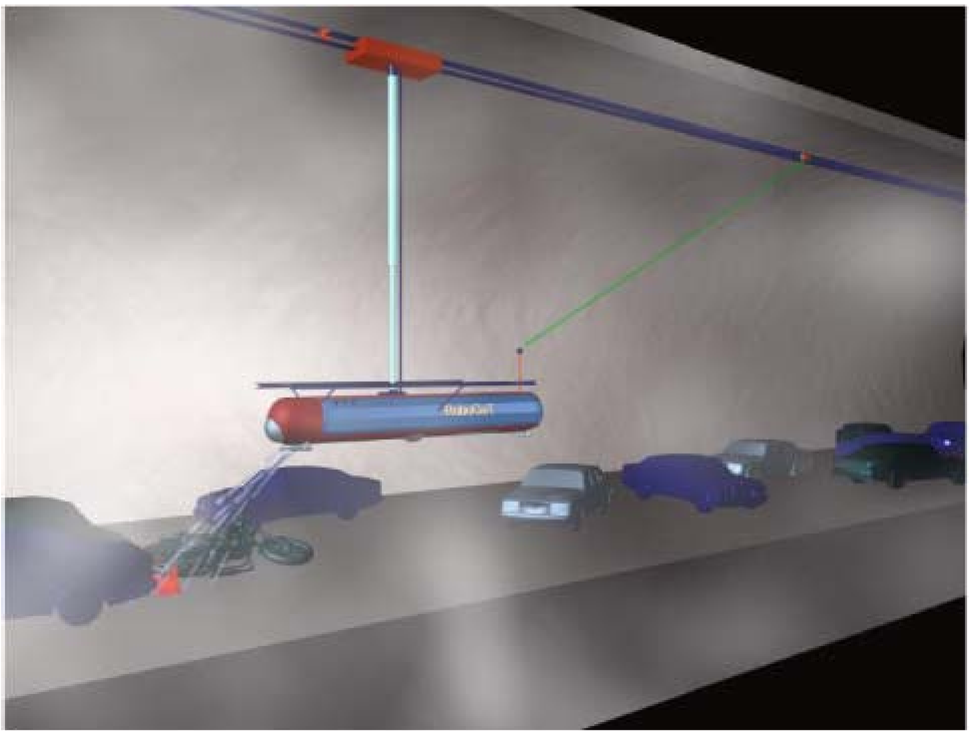


Figure 1.2. ROBOGAT
(Source: Celentano, et al. 2004)

The monorail has a double T cross-section which includes a pipe of suitable diameter, carrying high pressure extinguishing liquid. The pipe is connected from both sides to a liquid supply and a pumping system which guaranteed continuous liquid restocking and allows the cooling of the monorail and of the robot. The robot can be connected to a water supply when it reaches a place close to the fire. The mobile base of the robot and its equipment has a weight of about 1200 kg when the robot is not connected to the pipe and of about 1700 kg during the fire extinguishing phase. The rough robot dimensions are 8 m length, 0.7 m width, and 0.6 m height. The robot has a maximum velocity of about 80 km/h with maximum acceleration of 0.2 m/s^2. The robotic system is equipped sensors as thermal cameras, temperature sensors, pyrometers, gas chromatographs. (Celento, et al. 2005)

An English fire fighting robot which is called SAFFAR (UK's Security and Fire Fighting Advanced Robot) is intended as a relatively low cost high performance device. It was considered that using in internal environments, predominantly flat, structured environments such as warehouses, other large premises and also external use on good terrain and changes in floor level. This remote control robot can be detected fire, intrusion, gas, flood and unauthorized lights. SAFFAR's locomotion system is based on wheel to enable the robot to climb steps and stairs and it is moved with the speed of 1 m/s in normal conditions and if there is an urgent condition its speed can be reached 0,7 km/h. It uses mixture of lead acid and nickel cadmium batteries as power supply. (Brandshaw 1991)

SALAMANDER is a fire fighting robot adapted from an old robot which is iRobot's remotely controlled vehicle NeoMover Tactical Mobile Robot. The body of the robot has been altered to use materials that are less heat sensitive than the NeoMover and sensor system for fire conditions. A heat shield has been mounted on the front of the robot to protect it from the extreme directional heat of fire. Salamander has compressed air foam system fitted with an adjustable nozzle to extinguish fire. Firefighters are followed into the scene by Salamander with carrying heavy equipment, spare the firefighter extra effort, preserving the air supply and so minimize physical stress and enable more efficient team deployments. It has a 24 km/h and can operate 5 hours on one battery charge. It weighs 113 kilograms and can carry a payload of 68 kilograms. It has also a small turning radius and can turn around in corridors or on landings. (Gross 2006)

The most known and the basic fire fighting robots are manufactured every year to join a competition which is composed by Trinity college. These robots are not commercial and not employable, they are autonomous robots which must be finished their work within the 5 minutes. Their purpose is to find a litting candle in a labyrinth field and extinguish it. The dimensions are not larger than 31cm x 31cm x 31cm. They have sensor system such as light sensor, temperature sensor, detector and encoder, etc. (Trinity College 2007)

Table 1.3. Specifications of fire fighting robots

Robot	Dimension (L x W x H) (m)	Weight (kg)	Speed (km/h)	Locomotion system	Control
Japanese 1	120x0.74x0.45	180	N/A	Crawler	Remote control
Japanese 2	3.97x1.90x2.38	5000	10	Crawler	Wired system
Japanese 3	1.59x0.89111x0.8	750	N/A	N/A	Remote control
Likes an electric wheelchair	N/A	58	N/A	Wheeled	Remote control
ROBOGAT	8x0.7x0.6	1700	80	Monorail	Remote control
SAFFAR	N/A	N/A	0,7	Wheeled	Remote control
SALAMANDER	1.02x0.81x0.46	113	24	Tracked	Remote control
Trinity College	31x31x31	N/A	N/A	Wheeled	Autonomous

SALAMANDER and SAFFAR are only in planning stage; they have not been constructed or used. All of these firefighting robots have different properties but they have only one property in common; none of them go in the fire all of them spray extinguisher for away from fire. They have no insulation their outside's so if they come close to the flames they should be damaged from the heat. Some of them are big and also heavy to go in fire scenes.

The firefighting robot which is the subject of this thesis;

- goes between flames because it would be more efficient than extinguishing fire from far, to spray foam directly to fire and also it would be taken short time to extinguish it
- has thermal insulation to protect electronic circuits which are easily get harms from highest temperatures and than the robot would be broken down while trying to extinguish fire
- is smaller than most of the robot which were made before to pass off possible small hole
- is lighter than most of the robot which were made before not to give damage to fire area and fall down from ground to downstairs
- is mobile, it has no connection like wire or hose outside of the fire scene so it would be gone as near as fire freely except range of remote control
- has camera to record it and send signal to outside so that behavior of fire would be determined.

1.1. Aim and Difficulties

When a fire incident is happened, fire rescue robots will be sent at first to prevent spreading of fire and extinguish it, also to find the victims' destination. The common and main objective of these robots is to decrease the amount of loss in terms of both life and material. Fire rescue robots' main task is to avoid the firemen going into dangerous region of fire. Furthermore it can extinguish fires in less time than fireman can and save more monetary amount. Hence; day after day with improving technology the numbers of fire departments around the world which use firefighting robots are increasing. When robots put together with fire fighters, who face life threatening situations every day responding to difficult and dangerous situations, and firefighting will become safer, and more effective than interfere the fire with only firefighters. Because firefighting is an extremely physically demanding occupation, working at a fire scene is physically and emotionally stressful. Firefighters face risky situations when extinguishing fires and rescuing victims; it is a handicap of being a firefighter. The leading cause of death of fire fighters has been stress and overexertion, leading to hearth attacks, strokes and similar complaints. Also, fire creates hazardous atmosphere;

depriving oxygen and heating. Although fire filling air with toxic gasses like carbon dioxide, and from incomplete combustion carbon monoxide which are both life threatening at high concentrations; lethal to firefighters. Burning plastics and polymers can produce hydrogen chloride, a highly toxic asphyxiant. In other words, robots decrease the number of firefighters to get into dangerous situations. Further, if the robots replace or support firefighter in fire incidents, the work load for fire fighters reduced. (US Fire Administration 2007)

The robot technology makes possible to rescue much more victims. There is a particular limit of fire departments' power, it is impossible to extinguish fire and rescue many victims at a time in a huge disaster but with the help of the robots it will be changed. (Amano 2002)

Other than these, fire rescue robot should work at very high temperatures especially in the middle of fire and it should be covered with a low thermal conductivity insulation material to protect electronic circuits in it. From ignition to decay of fire, heat can be transmitted to a firefighter through conduction, convection and radiation. The increase in temperature begins at ignition, which is the point the combustion begins. The fire grows and continues with the increasing temperature. In a compartment fire (a fire that takes place in an enclosed space) the temperature increases to a point at which all combustible materials present ignite. The temperature at this flashover point can reaches 500°C for conventional fires, and the heat release at the time of flashover can be greater than 10.000 kW. For chemical fires, the temperature of the flashover point may even exceed 1200°C. Flashover conditions are almost always immediately deadly to anyone in the compartment.

Addition to these the firefighting robot should go in fire, not to spray extinguisher far point from the fire, to be more effective and to extinguish less time without spreading. Not to catch a fire the robot is covered with non-flammable material.

The firefighting robot use ABC (dry chemical) type fire extinguisher because it is wanted to use the robot at any type of fire which can be possible. The ABC type of fire extinguisher extinguishes class A (wood, paper, plastic, cloth), B (flammable liquids, grease, gas), C (electrical) and D (combustible metals) fires. Also these types of extinguishers are found easily.

Steel chains are used for crawlers against 850°C heat. Steel's thermal resistance is high and is not melt at this temperature. The area where the robot works is the biggest problem because robot should have the ability to move through rough surfaces with a lot of obstacles. While the surface characteristics may change from one place to another, also fire plays an important role in manipulating the existing characteristics, by means of heat. Also it creates additional obstacles throughout the environment by weakening the physical structure of the building and collapsing additional parts from it. The stable structure of steel is adequate for locomotion system; it gets over blazes and debris easily.

Mainframe of the robot is made of aluminum which is easy to machine and light material. Also it is easy to find and cheap material. On the other hand it is a good conductor of heat but the insulation material will be chosen considering this property of aluminum. At fire scene building collapse or goods can also fall onto the robot directly. If such thing occurs, the robot's mainframe should have the strength to withstand the magnitude of the impact and aluminum is optimum material when all these things are considered.

The firefighting robot is controlled with a remote control unit by an operator. It is the simplest, safety and cheapest way of controlling the robot because semi-autonomous and autonomous robots need more and sensitive sensors. That is hard to find and mount on the robot; also their working temperatures are critic to supply. Addition to this, it is more reliable to make a decision about where and how interfere fires by an operator.

A camera is used in firefighting robot for searching the environment and watching the fire from outside by the operator. A high temperature resistance glass is mounted in front of the camera for protecting from heat. This camera makes the control of the robot easy because the camera sends data outside and with the help of these data behavior of the fire can be predicted. These information also help firemen to generalize where and how the fire is going on and how firemen should continue their work.

The robot should be that big to overcome all obstacles but also it should be that small to pass the smallest holes which may be encountered in a fire scene. In the area of fire small holes, ditches, narrow ways, wide gaps, big obstacles would be encountered. All these physical conditions set the physical design limitations of the robot. In addition to these, the robot should be small and light not to give any damage fire environment like collapse the basement and fall down, itself and victim, also when the robot find any victim it should not hit and injure him with its huge body. If there were no physical limitations on the robot, the natural intention will be making the robot bigger to overcome any obstacle. However, in general, robots for rescue operations should be small to penetrate the rubble better and should be light in order to apply less pressure on trapped people, or unstable parts of the building. After considering the worst condition that the robot may encounter in the fire area during the incident, design criteria of the fire rescue robot can be chosen properly.

One of the most important things is to choose the optimum battery that the robot needs. The weight of the power supply increases if its capacity increases. A power supply must give enough energy in the fire extinguish operations for certain time to go in fire, spray the extinguisher and return to outside with lightest weight. Energy choice is determined with respect to the electrical properties of electronic components. For that reason energy consumption is as important as the electronic devices precision.

Additionally the process temperatures of the devices on search and rescue robots should be checked. The devices should be chosen such that the operating temperatures must be suitable for hard winter days to hot summer days. A very well designed robot does not mean anything if its sensor or camera does not work in hard conditions.

After all part of the fire rescue robot are chosen roughly, the last step to conclude the determining of the robot's parts is to look for manufacturing difficulties and cost of them. Robots which have special purpose like fire rescue robots are custom made products so the parts of the robot are specific parts. It is hard to substitute with another material or part. The cheapest material for every specific part should be chosen while considering the difficulty of machining. Because the worst possibility that may be encountered should be considered, it is thought that the robot will be trapped in fire and not to go back outside. Addition to this, some parts of the robot can be broken by a strike or fall of something on it. As a result, parts of the robot should be chosen to be easily found and manufactured with the lowest budget.

CHAPTER 2

THERMAL CONTROL

Most equipment only operates correctly if maintained at the right temperature and if temperature changes are within acceptable limits, e.g. electronic units often must be kept at room temperatures and electronic circuits at very stable temperatures. Above all the fire scenes are completely different because of very high temperatures, radiation, heated obstacles so that thermal conditions are very particular and likely to cause dangerous changes in temperature. Correct temperature can only be supplied by thermal control systems.

Throughout the fire extinguishing, thermal control ensures that each part of equipment is maintained at particular temperatures.

Three are different types of heat transfer which adds heat to equipment:

1. Conduction (heat transfer through a solid)
2. Convection (heat transfer through a fluid)
3. Radiation (heat transfer through a vacuum)

Convection and radiation which illuminates the firefighting robot's surfaces are the main sources of heat which makes us build a thermal control system. This environment causes extreme temperature in the surface of the robot; the outside layers of the robot can reach temperatures of 850°C.

The goals of thermal control systems in equipments are;

1. To maintain equipment temperature in specified ranges (usually room temperature) during all operating time
2. To guarantee optimum performances when equipment is operating
3. To avoid damage when equipment is not operating
4. To keep the specified temperature stability for delicate electronics, or stable optical components.
5. To maintain boundary temperatures at interface between subsystems, to ease interface management

6. Guarantee the correct operation of thermal control system by means of design, analysis and test. (European Space Agency 2007)

2.1. Active and Passive Thermal Control Systems

In general, there are two types of thermal control systems; these are passive and active thermal control systems.

2.1.1. Active Thermal Control Systems

An active thermal control system is used in addition to the passive system when passive system is not adequate.

