CLOTHING ROBOTS FOR RESCUE OPERATIONS FOR RADIATION PROTECTION

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By

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ABSTRACT

Rescue robots are preferred over humans in situations, where human lives can be adversely affected. For instance, in Fukushima nuclear disaster, rescue robots were sent to the irradiated environment of the site to carry out investigations and rescue works. However, rescue robots can also be hurt by the radiations. For instance, electronic components of a rescue robot can malfunction when exposed to radiations, which may hinder rescuing tasks. Therefore, the protection of electronic components in an irradiated environment is the bottleneck problem for such rescue robots to work. The contemporary solution to this problem is to design a specialized rescue robot with a specialized material or coating material to build such robots. Such a solution proved to be ineffective in the Fukushima nuclear disaster management as well as to be costly.

This thesis proposes a new concept – namely to wrap a robot with clothes that stop radiations. That is to say, any robot that may certainly not be specifically designed for working in an irradiated environment can clothe itself and then work in an irradiated environment. Feasibility of the concept of clothing a robot along with its technology was investigated in this thesis, and this includes classification of rescue robots in an irradiated environment, development of the architecture of clothes for robots, selection of materials for the clothes for radiation protection. A case study to validate the concept and technology was also conducted.

To the best of the author's knowledge of the available literature, no one in the field of robotics mentioned the concept of clothing robots. The result of the study in this thesis will have a huge benefit to the nuclear energy industry worldwide.

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of us but I hope in the future we can be together. Also, I want to express my heartfelt appreciations to my aunts Tasneem and Asma and uncles Juzer and Noorudin for their support.

This thesis is dedicated to

My father Saify Chinoy

My mother Farida Chinoy

My wife Sakina Chinoy

My sisters Umme Kulsoom and Sakina

And my son (Late) Saifuddin (you will always live in my heart)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADT	Axiomatic design theory
ALARA	as low as reasonably acceptable
Cd	Cadmium
cm	centimeter
Cs	Cesium
DOF	degree of freedom
DP	Design parameter
dpa	displacements per atom
FR	Functional requirement
GE	General Electric
GM	Geiger Muller
GPS	global positioning system
GW	Gigawatt
Gy	Grays
LWIR	Long width infra-red
Hr	hour
keV	kilo electron volts
Mbq	Megabecquerel
MeV	million electron volts
mm	millimeter
OV	overall

Pu	Plutonium
RPM	rotations per minute
Sr	Strontium
Tbq	Terabecquerel
Te	Tellurium
U	Uranium
VLSI	very large scale integration
Xe	Xenon
Y	Yttrium
Z	atomic number

CHAPTER 1

INTRODUCTION

In the present day and age, the use of rescue robots is generally preferred in those areas that are unstable and hazardous for the humans to operate. Rescue robots are used for search and surveillance inside hazardous areas such as the rubble of buildings after earthquakes, mining incidents and nuclear disasters. In Fukushima nuclear disaster, rescue robots have played an important role in the surveillance and investigation activities inside the disaster-stricken power plant. However, it has been reported that rescue robots have malfunctioned inside the Fukushima nuclear power plant; in particular, the rescue robots malfunctioned due to the effects of radiations. Therefore, an interest has arisen in the scientific community to study how to shield rescue robots from radiations.

The prevailing shielding processes include some specialized manufacturing processes and material coatings on vulnerable parts. These processes are useful for a particular environment or a range of environments. For instance, radiation hardening is one of the most common techniques, which is used for radiation protection for electronics. But the radiation hardened electronics are somewhere between two to four generations behind commercial electronics in terms of performance (Courtland, 2011).

A question arises: why not develop some sort of “coating” which can be used for robots when the need arises? Such a coating would be a kind of shielding which is movable. This leads to an idea that clothing is taken as an appropriate type of shielding, that is, clothes may be wrapped on a robot[1] when the need arises and also eliminates the need for any specialized robot or processes for a nuclear-irradiated environment. The robotic clothing concept may be called “human inspired”; protective clothing for a robot would be designed to protect its components, similar to protective clothing for human operators.

The robot is a combination of mechanical and electrical components (see Appendix E for details). Based on the above discussion, a few more questions emerge, and they are stated below:

Question 1: What is the effect of radiations on the mechanical components - particularly metals?

Question 2: What is the effect of radiations on the electronic and communication components?

Question 3: How are the rescue robots designed with a particular focus on working in a nuclear-irradiated environment?

Question 1 and question 2 helped in laying the groundwork for identifying those components of rescue robots that required shielding from radiations. Answers to these two questions can be achieved by literature review in my thesis. My thesis was focused on generating an answer to Question 3. In particular, my idea was the concept of clothing

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[1] The robot may be for any general-purpose but may fulfill needs of operations in a rescue mission.

a general-purpose robot (its vulnerable parts to radiations) to be a special rescue robot in a radiated environment. My thesis focused on the proof of this idea.

1.1 Objectives

The overall research objective of my thesis was to develop the clothing concept along with its technology for robots to allow a general-purpose robot to work in an irradiated environment along with generating an answer to the question 3 described above. Two specific objectives were defined with respect to the overall objective.

Specific Objective 1: To classify the current rescue robots which are expected to work in an irradiated environment in terms of their function as well as their conceptual structure or principle (Zhang, 2016). For this project, study of radiations, its effect on electronics and materials was not investigated but the application of the knowledge relevant to radiations for developing a robotic clothing was focused. Furthermore, the design of rescue robots and the management of operations of rescue robots was not studied.

Specific Objective 2: To develop a generalized architecture of the clothing system for rescue robots with consideration to the classification performed in Specific Objective 1. This architecture should allow for the clothing to cover all the vulnerable parts of the robot, which can be affected by the radiations. The selection of the existing materials to be used for the clothing purposes was focused on, but the new material including its coating was out of the scope of this thesis. The clothing concept was proposed for only those robots which were classified Specific Objective 1.

1.2 Organization of the thesis

Chapter 2 provides a comprehensive review of the effect of nuclear radiations on mechanical and electrical components to demonstrate relevancy and the need for the foregoing research questions and objectives. Chapter 3 presents the classification of rescue robots used at the Fukushima nuclear power plant. The research content of this chapter is intended to fulfill Specific Objective 1. Chapter 4 offers the development of the architecture of clothing for rescue robots and its special equipment, and its content is intended to fulfill Specific Objective 2. Chapter 5 presents the case study to demonstrate how clothing for radiation protection can be applied to a rescue robot. This will demonstrate the feasibility of the research outcome stemming from this thesis. Furthermore, Chapter 6 presents the conclusions as well as indications for some important future work.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

This chapter is to provide a detailed literature analysis in order to offer a further justification on the need for the proposed research. Section 2.1 presents a review regarding the effect of radiations on mechanical materials, more specifically metals. Section 2.2 presents a review regarding the effect of radiations on electronic components. Section 2.3 reviews the design of rescue robots with a particular focus on the radiations protection. Finally, Section 2.4 concludes this chapter by making a conclusive statement on the need for the proposed research.

2.1 Effect of radiations on materials

The robot is a combination of mechanical and electronic components. This section will present an analysis of how the radiations damage the metals. Generally, due to the radiations, the following defects can form in metals: (1) impurity production (transmutation of nuclei of an atom into that of another atom), (2) atom displacement (see Figure 2.1), and (3) ionization (Holbert, 2013).