Active systems rely on pumps, thermostats, and heaters, use moving parts, and require electrical power. Heat pipes, louvers, second-surface mirrors, heat switches, electrical heaters, pumped-loop systems, radiators, heat exchangers are used for active thermal control.

When active thermal control systems are determined to use in equipment the calculations will be a handicap. Addition to this, these types of thermal control is expensive and need more energy to consume for thermal control. Also parts of an active thermal control system need more space in equipment to mount and that make the machine bigger and heavy.

2.1.1.1. Heat Pipe

Heat pipes use a closed two-phase liquid-flow cycle with an evaporator and condenser in which heat is dissipated by evaporation and condensation. Thermal energy is absorbed by the liquid in the pipe. The liquid is turned to a gas which transports the heat to the other end of the pipe. The gas then condenses, cooling back into a liquid and releasing the heat to a radiator. The liquid returns to the heated area by way of capillary wicks. Heat pipes provide a highly conductive heat path and extremely high heat transfer rates. In addition, they are lightweight, can be used for a wide range of temperatures, and can have a variable conductance. However, slow inert gasses can be generated depending on the material and fluid used, and their performance on earth changes with respect to their orientation to the gravity vector.

2.1.1.2. Louvers

Louvers are surfaces that are like venetian blinds mounted in front of a radiator. While most commonly placed is over external radiators. The blades and the base plate are covered with different thermal coatings. Therefore, opening and closing the blades exposes the base plate to varying degrees and also changes □ and □, which changes the thermo-optical properties of the surface. The blades are opened and closed by actuators.

2.1.1.3. Second-Surface Mirror

A second-surface mirror is a mirror which reflects incident energy and can radiate out internal energy. Second-surface mirrors are highly efficient and have all but replace louvers.

2.1.1.4. Heat Switches

A heat switch provides a direct conduction path between the heat source and the equipment mounting plate when the contacts are closed. They are also known thermal switches. Heat switches can passively control the temperature of warm electronics without use of thermostats and heaters, so reduced the power requirements. Also they reduced the need for heater control circuitry and software.

2.1.1.5. Electrical Heater

An electrical heater is a device that is controlled by a thermostat. They use to protect components under cold-case environmental conditions or to make up for heat that is not dissipated when an electronics are turned off. They generate heat by running electrical current through a resistor. Electrical heaters are used for temperature control, and usually only for short periods of time.

2.1.1.6. Pumped-Loop System

A pumped-loop system is a system which uses a fluid to absorb the thermal energy from a component and transfers it to a heat sink. If the coolant is expendable then the working fluid is rejected from the robot once. If it is nonexpendable coolant, the working fluid is re-circulated within the system once its thermal energy has been radiated to outer air by the help of radiator. There are three types of coolant loops: air coolant, water coolant, and Freon coolant.

Air Coolant Loop: It uses air flow to cool the cabin interior and transport heat to the water coolant loop by passing over cold plates. The air temperature is usually maintained between 18 °C and 27 °C.

Water Coolant Loop: This system uses cool water pumped through a network of pipes located in the walls of the equipment. These pipes surround heat generating equipment, and run through the cold plates to collect the heat from inside of the robot. The water coolant loop then transports heat to the Freon coolant loop at the Water/Freon Loops interchanger.

Freon Coolant Loop: Consists of piping outside the inside of the robot that transports heat from the water coolant loop to heat dissipation devices such as radiators and water evaporators. This type of coolant loop has the lowest operation temperature of the three.

2.1.1.7. Heat Exchanger

A heat exchanger is used to transfer thermal energy between two or more fluids at different temperatures. Heat exchangers can use direct or indirect contact. In direct contact heat exchangers, the working fluids come in contact with each other, exchange heat, and are separated. Indirect contact heat exchangers transfer heat through a wall or baffle.

2.1.1.8. Radiators

A radiator is a device with a large surface area used to reject heat by infrared (IR) radiation from their surfaces. Radiator size depends on both heat loads and required temperature.

2.1.2. Passive Thermal Control Systems

A passive system relies on conductive and radiative heat paths and has no moving parts or electrical power input.

Passive thermal control components are queued like phase change materials, multi layer insulation (MLI) and thermal doublers.

In passive thermal control systems, covering by an insulation material, calculation of system is easier than active thermal control systems' because there are no phase change only heat transfer from outside to inside. And also it is easy to construct passive thermal control systems on equipment by covering with insulation material; it doesn't need space in equipment. On the other hand it makes the mainframe of equipment thicker.

2.1.2.1. Phase Change Materials (PCM)

A Phase Change Material (PCM) is a material that has a high heat of fusion is capable of storing or releasing large amounts of energy. Phase change materials absorb thermal energy by changing from a solid to a liquid. As the temperature decreases, the material turns again solid. It is especially useful for electrical equipments. The main disadvantage of phase change materials is that they are unable to absorb any more heat after melting. Then the temperature can increase.

The most common phase-change transformations are solid to liquid (melting and freezing), liquid to gas (vaporization), solid to gas (sublimation), and anhydrous salt transformations.

Most popular type of phase change materials are sodium sulfate which has been known as Glauber's salt, glycerol, acetic acid, butane and methane.

Table 2.1. Specifications of Phase Change Materials

Properties / Materials	Density (g/cm^3)	Melting Point (^oC)	Heat of Fusion (kJ/kg)
Sodium Sulfate	2.68	31	279
Glycerol	1.261	18	199
Acetic Acid	1.049	17	187
Butane	0.584	-135	76
Methane	$0.717x10^{-3}$	-183	59

2.1.2.2. Multi Layer Insulation (MLI)

Multi layer insulation and single-layer radiation barriers are among the most common thermal-control elements. Insulation reduces the rate of heat flow per unit area between two boundary surfaces. MLI blankets prevent both excessive heating loss from a component and excessive heating from environmental fluxes. Sensors and payloads can be wrapped in insulation blankets to thermally isolate them and reduce thermal control requirements. (Fortescue, et al. 2003)

2.1.2.3. Thermal Doublers

Thermal doublers a heat sink made of a highly conductive material placed in thermal contact with a component. Heat is conducted to the sink during an increasing temperature and then diffused by radiation or conduction. Thermal doublers function by conducting heat laterally from high-power dissipation regions before final transport to the mounting plate. The process also works in reverse and keeps components from experiencing severe cooling. They can also be used to spread heat out on radiator surfaces, and are frequently used to control the temperature of electrical equipment.

Because of their costs, calculating hardness, complex assembling passive thermal control is more suitable than active thermal control. Also in active thermal control robot gets bigger and heavier because of the components to be mounted, all of them need more electric power to work.

2.2. Insulation and Insulation Materials

It is known that if two objects of different temperatures are brought in contact with each other, the warmer one will transfer heat to the colder until they reach same temperature. Heat always flows from a warm object or area to a cold one. Thermal insulation is the process of controlling the transfer of heat from one object to another.

In other words, when the firefighting robot is thought, thermal insulation is the material that can be used to reduce the rate of heat transfer through fire in the robot.

When selecting insulation products, several performance characteristics are important:

- Thermal conductivity
- Fire resistance
- Weight

Generally, insulation is rated in terms of thermal resistance, called R-value, which indicates the resistance to heat flow. The highest the R-value, the greatest the insulating effectiveness. R-values are commonly used to characterize thermal insulation materials in buildings. The R-value of thermal insulation depends on the type of material, its thickness, and density. The SI units for thermal resistance are Km^2/W. R-values can be calculated from thermal conductivity, k, and the thickness of material, L;

$$R = L/k \qquad (2.1)$$

A machine in a laboratory gives a relative number that can be used to compare products, but a laboratory R-value does not give enough information about the effectiveness of those insulation products because R value performance testing is done in a 21 ^{0}C environment with no air movement. But in real insulation is subjected to a wide range of temperature conditions in a house. The insulation is affected by air movement, and it is also degraded by the convection forces that develop within the insulation material. This can result in the rated house insulation R value being higher than the actual effective R value. (Department of Energy Assistant Secretary Energy Efficiency and Renewable Energy 2007)

Different from house insulation k (thermal conductivity) is used in calculations about fire rescue robot. Because R value is improved for generally house insulation and the accuracy about their value is not enough.

Thermal conductivity, k, is the intensive property of a material that indicates its ability to conduct heat. It is defined as the quantity of heat, Q, transmitted in time t through a thickness L, in a direction normal to a surface of area A, due to a temperature difference ΔT, under steady state conditions and when the heat transfer is dependent only on the temperature gradient.

Thermal conductivity = heat flow rate × distance / (area × temperature difference)

$$k = \frac{Q}{t}\frac{L}{A\,\Delta T} \tag{2.2}$$

To IS0 and CEN Standards if a thermal conductivity of a material lower than 0,065 W/mK value than these materials are called heat insulation material. The lower thermal conductivity the higher heat insulation is.

Heat is transferred from one material to another by conduction, convection and radiation. Many different materials can be used as insulators. Many organic insulators are made from petrochemicals and recycled plastic. Many inorganic insulators are made from recycled materials such as glass and furnace slag. (Hyder, et al. 2003)

Some materials are good insulators against only one of the heat-transfer mechanisms, but poor insulators against another, like metals. Metals are good radiative insulators, but poor conductive insulators.

The most improvement thermal insulation can be seen at spacecrafts. Spacecrafts need lightweight insulators but they are expensive. In space, heat cannot be given off by convective heat transfer or conducted to another object. Multi-layer insulation (MLI) is used to control thermal radiation in spacecraft. The principle behind MLI is radiation balance.

When insulating the firefighting robot some insulation materials should be discussed by looking their physical properties. These materials should be firstly non-flammable and low thermal conductivity. The materials which have these properties and can be used as an insulation material are ceramic fiber blanket, ceramic fiber paper, fiberglass, rock wool and different kinds of ceramics. (Gilmore 2002)

Table 2.2. Thermal Conductivities of some insulation materials

Properties / Materials	Density (g) (kg/m^3)	Thermal conductivity (k) (W/mK)
Aluminum	2702	237
Ceramic Fiber Paper	200	0,08 at 600 °C 0,10 at 800 °C 0,18 at 1000 °C
Ceramic Fiber Blanket	128	0,14 at 600 °C 0,19 at 800 °C 0,27 at 1000 °C
Ceramic Mullite (3Al2O32SiO2), bulk	3220	4,18 at 600 °C 3.91 at 800 °C 3,76 at 1000 °C
Fiberglass < 250 ^{0}C	14-100 (22)	0,040 at 20 °C
Rockwool < 700 ^{0}C	30-200 (52)	0,040 at 20 °C

2.3. Heat Transfer

To protect electronic parts safe and working temperature range insulation is needed. At first step of insulation to obtain the right thickness of insulation layer some calculations should be done.

Three different calculation types were tried. First type is the basic one, which is known as a heat transfer equations. The others are analytical and numeric calculations.

2.3.1. Heat Transfer Equations

- **Conduction**

Conduction in a solid is the transfer of heat from one point in the solid to another as a result of a temperature gradient. It involves the transfer of kinetic energy from one molecule to the other and can also occur in liquids and gases. Molecules must be present for conduction to take place. That is, conduction cannot occur in a vacuum. An example of conduction is a length of pipe being heated at one end. Eventually the other end increases in temperature. The following equation computes the heat transfer by steady, unilateral flow:

$$Q = -kA\frac{dT}{dx} \quad (2.3)$$

where,

Q : Rate of heat conduction (W)

k : Thermal conductivity (Wm/K)

A : Cross-sectional area of the path (m^2)

$\frac{dT}{dx}$: Temperature gradient along the path (K/m)

The equation above can also be written as:

$$Q = -kA\frac{T_1 - T_2}{x} \quad (2.4)$$

where

T_1,T_2 : Surface temperatures kept at steady temperature (K)

x : Thickness of the material being analyzed (m)

- **Convection**

Convection is the heat energy transfer between a solid and a fluid when there is a temperature difference between them. Generally, convection heat transfer can not be ignored when there is a significant fluid motion around the solid.

$$Q = -hA\Delta T \quad (2.5)$$

where

Q : Rate of heat convection (W)

h : Convection heat transfer coefficient (Wm^2/K)

A : Cross-sectional area of the path (m^2)

ΔT : Temperature difference (K or °C)

The temperature of the solid due to an external area can cause a fluid motion. This is known as "natural convection" and it is a strong function of the temperature difference between the solid and the fluid. Blowing air over the solid by using devices such as fans and pumps can also generate a fluid motion but this is known as "forced convection".

Fluid mechanics plays a major role in determining convection heat transfer. The fluid flow can be either laminar or turbulent. Laminar flow generally occurs in relatively low velocities in a smooth laminar boundary layer over smooth small objects, while turbulent flow forms when the boundary layer is shedding or breaking due to higher velocities or rough geometries.

- **Radiation**

Radiation is the transmission of energy by electromagnetic waves. Radiation can be transmitted in every of wavelengths, but thermal radiation only travels in the range between 0.100 mm and 100 mm.

If a body is exposed to thermal radiation, it will absorb some, reflect some, and transmit some radiation through the body. Therefore:

$$\rho + \alpha + \tau = 1 \quad (2.6)$$

where,

ρ : Absorptivity

α : Reflectivity

τ : Transmissivity

A black body absorbs all incident radiation, and emits energy as follows:

$$E_{b} = \sigma T^4 \qquad (2.7)$$

where

E_b : Rate of Energy (W/m^2)

σ : 5.67X10^{-8}W/m^{2}K^4 : Stefan-Boltzmann constant

T : Absolute temperature (W/m^2)

This is known as the Stefan-Boltzmann Law.

The intensity of the energy radiated by a black body to a normal surface is:

$$I_n = \frac{E_b}{\pi} \qquad (2.8)$$

where,

I_n : Intensity (W/m^2)

If the source of radiation is at an angle, the intensity is calculated by:

$$I_{\emptyset} = \frac{E_b cos\emptyset}{\pi} \qquad (2.9)$$

where,

$I_{\emptyset}$: Intensity at angle (W/m^2)

Ø : angle of incidence

The exchange between two black bodies is described by the equation:

$$Q_{ij} = A_i F_{ij}\, \sigma\, (T_i^4 - T_j^4) \qquad (2.10)$$

where,

A_i : Surface area (m^2)

F_{ij} : View factor

The determination of the view factor is difficult, but view factors for different materials can be the found in prepared tables. (DeWITT and Incropera 1996)

2.4. Analytical and Numerical Calculations

Simplified heat transfer equations cannot be used for the existing situation because the problem of the firefighting robot is a time related problem. To take time dependence into account analytical and numerical calculations should be done to determine the thickness of insulation layer.

2.4.1. Analytical Calculations

Analytical equations are exact solutions. The most certain results are obtained with analytical solutions because it is the real solution of the existing problem. However, as the problem gets complicated, it is difficult to find a way to solve the differential equations. Usually, the preferred method is to simplify the equation by making additional assumptions. At this point it should be stated that numerical equations need less assumptions to obtain the results, and they are more favorable as the problems get complicated. However, with the same assumptions, generally both methods give nearly the same results.

Before getting into detail of the analytical solution, time-dependent heat transfer equation in one dimension had been written below:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2.11}$$

This is the main equation of heat transfer where,

$\frac{\partial^2 T}{\partial x^2}$: Second derivative of temperature with respect to distance

α : Heat dissipation constant

$\frac{\partial T}{\partial t}$: First derivative of temperature with respect to time

This equation is solved by using the separation of variables method in analytical solution.

$$T(x,t) = f(x)\, g(t) \tag{2.12}$$

The boundary conditions of this equation are;

$$T(0,t) = 0 \tag{2.13}$$

$$\frac{\partial T}{\partial x}(L,t) = 0 \tag{2.14}$$

From this method, the functions f (x) and g(t) had been found as:

$$f\,(x) = c_1 \sin\sqrt{\lambda}\, x \tag{2.15}$$

$$g\,(t) = c_3 e^{-\lambda\alpha t} \tag{2.16}$$

After finding f (x) and g (t) they are substituted into the main equation and equation (2.12) had been found as below:

$$T\ (x,t) = \sum_{n=1}^{\infty} B_n \sin\sqrt{\lambda}\, x e^{-\lambda\alpha t} \tag{2.17}$$

$$\lambda = \left[\frac{(n-\frac{1}{2})\pi}{L}\right]^2 \tag{2.18}$$

For the rest of the calculations 850 ^{o} C is subtracted from outer (850 ^{o} C) and inner (20 ^{o} C) temperatures so that they will have converted temperature values of 0 ^{o} C and -830 ^{o} C. The main reason of this subtraction is to obtain a boundary condition T(x,0) = -830, which simplifies the solution of the differential equation considerably. As a result the constant of the infinite series solution is found to be:

$$B_n = \frac{-1160}{(n-\frac{1}{2})\pi}\left[1-\cos(n-\tfrac{1}{2})\pi\right] \tag{2.19}$$

2.4.2. Numerical Calculations

It is usually easier to use numerical equations rather than analytical solutions even with the same simplifications, and they are more appropriate to use with complicated equations. However, it is very hard to use them without a computer and even with a computer it needs high processing power. With improving computer technologies, numerical solutions become everyday more practical.

As it is mentioned before, the same heat transfer equation, (Eq. 2.11) had been used for numerical calculations;

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2.12}$$

In numerical calculation the main equation will be improved by adding the time (k) and distance (i) steps to the rate of change of temperature with respect to time and location as it is given below:

$$\frac{\partial T}{\partial t} = \frac{T_{i+1}^k - T_i^k}{\Delta t} \tag{2.13}$$

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i+1}^k - 2T_i^k + T_{i-1}^k}{\Delta x^2} \tag{2.14}$$

Then equation (2.13) and (2.14) are substituted in equation (2.11) and by using explicit method the temperature value at $(k+1)^{th}$ time and i^{th} location (T_i^{k+1}) becomes:

$$T_i^{k+1} = \frac{T_{i+1}^k - (A-2)T_i^k + T_{i-1}^k}{A} \tag{2.15}$$

where A equals to $\frac{\Delta x^2}{\alpha \Delta t}$ and

i : distance step

k : time step

In numerical solution, the problem is divided into n items to solve easily and some assumptions will be needed. The assumption for the firefighting robot which should be adopted is an imaginary (n+1)th node which is identical with every property of (n-1)th node like distance and heat where the node n is at the wall that is inside the robot. This result comes from the insulated boundary condition assumption, which creates a surface that has the vertex point of heat gradient. It is thought that the robot was insulated inside because this is the worst possible condition, in which no heat is dissipated to the inside of the robot. As a result, a constant temperature value has been provided at T_{n+1} and $T_{n-1.}$ Also it is assumed that the outer surface temperature of the robot remains constant at 850 ^{o}C, that is T_1 = 850 ^{o}C for all time steps (for all k values). The resulted temperature equation at location n has been found as:

$$T_n^{k+1} = \frac{2T_{n-1}^k + (A-2)T_n^k}{A} \qquad (2.16)$$

2.5. Results of Calculation

While the equations are solving, some values about environment should not be changed. These things will be considered in calculations like inner space temperature of the root will be about 40 ^{o} C, and the robot should be work 900 seconds (15 minutes) without having any damage; namely its operation time should be at least 900 seconds.

The calculations should be done by the thinking of the worst conditions. In calculations outer space temperature is taken 850 ^{o}C because of that.

The equations are solved for only insulation layer because Al thermal conductivity is 237 W/mK at 300 K while insulation material's thermal conductivity is comparatively so low. Al layer do not affect the result so much and with only insulation layer results are more reliable.

One thing should not be changed in calculations is inner space of the robot can not exceed at about 40 ^{o} C not to cause having damage electronic parts. Then the insulation thickness of the ceramic fiber paper will be 7,25 cm at outer space 850 ^{o}C at 900 seconds operation time when the numerical equations are solved and the inner space temperature of the robot will be 41,83109 ^{o} C. Numerical solution is very close to analytical solution. In analytical solution for ceramic fiber paper the insulation layer thickness is 7,25 cm at 900 seconds for outer space temperature 850 ^{o} C and inner space temperature about 40 (41,94479) ^{o} C.

If ceramic fiber blanket is used instead ceramic fiber paper, the insulation thickness will rise to 12,5 cm for same conditions only inner space temperature changes from 41,83109 ^{o} C to 41,74931 ^{o} C in numerical solution. And ceramic fiber blanket is used for insulation material the result thickness will be changed to 12,5 cm at 900 seconds for outer space temperature 850 ^{o} C and inner space temperature about 40 (41,86292) ^{o} C in analytical solution.

Table 2.3. Thickness' to specify inner temperature at about 40 ^{0}C

Properties / Materials	**Density (g) (kg/m^3)**	**Thermal conductivity (k) (W/mK)**	**Specific heat (c_p) (J/kgK)**	**Last temperature (^{o}C)**		**Thickness (cm)**
				Numeric	**Analytic**	
Aluminum	2702	237 at 27 °C	903	40,19269	40,08115	109
Ceramic Fiber Paper	200	0,08 at 600 °C 0,10 at 800 °C 0,18 at 1000 °C	1,13	41,83109	41,94479	7,25
Ceramic Fiber Blanket	128	0,14 at 600 °C 0,19 at 800 °C 0,27 at 1000 °C	1,13	40,71435	40,60212	800

By looking the results ceramic fiber paper is the most appreciate insulation material for the firefighting robot. It has the thinnest insulation layer thickness and low thermal conductivity.

CHAPTER 3

LOCOMOTION SYSTEM

Although researches and practices of years it is still a big dilemma to choose the right locomotion system (track or wheel) for robots. Both of them have advantages and disadvantages related to their using area and tasks.

Nowadays most of the mobile robots, especially which is for military applications, are used tracked robots which is moved on rubber tracks driven by electric powered motors. Since tracks have high traction characteristics on rough terrain compared to wheels. In addition to the advantage of higher traction, tracks provide high maneuvering ability due to the motion principle of tracks and easy steering.

Also tracked vehicles can turns more sides than wheeled vehicles that is required to operate in diverse terrain and tracked vehicles are provided a bigger surface area than wheels. Addition to this tracked vehicles provide shorter mission travel times.

When the robots should be driven on roads, wheeled vehicles are showed excellent mobility and speed; but when off-road usage was required and wet or snow conditions are occurred, wheeled robot is inadequate.

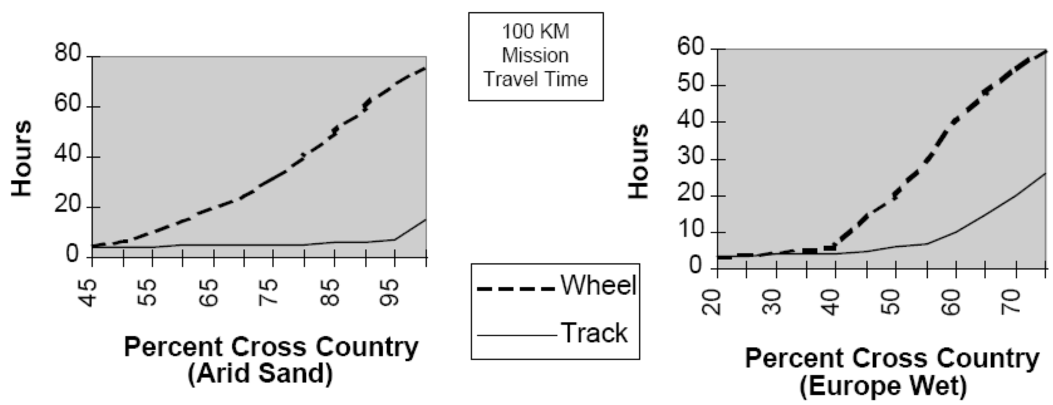


Figure 3.1. Compares the 100 km travel time as off-road usage increases (Source: Hornback 1998)

Tracked vehicles are more compact than wheeled vehicles if design is considered. The primary reasons for a tracked vehicle's compactness are reduced suspension clearance. Wheel turning clearance, and the absence of multiple transfer cases and drive shafts that are integral to the design of multi-wheeled vehicles.

When the studies are analyzed it can see that the same gross vehicle weight, wheeled platforms require up to six times more volume for drive train and suspension components than tracked platforms. This results in up to a 28 % increase in vehicle volume if the same interior volume is maintained.

Wheeled vehicles may now be able to continue movement for limited distances at reduced speeds when tires are punctured by small obstacles or debris, due to the advent of run-flat tires.

Moreover, wheeled vehicles provide a reduced noise signature while moving because of less vibration and metal to metal contact on running gear.

Wheeled vehicles traditionally offer better fuel economy. It means directly that smaller on-board fuel storage requirements or greater operating ranges.

Wheeled vehicles are more reliable than tracked vehicles therefore they require less maintenance. However, it must not be forgotten that wheeled vehicles generally have a higher usage percentage on-road while tracked vehicles generally use on off-roads. Obviously, the more severe cross-country terrain results in reduced reliability for the tracked vehicle.

Wheeled platforms offer better fuel economy and reliability, then operating and support costs are lower than those demonstrated by tracked platforms. But tracked vehicles provide smaller area, reduced volume, improved maneuverability, and adequate to severe off road conditions. So tracks should be appropriate for firefighting robot's locomotion system. (Hornback 1998)

3.1. Kinematic Analysis

Kinematics is the science of motion. In the firefighting robot movement, it is the study of the positions, velocities and accelerations during motion without considering the forces that cause this motion. The relationship between motion, and the associated forces and torques is studied in dynamics.

To be used in the firefighting robot calculations, it is assumed that the centre of mass of the tracks and track frame is located above the centroid of the combined track areas. (Garcia-Cerezo, et al. 2004)

As drawn, the vehicle is turning to the left, and may be accelerating in the x, y and Ø directions. The velocity components of the robot is x’, ý and Ǿ. The y-velocity is termed the sideslip velocity, Ǿ is the yaw rate.

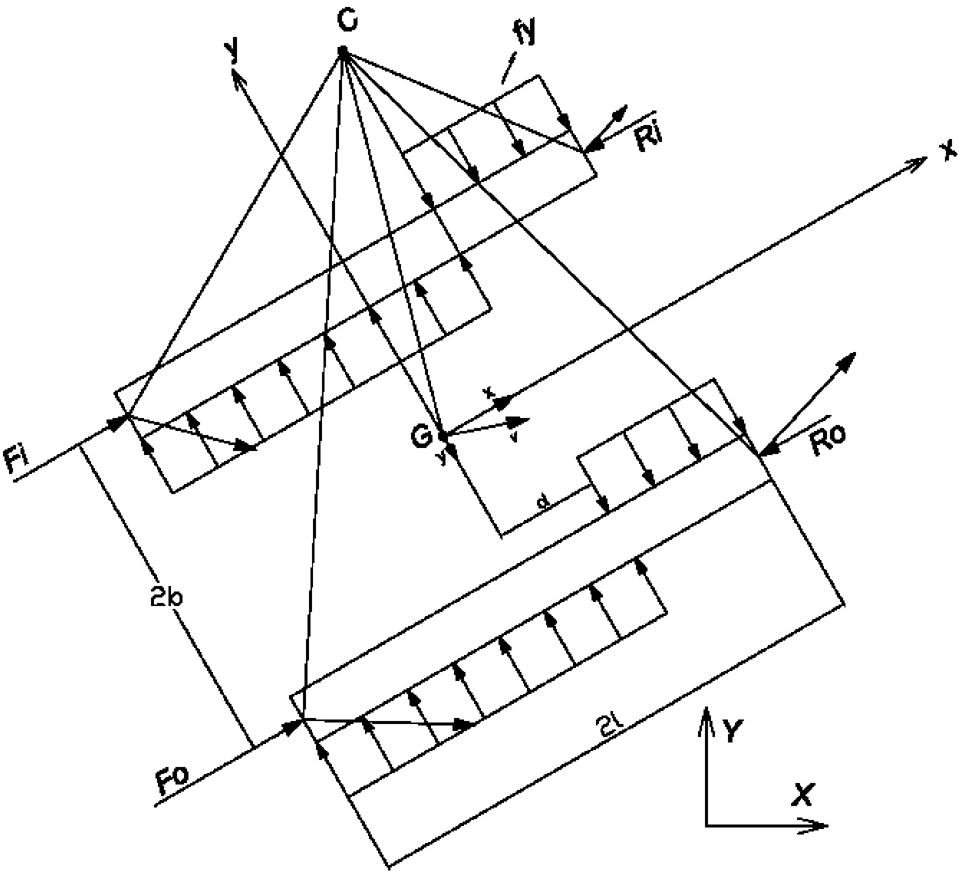


Figure 3.2. Forces acting the fireproof fire rescue robot when it is turning
(Source: Ahmadi, et al. 2000)

C is the instaneous centre of the vehicle and the frame is rotating around C point. In general, velocity of the robot (ϑ) can be given as;

$$\vartheta = r\eta \quad (3.1)$$

where r is the radius of pulley and η is the motor turnover speed at the value of rev/min.

For calculating turning radius first some illustrations should be done; like the velocity of robot's left and right tracks are by order of v_L and v_R when the robot turns right. So the robot velocity is;

$$v = \frac{v_L + v_R}{2} \tag{3.2}$$

If R is described as a radius of curvature then;

$$v_L = R\omega_L \tag{3.3}$$

$$v_R = R\omega_R \tag{3.4}$$

where

ω_L : angular velocities of the outside (left side) track

ω_R: angular velocities of the inside (right side) track

If slips are considered then equation (3.3) and (3.4) became;

$$v_L = R\omega_L(1 - i_L) \tag{3.5}$$

$$v_R = R\omega_R(1 - i_R) \tag{3.6}$$

After substituting (3.5) and (3.6) velocity is;

$$v = \frac{R\omega_L(1-i_L) + R\omega_R(1-i_R)}{2} \tag{3.7}$$

where R is the track rolling radius.

A kinematic model of the vehicle that relates the slip parameters to the track frame velocities is required for slip estimation. A suitable model can be written in the frame like;

$$x' = \frac{R\omega_R(1-i_L) + R\omega_L(1-i_R)}{2} \tag{3.8}$$

$$\acute{y} = -x' \tan \propto = -x'\delta \tag{3.9}$$

$$\acute{\emptyset} = \frac{R\omega_R(1-i_L) - R\omega_L(1-i_R)}{2b} \tag{3.10}$$

where 2b is the distance between tracks.

The slip parameters are the slip angle coefficient $\delta = \tan \propto = -\acute{y}/x'$, the left and right track slips i_L, i_R

$$i_L = V_{jL}/R\omega_L \tag{3.11}$$

$$i_R = V_{jR}/R\omega_R \tag{3.12}$$

where V_j, is the longitudinal velocity of track sliding with respect to the terrain. The relative sliding velocity depends on the vehicle's motion and the control inputs ω_L and ω_R.

$$V_{jL} = x' - b\acute{\emptyset} - R\omega_L \tag{3.13}$$

$$V_{jR} = x' + b\acute{\emptyset} - R\omega_R \tag{3.14}$$

Observe that R ω is the forward velocity of the track frame when the slip is absent. Slip is defined to be positive when the tractive effort produced assists the longitudinal motion. The kinematic equations become

$$X' = \frac{R\omega_R(1-i_L)+R\omega_L(1-i_R)}{2}\cos\emptyset + x'\delta\sin\emptyset \tag{3.15}$$

$$Y' = \frac{R\omega_R(1-i_L)+R\omega_L(1-i_R)}{2}\sin\emptyset - x'\delta\cos\emptyset \tag{3.16}$$

$$\acute{\emptyset} = \frac{R\omega_R(1-i_L)-R\omega_L(1-i_R)}{2b} \tag{3.17}$$

These are the equations for kinematic analysis of the robot. In forward chapters values will be substituted in these equations and find the number values for use only the firefighting robot. (Ahmadi, Polotski and Hurteau 2000)

3.2. Dynamic Analysis

The torque of a robot is its ability to rotate its shaft with resistance. To calculate torque at driving shafts the force at the wheel surface (F is N value) and the radius of the wheels (r is m value) are needed. Then torque is;

$$\tau = F * r \tag{3.18}$$

where F is;

$$F = m * g \tag{3.19}$$

If R is symbolizing the reduction of the gearbox between driving shaft and the motor then minimum motor torque, this is needed to climb at slope surface is;

$$\tau_m = \tau * R \tag{3.20}$$

While the acceleration of the robot is constantly 1 m/s^2 angular acceleration of the driving shaft is needed to calculate minimum torque.

$$\alpha = \omega^2 r \tag{3.21}$$

where is angular velocity of the driving shaft (rad/s). Then angular acceleration of the driving shaft is:

$$\tau = I\alpha \tag{3.22}$$

where I is inertia of the system. When equation (3.21) is substituted to equation (3.22) then angular acceleration of the driving shaft (Nm) turns to;

$$\tau = I\omega^2 r \tag{3.23}$$

Also angular acceleration of the driving shaft can be written as

$$\tau = I\frac{\vartheta^2}{r} \tag{3.24}$$

where $\omega = \vartheta/r$, (m/s) is velocity of the system.

And P is the power in watt as

$$P = \tau\omega \tag{3.25}$$

CHAPTER 4

MECHANICAL DESIGN OF FIREPROOF FIRE RESCUE ROBOT

As it was told before, within the context of this thesis it was planned to build a mobile fireproof firefighting robot which will get into fire which is worked on different type of ground.

Main purpose of the robot is to reach fire area, spray the extinguisher foam after operator's order and extinguish it while having information about fire behavior with the help of camera, microphone. There are some firefighting robots which were built for the same reason but they are not mobile robots in the proper sense; they have cable or hose connection from fire area to outside. Also they are sprayed extinguisher near of the fire not in the middle of fire.

There are some difficulties to over come while extinguishing fire. These situations must be considered while designing the firefighting robot. When building a robot firstly its restrictions should be thought after that the robot is started to design and manufactured. These restrictions can be on different parameters like weight, height and manufacturing ease.

From the below there are short explanations for fireproof firefighting robot design parameters.

1. The robot velocity should be low enough to extinguish fire. Human walking speed (3 km/h) is adequate for it.
2. The weight of the robot should be as light as possible not to crumble debris.
3. Dimensions of the robot are also should be as small as possible to come into small holes.
4. Height of the robot from the ground desired to be high for not to tail obstacles.
5. Energy requirement will be effected proportionally with the weight and size of the robot and also motors power and number.

6. Also batteries are lasted along mission time at least 15 minutes.
7. The mechanical design should be allowed electronic parts dispose easily without interfere each other.
8. The less part make the robot simple and make the repair easy if it is ought to.
9. The manufacturing of the robot should be simple because the less operation time and the cheapest way of manufacturing are preferred.
10. Maneuver ability of the robot makes the robot more useful for its mission.
11. The programming of the robot should be as basic as possible so that understanding and changing of it will be easy.
12. The robot must have fire and heat resistance.

The design has to be able to move over on a ground and get into fire. Also the design has to be able to send and get camera views and radio frequencies from incident area to operator's area.

4.1. Sketches

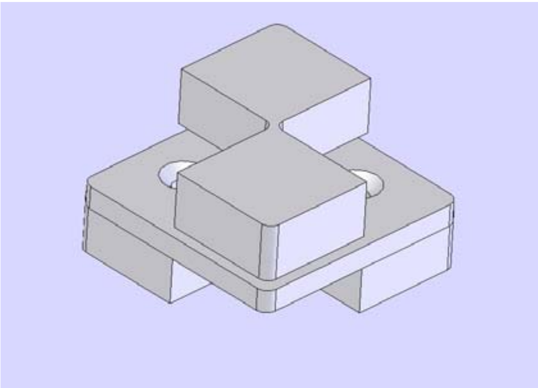
Matters that considered and decided for fireproof firefighting robot before manufacture is explained below:

- Design has to be able to get into middle of fire as its function
- A moving tracked mechanism will be used
- System has to have enough power to get into fire, spray extinguisher and works on camera and run at least for 15 minutes with full batteries.

At this step we should created more than one sketch. Then advantages and disadvantages of all mechanisms which were designed are examined shortly. After that one of them is chosen for manufactured as a prototype of fireproof firefighting robot.

- **Sketch 1:**

The thought of this sketch has different form for preventing itself from heat. Not to break down the robot because of heat ceramic tiles which are locked each other thus there is nowhere to enter outside heat, it is shown in Figure 4.1, are used. They are mounted robot's main body with the help of nuts and bolts.



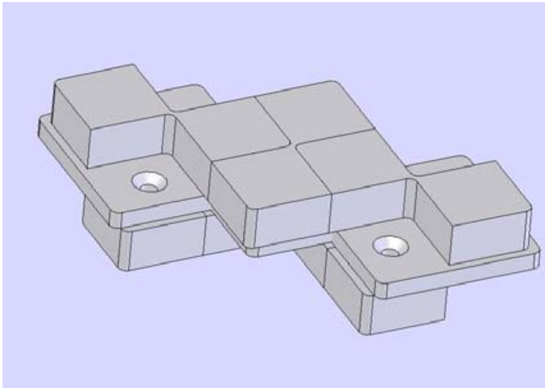


Figure 4.1. Ceramic tiles Figure 4.2. Locked ceramic tiles

But these ceramic tiles are not standard tiles, they are custom made. To manufacture them person who is master on this subject, a ceramic oven and money and time needs. Besides this they are brittle structures so they need attention while they are placing. Also these tiles should be problem while the robot moves along in the fire area, if a hard thing hit the robot outer part they should be break and then heat goes away from the fracture area.

- **Sketch 2:**

One of the sketches is the one which is thought to circulate liquid nitrogen between two walls (outer and inner walls) of the robot for cooling, shows in Figure 4.3. In case of necessity fire blanket and oxygen tube is given to victim so that victims can survive themselves.

Different from other sketches in this sketch it is required that work cooling system which uses liquid nitrogen automatically to prevent itself from heat. Phase change is included in this system. It is very efficient for cooling applications but this system is needed wide area, specific apparatus and parts which is expensive and hard to manufacture. Also it needs very complex calculations, accurate results and people who have knowledge about liquid nitrogen.

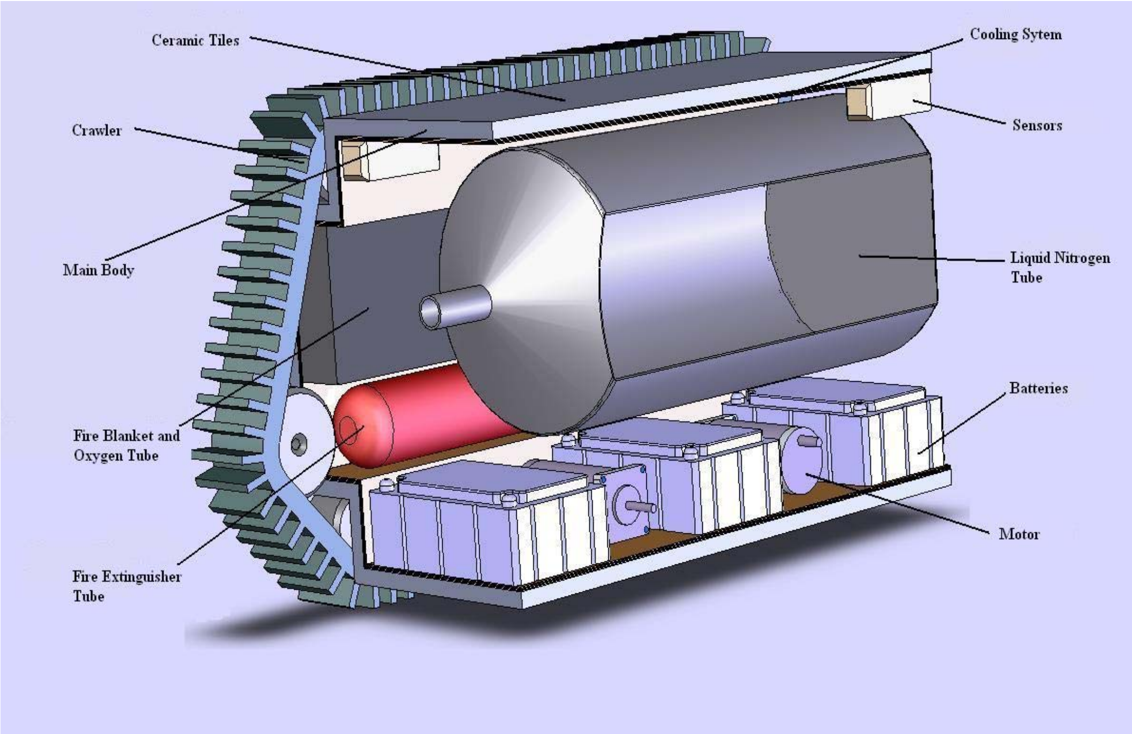


Figure 4.3. Cross sectional view of sketch 2

- **Sketch 3:**

This design is the basic design but the cheapest and easiest one. There is no cooling system in it or no brittle structure on it. This model is shown in Figure 4.4. The heat protection is ensured with adequate thickness ceramic fiber paper covering. The thickness of it is determined theoretically with using heat transfer equations only little variance. Heat and flame resistant ceramic fiber paper are found easily from suppliers. It is light, needs less area and not very expensive as compared with other designs' insulation methods. Moreover this it is easy to mount main body.

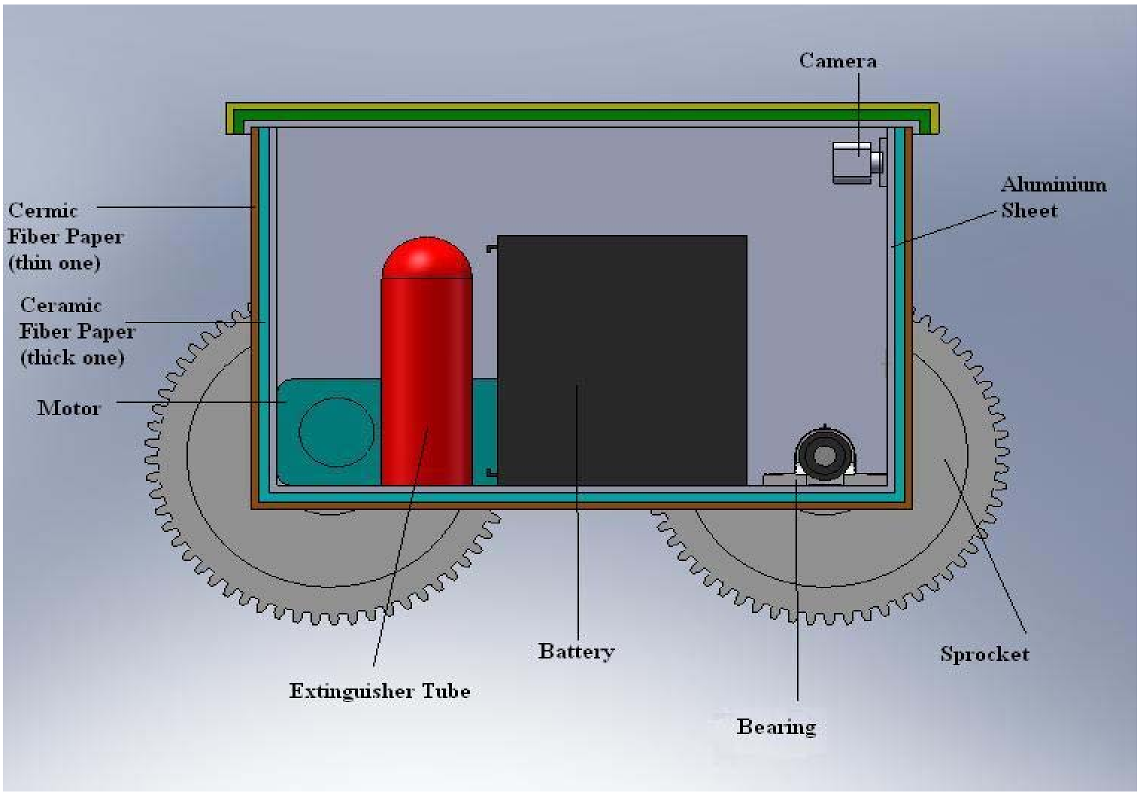


Figure 4.4. Cross sectional view of sketch 3

Because of all of these advantages and disadvantages the most comprehensible way for making the firefighting robot is the last design which is shown Figure 4.4.

Also all of the designs which are controlled by remote control to put together information about fire have camera, microphone and extinguisher tube. This kind of robot is called teleoperated robot that is commanded by a human and operated by remote control. The typical “tele-robot” uses a video camera that serves as the eyes for the human operator. From some distance the operator views the scene and commands it accordingly. Some kind of sensors like temperature sensors, carbon dioxide or oxygen level sensors, combustible gas sensors and location sensors is used optionally if they fit the system.

Furthermore it is consider that tracked type locomotion system has many advantages for our mission when compared to the wheeled one.

4.2. Track System

The most common tracked system is two–tracked system which is used in the fireproof firefighting robot. It is simple, easy to understand, and relatively easy to construct. Two tracks are attached to both sides of the robot's main chassis, and each is powered by their own motor. In this design, the motor mounted substantially inside the robot and attached directly to the drive sprocket.

Another locomotion system for two-tracked system is to place the two tracks inner part of the robot. In this system stability can be problem; it needs accurate calculations to state precisely where the tracks mount. It is more complex and hard to mount. Also this system has a big disadvantage for firefighting robot, because of being closer electronic parts heat can be pass easily against normal two-tracked system.

If the robot will be bigger the track system could change to more complex system which is to have the two tracks driven through a differential, and the robot steered by a conventional set of wheels mounted in front of the tracks. This design is about when large vehicles did not have enough traction on unprepared roads and replacing the rear wheels with track systems that took up solved that problem. These tracks were called half-tracks. For a mobile robot, this is a less satisfactory locomotion system since it can no longer turn in place like the basic two-track layout can.

4.3. Power Requirements for the Robot

Locomotion system of robots, which includes the motors, gears, wheels or tracks and other components directly related to robotic locomotion, allows the robot to move through the ground.

It is known that main part of the drive train is the motor. Although there are many different kinds of electric motors adapted for use in locomotion system DC motors and stepper motors are best fit for motion control systems.

DC motor uses magnets and windings of wire to generate rotation through electromagnetic induction and always uses direct current to power the motor. The current is provided from batteries or AC wall current with the help of converter. DC motors are in different sizes and weights depending on the robot's specification.

DC motors spin more quickly than the wheels need so that the high rotation speeds can make the use of DC motors difficult. Moreover additional mechanical systems (such as gears, belts, sprockets, and chains) are used to slow down DC motor speed and increase its torque. It is called servo motor which has together DC motor, gearbox (set of gear) and a motor controller that allows for precise control of the motion of the motor's axle, inside a housing that protects the whole assembly.

Even more important than moving power around, gears are used to convert the high-speed, low-torque output from a DC motor to the slow and strong motion you need to move arms, legs, and other robot body parts. Gears are the most compact way of upping the torque/lower revolutions per minute (RPM) of a motor.

A stepper motor operates on the same basic principles of DC motor, different from DC ones stepper motor has its magnets on the rotating shaft and its wire windings on the inside of motor wall. Because of this difference the rotating shaft can move from one discrete coil winding, which is called a stator, to the next. The move from one stator to another gives the motor its “step” name.

The stepper motors speed controlled can be done more precisely than DC motors. Also these types of motors do not need gears to slow down its rotation speed. But stepper motors have a big disadvantage like needing more power to operate, different electronic circuits and their efficiency less than other motor types.

Except from DC and stepper motor linear motor is counted another drive alternative. It is move the load rapidly without any additional mechanism. Also these motors are accurately went their destination at high speed because they have no moving parts in contact with each other. Linear motors are needed expensive sensors for feedback action than other types of motors. Moreover linear motors are inability to dissipate heat easily as the other types.

Stepper motors are cheap and reliable choices for many robot systems which do not require the rapid acceleration and accurate positioning. Increased position accuracy can be obtained by enclosing the motors in control loops. But DC motors are usually selected for applications that require more precise positioning.

To select an enough power motor a simple torque calculation had been done according to the weight of the robot. At first the robot’s weight was thought to be around 35kg. It shouldn’t be forgotten that this value was a theoretical value not the real one and even 1 kg of weight increases make the power consumption increased dramatically. To carry the load on ground, the motors should apply the forces more than as the frictional forces. Most dry materials in combination have friction coefficient values between 0.3 and 0.6. When finding the frictional forces it is assumed that the coefficient of friction is about 0.45 and the entire load on the robot is affected from this friction. The formula used for determining the motor rating is:

$$P_m = F_{app} \,.\, \nu \tag{4.1}$$

where,

P_m = the required power

F_{app} = applied force

ν = velocity of the robot

The velocity of the robot is found by multiplying the perimeter of the wheel with the expected revolution number of the sprocket. The velocity of the robot:

$$\nu = 2\pi r \eta \tag{4.2}$$

$$\nu = \pi \text{ x } 210 \text{ mm x } 0.2 \text{ rev / s} \tag{4.3}$$

ν = 132 mm / s = 0.132 m / s

So,

$$P_m = 31.5 \text{ kg} \,.\, 9.81 \text{ m / s}^2 \,.\, 0.3 \,.\, 0.132 \text{ m / s} \tag{4.4}$$

P_m = 12.24 W

To find the operating torque of the motor, the power could be divided by the rotational speed, that is:

$$\tau = P_m / \omega \tag{4.5}$$

where

ω = rotational speed,

$$\omega = \nu / r = 0{,}132 \text{ m/s} / 0.105 \text{ m} \tag{4.6}$$

$\omega = 1.257 \text{ s}^{-1}$

$$\tau = 12.24 \text{ W} / 1.257 \text{ s}^{-1} \tag{4.7}$$

τ = 9.74 Nm

As a result, a motor with torque of 10 Nm should be selected from the catalogs.

The fireproof fire rescue robot has two old DC servo motors (Figure 4.5), which provide enough torque and velocity to get over the obstacles. They were made in West Germany so there has been no knowledge about that motors. By controlling two engines separately robot can move towards to any direction. Furthermore it can turn around itself. Side tracks provide high mobility while overtaking the obstacles. Motors which are used in the fireproof fire rescue robot are fed with 12 V DC.

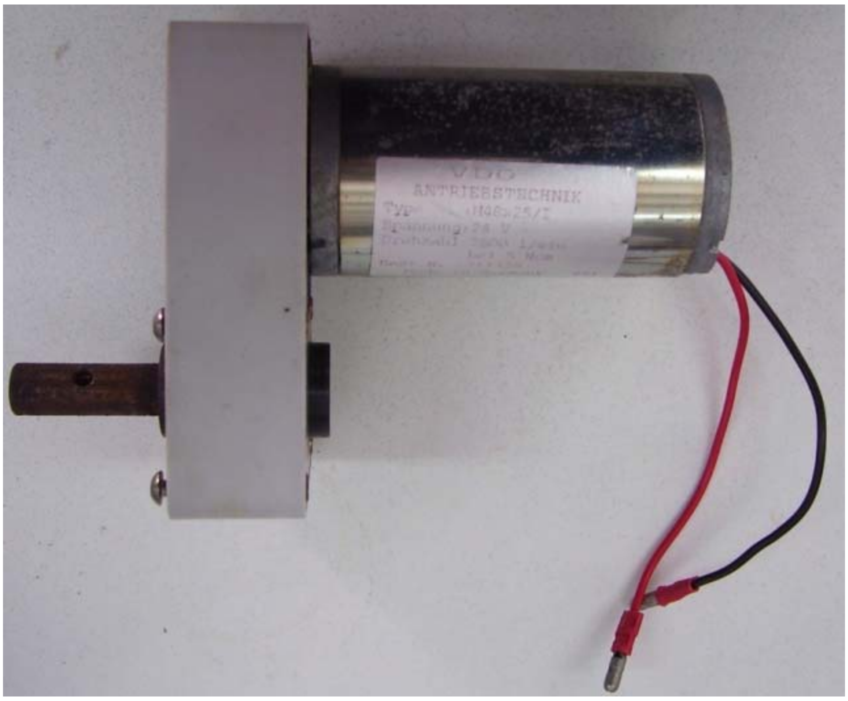


Figure 4.5. DC servo motor of the robot

4.4. Battery

Most of the robots are generally powered by batteries which process chemicals, either wet or dry. Batteries are important parts of robot design, as important as the frame, motor, and electronic circuit. They create an electrical current; it is sent through wires to actuators, sensors, and controllers.

From the chemical nature of batteries there are complex varieties of properties that determine the performance of a battery are:

- **Rechargeabi1ity:** A battery that cannot be recharged is called primary cell. One that can be recharged is called secondary cell or storage battery.
- **Energy Density:** The most important parameter of battery technology is energy density. Energy density is the maximum amount of energy per unit mass of a battery which is able to store. Energy density is measured in units of Watt-hours/kilogram (Wh/kg).

- **Capacity:** Battery capacity is the amount of energy stored in a cell. Capacity is usually reported in units of amp-hours.
- **Voltage:** The voltage produced by a cell is characteristic of the particular chemical reaction occurring in the battery. Although it is desirable for a battery to maintain a constant voltage under load that voltage changes with the state of charge.
- **Internal Resistance:** The current supplied by a battery is limited by its internal resistance. The internal resistance increases as the battery discharges.

It was wanted that a good battery would have very high energy density, maintain a constant voltage during discharge, have a low internal resistance, and therefore be capable of rapid discharge. It should also be rechargeable, and cheap. Unfortunately, there is no single battery type provides all of these characteristics. Hence, in practice, it is necessary to make decision at optimum characteristics depending on the requirements of the task. The information in Table 4.1 may serve as a guide when choosing the proper type of battery.

Table 4.1. Comparison of characteristics for selected batteries and sizes (Source: Flynn, et al. 1998)

Battery Chemistry	Recharge	Energy Density (Whr/kg)	Voltage	Capacity (mAh)	Internal Resistance (ohms)
Alkaline	No	130	1.5	AA 1400 C 4500 D 10000	0,1
Lead-Acid	Yes	40	2	1,2-120 Ah	0,006 (C-size)
Lithium	No	300	3	A 1800 C 5000 D 14000	0,3
NiCd	Yes	38	1.2	AA 500 C 1800 D 4000	0,009
NiMH	Yes	57	1.3	AA 1100 4/3A 2300	

Battery capacity, usually listed as some number of ampere-hours (informally, amp-hours) or milliamp-hours which is a practical term, not a proper unit of energy, can be misleading. To get unit of energy value, the amp-hour rating is multiplied by the voltage of the cell and gets Watt-hours. The capacity published by the manufacturer assumes a favorable discharge rate.

Secondary cells are of particular importance to robots. Also a recharging circuit built into the robot can make it truly autonomous. All it needs to do when the power is low is to find an outlet and plug itself in. But they are expensive and need space in the robot.

Main disadvantage of recharging is that it takes a several hours for the battery to regain a full charge. More sophisticated battery chargers charge batteries at much higher rates. (Flynn, et al. 1998)

4.4.1. Lead Acid Batteries

Lead-acid batteries are often used as a backup or emergency power supply for computers, lights, and telephone equipment. Lead-acid batteries typically come in self-contained packs. The existing pack can be taken apart by unsoldering the cells and use them separately. It is made up of lead plates crammed in a container that's filled with an acid-based electrolyte. These batteries have an admirable charge life. Lead-acid batteries are powerful but they are heavy. The cells are commonly available on the surplus market, and although used they still have many more years of productive life.

Lead-Acid batteries are usually sealed not to spill out the acid in it. These batteries are called as sealed lead-acid, or SLA. In these types of batteries during charging gases develops inside the battery and is vented out through very small pores, without these pores, the battery would be ruined after discharging and recharging. SLA, are common in robotics because of their high-current capabilities, reasonable cost, and relative safety but they are big and heavy batteries, this is a big disadvantage for robotic applications. They weight more than any other common robot battery type.

Sealed lead-acid batteries are available in different rectangular sizes. However energy density of these type batteries is poor, they are cheaper, have very low internal resistance, and can be recharged.

SLAs are also frequently referred to as gel-cell batteries. A gelled electrolyte battery uses a special gelled electrolyte and is the most common form of SLA batteries. They are rechargeable and provide high current for a reasonable time, which makes them perfect for robots.

The main power supplies generally used in the robotic applications are two 12V 7Ah batteries. These batteries supply 84 Watt that is enough for the fireproof fire rescue robot when the motors are loaded. Therefore, a 12V 7Ah battery is used for the robot. But these batteries are only for motion system. Although the existing battery power seemed as though it can supply the motors for several hours (Power consumption of the motors are around 12 W), this is not the case since most of the power drawned from the battery consumed by the battery’s internal resistance. By using sophisticated batteries with lower internal resistances, the runtime of the robot can be increased considerably.

Since the electronic circuits used in the robot work with 5V, the electronics need a different power supply. Two 12V 2.3Ah batteries at 27.6 W were used for circuits.

Figure 4.6. SLA Battery of the robot

4.5. Force Analysis and Strength Calculations

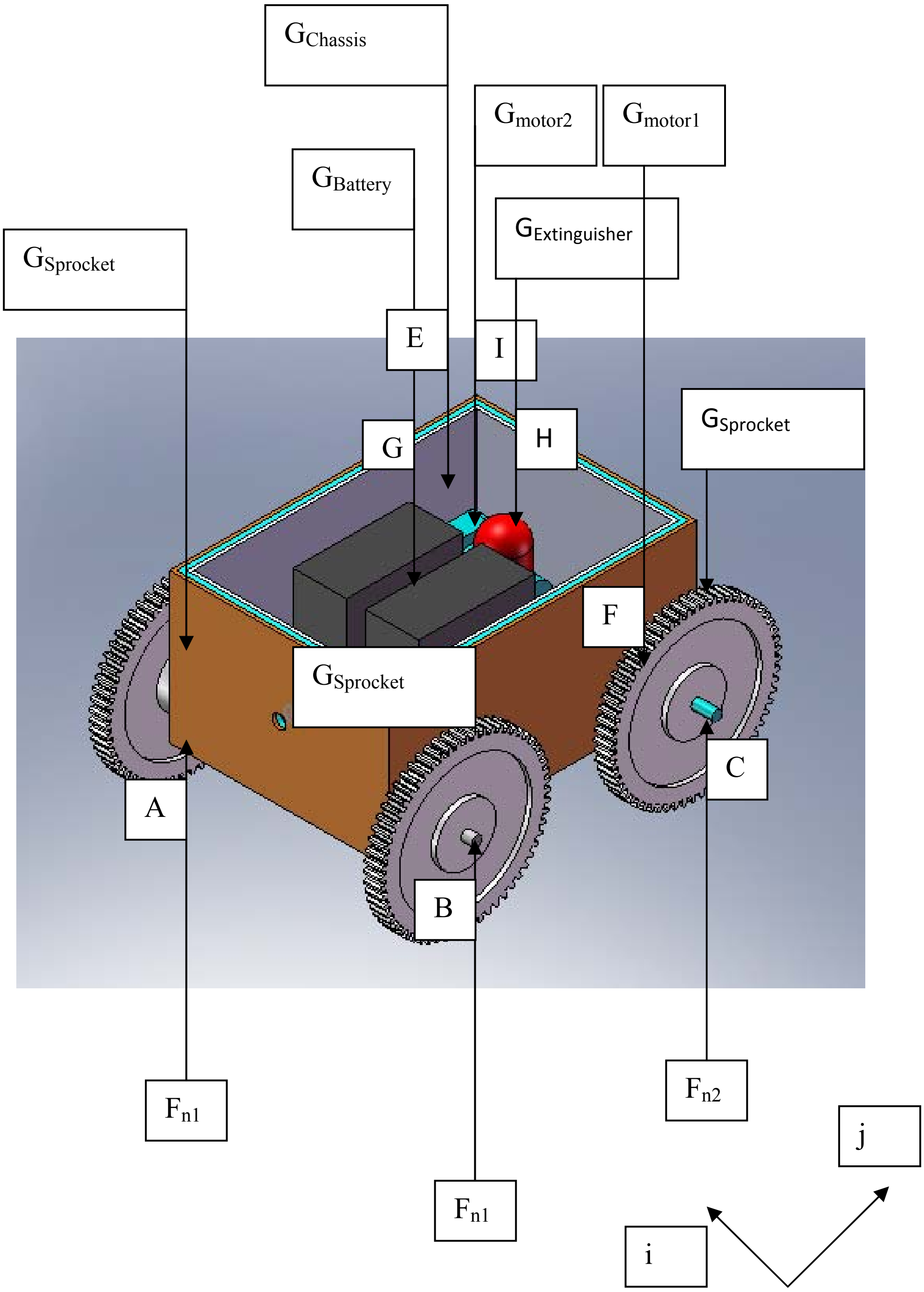


Figure 4.7. Forces acting on chassis

The forces acting on the chassis has been shown in Figure 4.7 where:

F_n = Normal force applied by the ground

$G_{Battery}$ = Force applied by the battery, 22 N

G_{Motor} = Forces applied by the motors on the chassis, each of them 11.75 N

$G_{Extinguisher}$ = Force applied by Extinguisher, 34 N

$G_{Sprocket}$ = Force applied by the sprockets, each of them 35.8 N

$G_{Chassis}$ = Force applied by the chassis, 68.65 N

If the moment with respect to point B has been found:

$$M_B = 0 \quad (4.8)$$

$$M_B = R_{BC} \times (G_{Sprocket} - F_{n2}) + R_{BA} \times (G_{Sprocket} - F_{n1}) + R_{BG} \times G_{Battery} + R_{BH} \times G_{Extinguisher} + R_{BF} \times G_{Motor1} + R_{BE} \times G_{Chassis} + R_{BI} \times G_{Motor2} + R_{BD} \times (G_{Sprocket} - F_{n2}) \quad (4.9)$$

$R_{BC} = 380\ \mathbf{j}$ mm

$R_{BA} = 482.5\ \mathbf{i}$ mm

$R_{BD} = (482.5\ \mathbf{i} + 380\ \mathbf{j})$ mm

$R_{BH} = (241.25\ \mathbf{i} + 130\ \mathbf{j} - 170\ \mathbf{k})$ mm

$R_{BG} = (241.25\ \mathbf{i} + 255\ \mathbf{j} - 13.75\ \mathbf{k})$ mm

$R_{BE} = (241.25\ \mathbf{i} + 190\ \mathbf{j} + 157.5\ \mathbf{k})$ mm

$R_{BF} = (110\ \mathbf{i} + 380\ \mathbf{j})$ mm

$R_{BI} = (302.5\ \mathbf{i} + 380\ \mathbf{j})$ mm

$G_{Chassis} = 68.65\ \mathbf{z}$ N

$G_{Sprocket} = 35.8\ \mathbf{z}$ N

$G_{Motor1} = G_{Motor2} = 11.75\ \mathbf{z}$ N

$G_{Battery} = 22\ \mathbf{z}$ N x 2 = $44\ \mathbf{z}$ N

$G_{Extinguisher} = 34\ \mathbf{z}$ N

$$M_B = (380\ \mathbf{j})\ \text{mm} \times (35.8 - F_{n2})\ \mathbf{k} + 482.5\ \mathbf{i}\ \text{mm} \times (35.8 - F_{n1})\ \mathbf{k} + (241.25\ \mathbf{i} + 255\ \mathbf{j} - 13.75\ \mathbf{k})\ \text{mm} \times 44\ \mathbf{k}\ \text{N} + (241.25\ \mathbf{i} + 130\ \mathbf{j} - 170\ \mathbf{k})\ \text{mm} \times 34\ \mathbf{k}\ \text{N} + (110\ \mathbf{i} + 380\ \mathbf{j})\ \text{mm} \times 11.75\ \mathbf{k}\ \text{N} + (241.25\ \mathbf{i} + 190\ \mathbf{j} + 157.5\ \mathbf{k})\ \text{mm} \times 68.65\ \mathbf{k}\ \text{N} + (302.5\ \mathbf{i} + 380\ \mathbf{j})\ \text{mm} \times 11.75\ \mathbf{k}\ \text{N} + (482.5\ \mathbf{i} + 380\ \mathbf{j})\ \text{mm} \times (35.8 - F_{n2})\ \mathbf{k}\ \text{N} = 0 \quad (4.10)$$

If the **i** components of the forces are set equal to zero:

F_{n2} = 85.29 N in (- k) direction

If the **j** components of the forces are set equal to zero:

F_{n1} = 69.68 N in (-k) direction

When the load on the motor is considered, there have been problems since the motors are old and there are no data sheets. To determine the static load on the shaft of the motor it is assumed that the entire load on the motor is taken by the bearings. Again, there are no catalog values for the bearings. The free-body diagram is shown in Figure 9.2. To find the static loads on the bearings F_{b1} and F_{b2}:

To find the moment with respect to point A:

$$M_A = R_{CA} \times F_{n2} + R_{BA} \times F_{b1} = 0 \qquad (4.11)$$

R_{CA} = 110 **j** mm

R_{BA} = 35 **j** mm

F_{n2} = -85.29 **k** N

$$110\ \mathbf{j}\ \text{mm} \times -85.29\ \mathbf{k}\ \text{N} + 35\ \mathbf{j}\ \text{mm} \times F_{b1}\ \mathbf{k} = 0 \qquad (4.12)$$

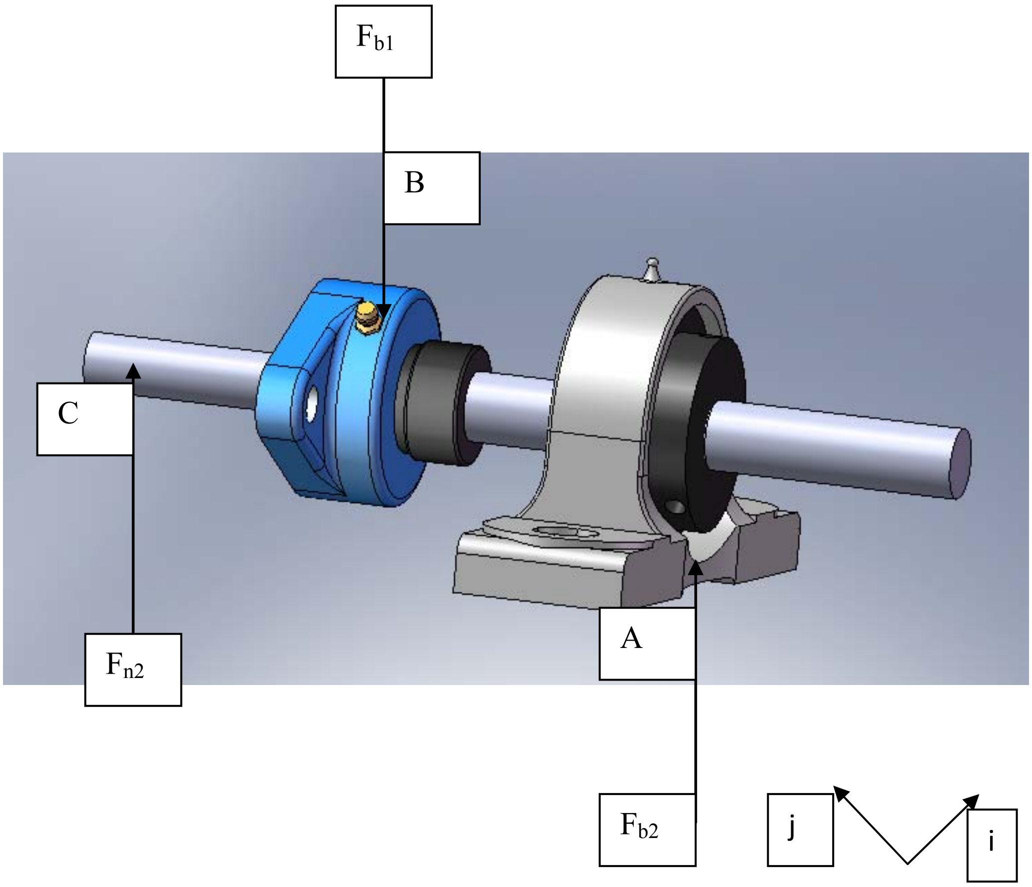


Figure 4.8. Normal force acting on the wheel and the bearing

$$35F_{b1} = 9381.9 \text{ N.mm} \quad (4.13)$$

$F_{b1} = 268.05$ N

$$\Sigma F = 0 \quad (4.14)$$

$$F_{n2} + F_{b2} - F_{b1} = 0 \quad (4.15)$$

$$85.29 \text{ N} + F_{b2} - 268.05 \text{ N} = 0 \quad (4.16)$$

$F_{b2} = 182.76$ N

Since the bearings are the same, the load on the first one is critical. To resist this load, the bearing should have a catalog rating F_R that equals to:

$$F_R = F_b (N_b / N_R)^{(1/a)} \quad (4.17)$$

where

F_b = required radial design load

N_b = total number of design revolutions

N_R = total number of revolutions of the catalog bearing

To find the number of revolutions:

$$N_b = 60\ L_b\ .\ n_d \tag{4.18}$$

$$N_R = 60\ L_R\ .\ n_R \tag{4.19}$$

L_b = required design life, h

L_R = catalog rated life, h

n_d = required design speed, rev/min

n_R = catalog rated speed, rev/min

To find the required design life of the bearing, it is assumed that the motor will be used for half an hour per fire and there will be 260 fires in one year. The robot is assumed to be functional for five years. Also, since the motors had been used for about 25 years, it is important to add this to the calculations. It is thought that they were used for 200 days in a year and 3 hours a day. Therefore the design life should be:

$$L_b\text{=0.5h/fire x 260fires/year x 5years + 3h/day x 200days/year x 25years} \tag{4.20}$$

L_b=15650 hours

The required design speed is 12rev/min when the motor is used at a voltage level of 12V. To find the catalog rated life of the bearing, the bearings of Timken Company are taken as examples. Timken Company rates their bearings for 3000 hours t a speed of 500rev/min. Then the catalog rated life becomes 3000 h and the catalog rated speed is 500rev/min.

The constant "a" equals to 3 for ball bearings. From the found values the catalog rating is calculated:

$$F_R = 268.05\text{ N }[(15650 \text{ x } 12) / (3\ 000 \text{ x } 500)]^{(1/3)} \tag{4.21}$$

F_R = 134 N

The AFBMA has established a standard load rating for bearing called the basic load rating, C. It is defined as the constant radial load which a group of apparently identical bearings can endure for a rating life of one million revolutions of the inner ring. It equals to:

$$C = F \text{ x } L^{(1/a)} \tag{4.22}$$

The rated revolution value for bearings of Timken Company is:

$$L = 3000\text{h x 60 min/h x 500 rev/min} = 90 \text{ x } (10^6)\text{ rev} \tag{4.23}$$

So, the load rating equals to:

$$C = 134 \text{ N x } 90^{(1/3)} \qquad (4.24)$$

C = 600 N

When the catalog of the Timken Company is considered for their single-row angular-contact ball bearings, it can be seen that the bearings with a bore diameter of 12 mm, can resist loads round 7.02kN, that is more than ten times the found load rating. So, the bearings that are found inside the motor housing will be enough for carrying the service load. (Mischke and Shigley 1989)

4.6.Shaft Analysis

The loads on the manufactured shaft have been shown in Figure 4.9 below.

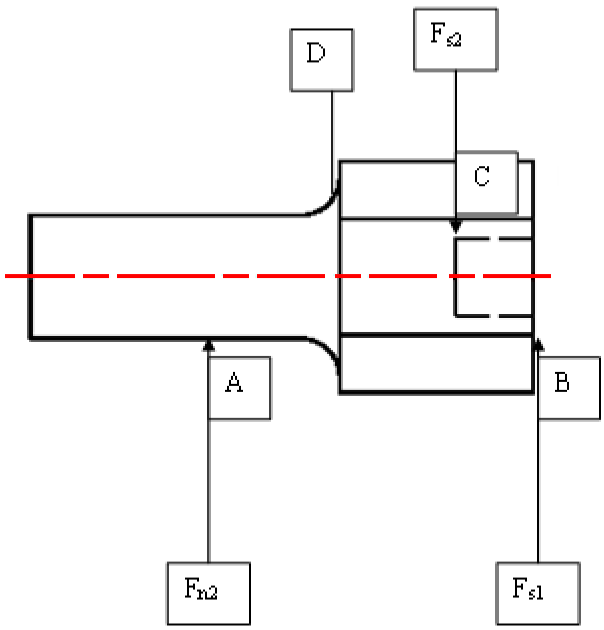


Figure 4.9. The loads on the shaft between the motors and the wheels

F_{n2} equals to 85.29 N. When the moment with respect to B is found:

$$M_B = R_{BC} \times F_{s2} - R_{BA} \times F_{n2} = 0 \qquad (4.25)$$

R_{BC} = 25 mm

R_{BA} = 72.5 mm

$$72.5 \text{ mm x } 85.29 \text{ N} = 25 \text{ mm x } F_{s2} \quad (4.26)$$

$$F_{s2} = 247.341 \text{ N}$$

$$\Sigma F = 0 \quad (4.27)$$

$$F_{s1} + F_{n2} - F_{s2} = 0 \quad (4.28)$$

$F_{s1} = 162.051$ N

The material of the shaft is 2017 wrought Aluminum. The ultimate tensile strength is found to be 179MPa. When the shape of the shaft is examined, the failure will probably occur at point D, since it has the smallest cross-section, a higher bending moment and a higher stress concentration factor than elsewhere.

To find the estimated life of the shaft, it is decided to find the strength at point D first and then compare this value with the stress on that point. For the strength of the shaft, its endurance limit should be found from its ultimate tensile strength:

$$S_e^{'} = 0.504 \text{ x } S_{ut} = 0.504 \text{ x } 179 \text{ MPa} \quad (4.29)$$

$S_e^{'} = 90$ MPa

The endurance limits modifying factors such as surface factor, size factor, load factor and miscellaneous effect factor.

- **Surface Factor (k_a)**

The surface characteristic of the shaft affects the endurance limit. The surface factor can be found by the formula:

$$k_a = a \text{ x } S_{ut}^{b} \quad (4.30)$$

where a and b are constants that depend on the surface characteristic of the shaft. The shaft is made of machined Aluminum and

a = 4.51 MPa

b = -0.265

Than,

$$k_a = 4.51 \text{ x } (179)^{-0.265} \quad (4.31)$$

$k_a = 1.14$

- **Size Factor (k_b)**

The diameter of the shaft affects the endurance limit. The size factor can be found by the empirical formula:

$$k_b = (d/7.62)^{-0.1133} \quad \text{for } 2.79 \text{ mm} < d < 51 \text{ mm} \tag{4.32}$$

The smallest shaft diameter is 20 mm. So:

$$k_b = (16/7.62)^{-0.1133} \tag{4.33}$$

$k_b = 0.919$

- **Load Factor (k_c)**

The load factor equals to unity for bending, that is:

$k_c = 1$

- **Miscellaneous-Effect Factor (k_e)**

There is a fillet that acts as a stress riser. To find the effect of this fillet, the charts of theoretical stress-concentration factors are used in Figure 4.10.

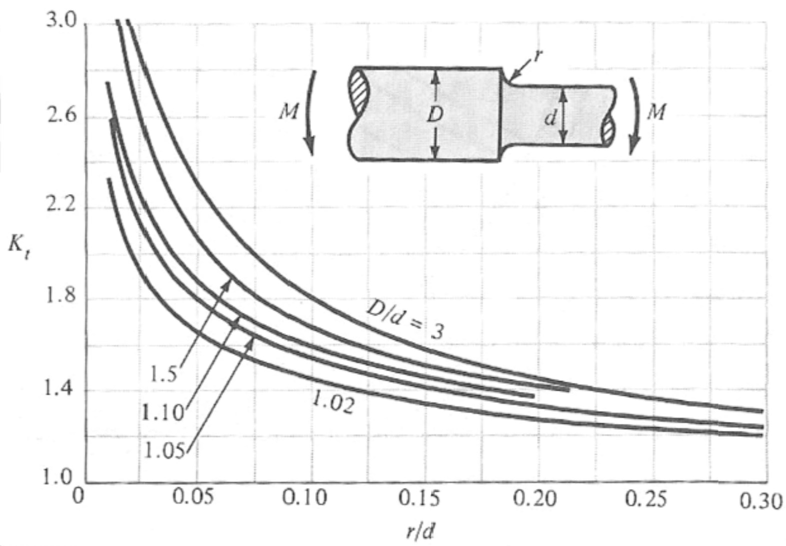


Figure 4.10. Round shaft with shoulder fillet in bending

(Source: Mischke and Shigley 1989)

The equivalent diameter the shaft is:

d_e = 20 mm = D

Then D / d equals to 1.25. Fillet radius is 4 mm and r / d equals to 0.25. From the figure, the K_t equals to 1.41. To find K_f from K_t:

$$K_f = 1 + q \times (K_t - 1) \qquad (4.34)$$

where the notch sensitivity, q, equals to 0.82 from Figure 4.11.

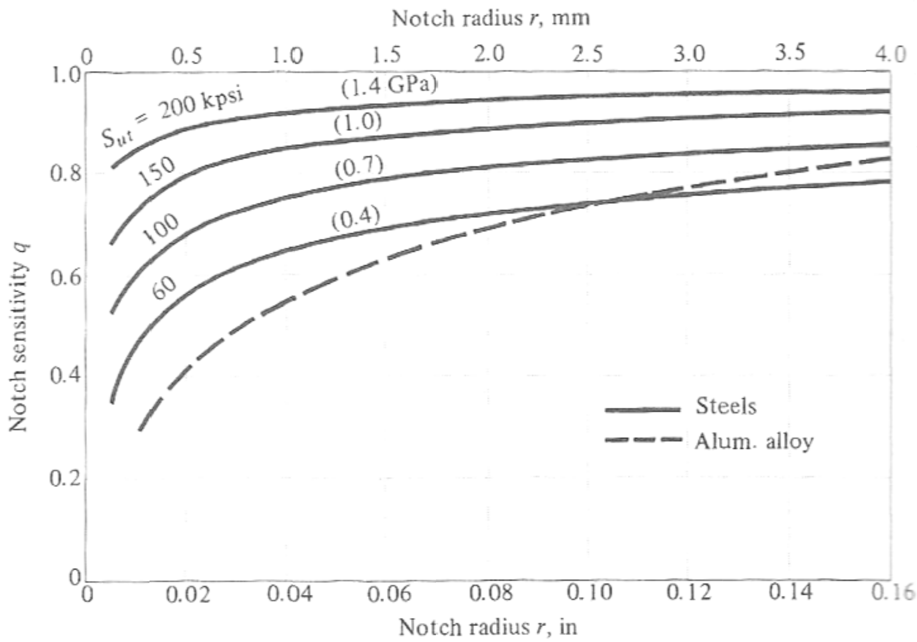


Figure 4.11. Notch sensitivity chart

(Source : Mischke and Shigley 1989)

Then:

$$K_f = 1 + 0.82 \times (1.41 - 1) = 1.3362 \qquad (4.35)$$

$$ke = 1 / K_f = 1 / 1.3362 \qquad (4.36)$$

$$k_e = 0.748$$

After finding the limiting factors of the endurance limit, the corrected endurance limit is found from equation:

$$S_e = S_e' \times k_a \times k_b \times k_c \times k_e = 90 \text{ MPa} \times 1.14 \times 0.919 \times 1 \times 0.748 \qquad (4.37)$$

S_e = 70.53 MPa

To find the bending moment at point D,

$$M_D = R_{BC} \text{ x } F_{s2} = 25 \text{ mm x } 247.341 \text{ N} \quad (4.38)$$

$$M_D = 6183.53 \text{ N.mm} = 6.18 \text{ N.m}$$

The section modulus is:

$$I / c = (\pi \,.\, d^3) / 32 = (\pi \,.\, 16^3) / 32 = 402.124 \text{ mm}^3 \quad (4.39)$$

Therefore the bending stress is:

$$\sigma = M / (I / c) = 6183.53 \text{ N.mm} / 402.124 \text{ mm}^3 \quad (4.40)$$

$$\sigma = 15.38 \text{ N / mm}^2 = 15.3\text{MPa}$$

This stress is smaller than the endurance limit, which is 70.53MPa. As a result of that, it could be assumed that the shaft will have an infinite life.

After determining the fatigue life of the shaft, it is possible to say that there is no need to implement additional bearings on the shaft. (Mischke and Shigley 1989)

The torsion on the shaft is determined by using Equation 4.41.

$$P = T\omega \quad (4.41)$$

The power of a motor used is 12 Watt and its revolution is 12 per minute. So T is found 60 Nm.

To calculate elastic torsion of the uniform shafts Equation 4.42 is used. They may also be used for a shaft of variable cross section or for a subjected to torques at locations other than its ends. Solving for τ_{max},

$$\tau_{max} = \frac{Tc}{J} \quad (4.42)$$

where J means the polar moment of inertia and T represents the internal torque.

$$J = \frac{1}{2}\pi c^4 \quad (4.43)$$

After substitution of values to related places J is found $1.57\text{x}10^{-8}$ m^4. τ_{max} 30.57 MPa where c equals to 16 mm. Proper works on shafts is obtain when equation 4.44 is satisfied.

$$\tau_{max} \leq \tau_s \quad (4.44)$$

For the investigated case it is found that τ_{max} value is smaller than τ_s which is equal to 35.265 MPa then the shaft is working on in the safe region.

4.7.Center of Gravity

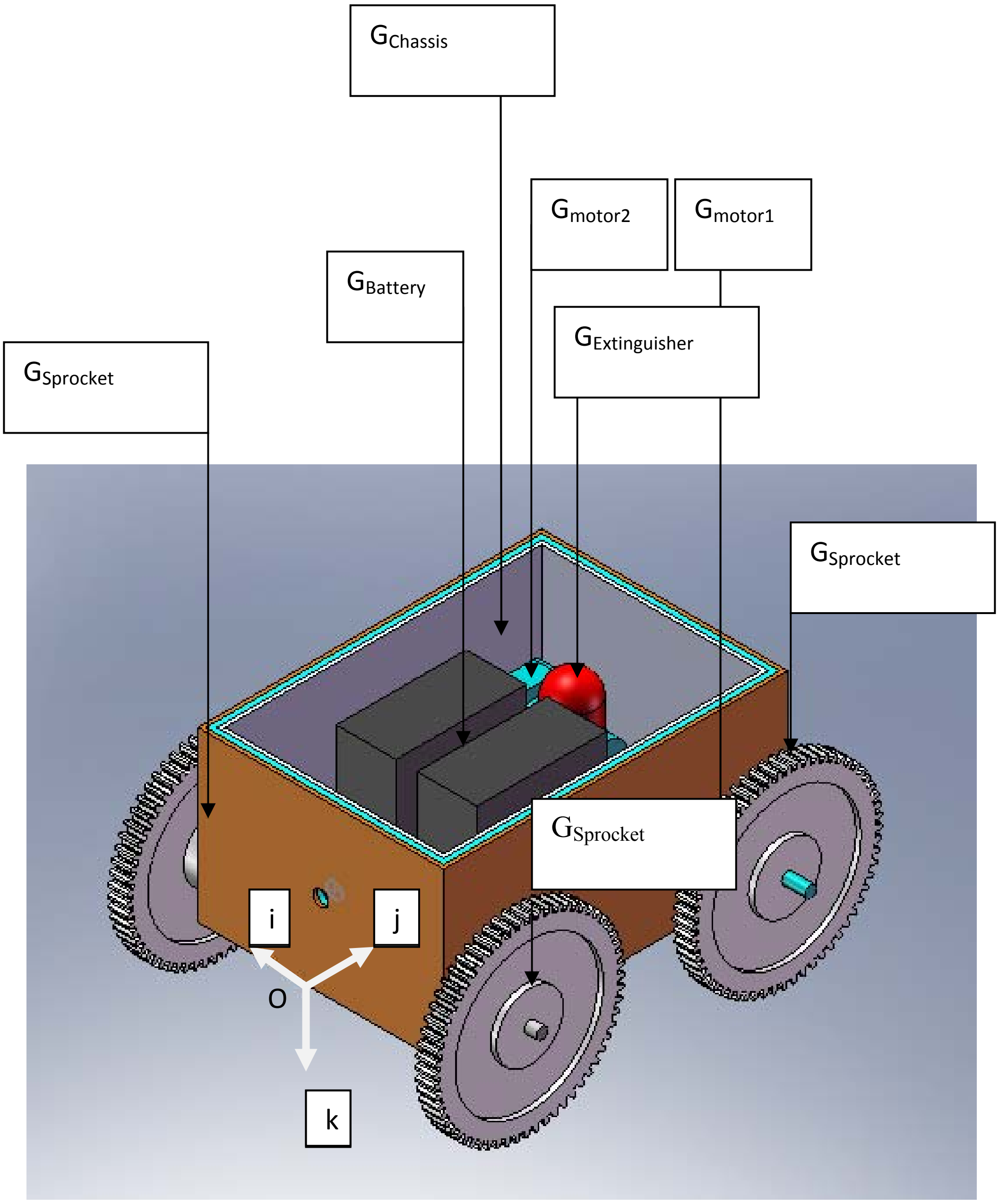


Figure 4.12. Weights of the robot parts

To find where the center of gravity of fireproof fire rescue robot is a basic equation should be solved. The equation is given as

$$r = \frac{\sum Gr}{\sum G} \tag{4.45}$$

where

G : mass of the each part of the robot

r : distance between each part's center of gravity and point O

This equation should be applied three times according to Cartesian coordinate system to find all components of the robot's center of gravity. Distances to reference point and gravity values are shown at Table 4.2 as below.

Table 4.2. Coordinates and weights of the robot parts

	G (Newton)	**i**	**j**	**k**
Sprocket A	35.8	24.75	6.75	-3.5
Sprocket B	35.8	-24.75	6.75	-3.5
Sprocket C	35.8	-24.75	44.75	-3.5
Sprocket D	35.8	24.75	44.75	-3.5
Battery	22	0	34	-4.875
Motor 1	11.75	-15.5	46.5	-3.5
Motor 2	11.75	15.5	46.5	-3.5
Extinguisher	34	0	21.5	-20.5
Chassis	68.65	0	27.5	-22.75

$$r_i = \frac{\sum G_i r_i}{\sum G_i} \quad (4.46)$$

$$r_j = \frac{\sum G_j r_j}{\sum G_j} \quad (4.47)$$

$$r_k = \frac{\sum G_k r_k}{\sum G_k} \quad (4.48)$$

After solving these equations coordinates of the center of gravity was found exactly;

r_G = 27.96302 j - 10.1235 k.

This shows that center of gravity was on the equal distance of both left and right side of the fireproof fire rescue robot so it can be said that it is at the middle of x axis. Also it is far from front approximately 28 cm and also 10 cm from bottom side of it.

Height of the fireproof fire rescue robot’s main frame is 455mm, length is 550mm and width is 330mm. Distance between two sprockets is 495mm and axle width of the robot is 515mm, axle length is 380mm. Distance of the main frame from ground is 80mm. Thickness of the main frame is 94mm which comes from 72.5 insulation thickness and 21,5mm aluminum thickness. The biggest dimension of the fireproof fire rescue robot is 515 x 557.5 x 125.5mm.

Parts of the fireproof fire rescue robot are mounted in the main frame carefully not to make robot instable. Motors were mounted back part of the robot so that the robot has rear-wheel drive ability. Batteries and extinguishers are mounted as close as mid point. Two batteries are exactly same to each other so two of them mounted same distance from side walls. Electronic circuits are not very important to where they are mounted because they are not affecting the place of center of gravity considerably. Camera is attached to the front wall of the robot to see fire.

CHAPTER 5

MANUFACTURING OF FIREPROOF FIRE RESCUE ROBOT

Up to now, the robot is sketched; scheme drawings and mechanical design of all system are done. In this chapter, the part list of the fireproof firefighting robot, which contains manufactured or purchased parts, is presented. Also manufacturing and mounting steps are explained for the robot parts.

After finishing the firefighting robot design step, manufacturing process was started. At first, some decisions should be made about which parts of the robot will be manufactured with facilities we have which parts not. The parts which will not be manufactured are purchased; also standard parts like bearings, gears are too. Purchasing as many parts as possible is the easiest way and takes the shortest time. The other parts which will be manufactured are generally made by milling cutter, bending machine and print cutter.

Mechanically fireproof firefighting robot is formed by two parts like main body of the robot and inner part of it, which includes electronic circuits, motors, batteries, fire extinguisher, and camera. Also locomotion system can be discuss as another part under main body.

Part List

Main body;

- Aluminum sheet
- Locomotion system:
    - Bearings
    - Chain
    - Shafts
    - Gears

Inner parts;

- Motor
- Battery
- Electronic Circuits
- Fire Extinguisher
- Camera

Materials used to manufacture the robot are; 2,15 mm wall thickness aluminum sheet, 20,50 mm diameter round aluminum form, 1/2" (12,7 cm) 51 teeth four sprockets, approximately 3 m length standard roller chain, two 24 V motors, two batteries which are 12V 7Aph, roller bearings, fire extinguisher tube and stainless steel pipe for it, camera, ceramic fiber paper for insulation and double side tape to attach ceramic fiber paper robot’s outer body and also cables, nuts and bolts, nut washer for mounting.

Main body of firefighting robot is constructed from four aluminum sheet parts. The last shapes of sheets were done by bending machine and print cutter machine. One of these sheets composes front, bottom and back sides, two of them are right and left side.

The rest part is upper side and this part is used to open body to work inside of the robot. These parts are mounted to each other with aluminum “L” forms.

All holes on the aluminum sheet body were made by using hand drill and power drill machine.

To provide turnings one shaft needs for all sprockets. The shafts were made from 20,50 mm diameter aluminum round form. With the help of lathe shafts diameter decreases 20 mm and surface finishing was done. Then all of them threaded M16 with man power.

Shafts which are used for front sprockets were attached the main body of the robot with two different shape roller bearings. One type which looks like diamond shape was adjusted lateral sides, the other type adjusted bottom side. Back shafts were mounted motors shafts with a screw to make proper shaft length for sprocket.

Normally sprocket and chain type is selected after some calculations were done. These calculations’ results show in a Table 5.4. But the sprockets and chain type, which are sold generally, is the most-preferred types so that the selection should be done in through them.

Table 5.1. Chain selection calculations' result

Chain type		60-H	
Service Factor	C_s	1.000	
Speed ratio	R	1.000	
Design Power	P_d	414.384	W
Rated Power	P_r	418.350	W
Pitch	P	19.050	mm
Actual center distance	C	571.70	mm
Number of chain		1.000	
Length of chain		92.000	pitches
Lubrication type		Type A	
		Input	**Output**
Number of teeth in sprockets	**N**	32	32
Actual speeds of sprockets	**N**	41.883	41.883
Pitch diameters of sprockets	**D**	194.354	194.354
Outside diameter	$\mathbf{D_0}$	204.848	204.848

For one track of the robot 1.4 m length standard roller chain which best fits the sprockets specifications was used. After the determination of the chain length, two open ends of the chain were fixed each other with a special pin by man power.

Also more than one chain strand can be used efficiently but these types of chain are sold only two or three modal, too. It needs to order a manufacturer and it takes time and more money.

Four sprockets were bought 1/2" and 51 teeth specifications. They were manufactured mass production, because of that, all of them have a flange part which have not been used in robot and made unnecessary weight. It is easy to place these parts by using lathe because they were attached to the sprockets by welding.

A small fire extinguisher tube is used for spraying out fire extinguisher foam. To control spraying with remote control a solenoid valve was assembled on it. Solenoid valve uses electrical energy from the same batteries of motors. With the valve its height becomes 42 cm and this dimension is the most important measurement which is restricted in robot dimensions. The tube can be filled in with extinguisher foam by the help of authorized person in a store.

To decrease the rate of heat transfer from outside to inside of firefighting robot ceramic fiber paper was used which is non flammable until its temperature reaches 1260^{o}C. Paper was mounted on the main body with double sided tape. Ceramic fiber papers with two different thicknesses, 2 mm and 3 mm, were used to reach 7,25 mm insulation thickness as calculated before.

CHAPTER 6

FINAL TESTS

After theoretical calculations had been done to obtain fire resistance property of the fireproof fire rescue robot a test was performed for comparisons. For this reason a small fire was lit from outside with the help of wisp of papers, kindling and combustible liquid.

Using remote control the robot was driven through the fire as near as possible. When the robot was close enough to reach the fire, using the other remote control solenoid valve was opened and the extinguisher tube sprayed extinguisher foam on flames and extinguish the fire. Although that operation was lasted for 6 minutes and 20 seconds the robot was driven approximately 9 minutes to determine whether the batteries can last for 15 minutes of operation time. As a result, the batteries were sufficient and still hadn't been depleted at the end of the test.

While the pressure inside the extinguisher is high, its range is higher so it can spray foam to a very far place. Since the robot was not very close to the fire it could not be understood if the robot was going to be affected from heat or not. To solve this problem, after the robot extinguished the fire, a new fire had been lit and while trying batteries' operation time the robot was taken near to the flames of new fire. By an infrared thermometer both fire temperature and outside surface temperature of the robot was measured at different time intervals. At the time the test had conducted, outside temperature was 31 ^{0}C and the ground was made of concrete. At this time the robot's outer surface was at 27 ^{0}C and it was changed by time.

Table 6.1. Temperature change of robot's surface with time

Time (sec)	Heat Of Fire (^{0}C)	Surface Heat Of The Robot (^{0}C)
0	320	27
180	372	28
300	400	30
380	480	30

After the test, the heat did not have much effect on the robot, therefore the fireproof fire rescue robot was still working properly. At the end, the test showed that the robot extinguish fire without taking any damage, the insulation layer fulfilled its duty successfully.

Another test was done to learn how much angle the robot can climb. This test was made with an inclined plane which has a flexible climbing angle. Test was started at 10 ^{0} and the angle value increased step by step.

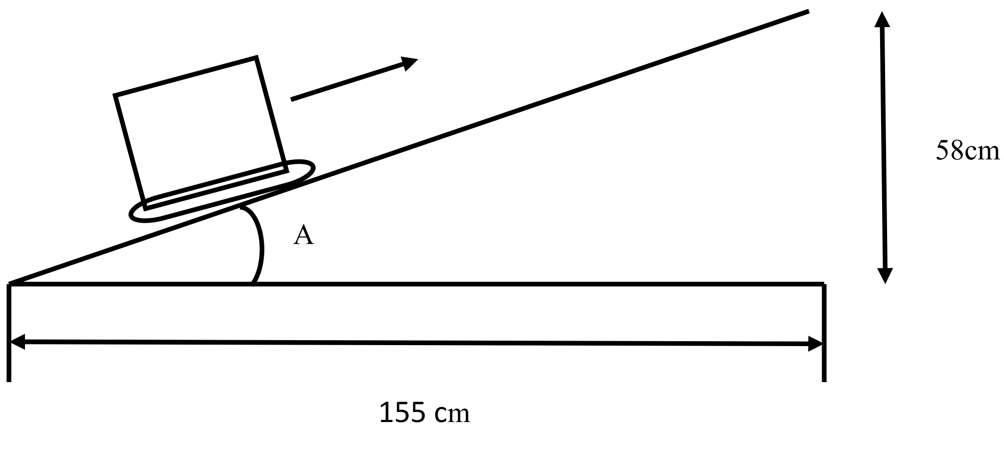


Figure 6.1. Maximum slope that robot can climb

After tests were done the maximum angle which the fireproof fire rescue robot could climb was found as 20.5^{0} at a wooden ground.

$$\tan A = \frac{58}{155} \tag{7.1}$$

$$\tan^{-1}\frac{58}{155} = 20.5 \tag{7.2}$$

$A = 20.5^{0}$

CHAPTER 7

CONCLUSION AND FUTURE WORK

This thesis is about designing and manufacturing of mobile fireproof firefighting robot for extinguishing fire before spreading in a short period of time and getting knowledge about fire behavior. Also helping and protecting firemen are other objectives.

Through out this study, thought and design of a fireproof firefighting robot is discussed. The robot was manufactured and tested according to its properties. The robot, which was manufactured, is only a basic prototype of what was planning to be manufactured. The budget was limited and advanced manufacturing machines cannot be used, so the robot had to be manufactured by using the cheapest parts that can be found in the market. Despite these disadvantages, the fireproof firefighting robot was working properly at tests. At …^{0}C, that is the temperature of ground where the fire was burnt because IR thermometer can not measure blames, fireproof firefighting robot extinguished fire on the concrete ground without getting any damage. The batteries were full before this test, and they last until the operation had finished.

By further development and improvements, the robot will become more reliable in accomplishing its purpose. To improve the fireproof firefighting robot some additional and changes must be done.

For example attaching different kind of sensors - like for temperature, gas and sound detection - for understanding the behavior of fire more easily and also encoders, accelerometers for controlling the robot motion properly. Advanced sensors are generally expensive devices and must be supported by sophisticated electronic circuits. Furthermore, they require authorized person for installation.

Main body of the robot can be made from different material instead of aluminum. New material should have higher melting point than aluminum. For example the steel alloys which have vanadium (1910^{0}C), wolfram (tungsten) (3410^{0}C) and molybdenum (4639^{0}C) in its structure are appropriate for firefighting robot's purpose. But they are expensive, heavier and more difficult to process than aluminum. Except these materials composite materials like special ceramic tiles can be used for preventing parts of the robot from the adverse effect of heat. But ceramic tiles have disadvantages like manufacturing and mounting difficulties.

For better operation, the range of remote control can be expanded. Also the robot can be changed semi-autonomous to autonomous robot with the help of sensors, advanced software programming and step motors. These changes need a considerable budget and authorized person to install because electronic circuits can be so complex and may interfere with each other.

Another improvement can be made for the locomotion system. For example, the chain and sprockets can be changed to double or more stranded chain. Also contact area of the chain with the ground can be expanded by using thicker chains. Choosing sprockets with bigger diameter expand the obstacle passing over ability and not to harm itself because of higher bottom base.

Small changes like battery monitors; light-emitting diode (LED); can make the robot more useful. It can be mounted into the robot which will show voltage level to operator. Also the power of the motors can be increased for heavy duty conditions and ratio of gear box can be changed according to motors power. Battery type can be changed too – from sealed lead acid to possible lithium technology battery - for leading to better result.

To save time the extinguisher foam can be sprayed from more than one place of the robot. Addition to that not to finish extinguisher foam too quickly, the tube can be made bigger or designed specially to fit into the existing gap inside the robot.

Moreover design of the robot can also be improved. It can be made smaller and in different shapes to access remote places.

After all it is known that any small change can affect the weight or size of the robot directly and then a chain reaction starts automatically, which leads the design process into optimization of dimensions, weight and other required specifications.

REFERENCES

Ahmadi, M., V. Polotski, and R. Hurteau. 2000. Path Tracking Control of Tracked Vehicles. *IEEE* 3: 2938-2943.

Amano, H. 2002 Present Status and Problem of Fire Fighting Robots. *IEEE* 2: 880-885.

Brandshaw, A. 1991 The Uk Security and Fire Fighting Advanced Robot Project. *Advanced Robotic Initiatives in the UK*: 1/1-1/4.

Celentano, L., F. Garofalo, B. Siciliano, and L. Villani. 2004. A fire fighting robotic system for road and railway tunnels. *IEEE International Workshop Safety, Security, and Rescue Robots.*

Celento, L., B. Siciliano and L. Villani. 2004. Design Issues for a Fire-Fighting Robot on Tunnel Intervention. *International Conference on Mechatronics and Robotics*.

Celento, L., B. Siciliano and L. Villani. 2005. A Robotic System for Fire Fighting in Tunnels. *IEEE International Safety, Security and Rescue Robotics, Workshop* : 253-258.

Desjarlais, André. Department of Energy Assistant Secretary Energy Efficiency and Renewable Energy. http://www.ornl.gov/sci/roofs+walls/insulation/ins_02.html. (accessed May 28, 2007).

DeWITT, David P., and Frank P. Incropera, eds. 1996. *Fundamentals of Heat and Mass Transfer*. Canada : Wiley & Sons, Inc.

European Space Agency (ESA). 2007. Spacecraft Thermal Control. *http://mechanical-engineering.esa.int/thermal/aboutthermal.html.* (accessed May 26, 2007).

Flynn, Anita M., Joseph L. Jones, and Bruce A. Sieger, eds. 1998. *Mobile Robots : Inspiration to Implementation.* Massachussets : A. K. Peters Ltd.

Fortescue, Peter, John Stark, and Graham Swinerd, eds. 2003. *Spacecraft Systems Engineering.* Canada : Wiley & Sons, Inc.

Garcia-Cerezo, A., A. Mandow, J. L. Martinez, J. Morales, and S. Pedraza. 2004. Kinematic Modelling of Tracked Vehicles by Experimental Identification. *IEEE* : 1487-1492.

Gilmore, David G., eds. 2002. *Spacecraft Thermal Control Handbook.* USA : The Aerospace Press.

Gross, Ashley. 2006. SALAMANDER: A Firefighting Robot. *Technical Opportunities Conference*.

Hornback, Paul. 1998 The Wheel Versus Track Dilemma. *ARMOR* : March-April 1998: 33-34.

Hyder, A. K., G. Halpert, D. J. Flood, S. Sabripour, and R. K. Wiley, eds. 2003. *Spacecraft Power Technologies.* London : Imperial College Press.

International Association for the Study of Insurance Economics. *2006.* World Fire Statistics. Information Bulletin of the World Fire Statistics 21 : 1-12

Johnston, E. Russel Jr., and Ferdinand P. Beer, eds. 1992. *Mechanics Of Materials.* Singapore: McGraw Hill.

Mischke, Charles R., and Joseph Edward Shigley, eds. 1989. *Mechanical Engineering Design.* Singapore: McGraw Hill.

Dave Ahlgren. 1993. http://www.trincoll.edu/events/robot/Rules/default.asp. 2007. (accessed May 10, 2007).

US Fire Administration. 2006. https://www.usfa.dhs.gov/. (accessed March 12, 2007).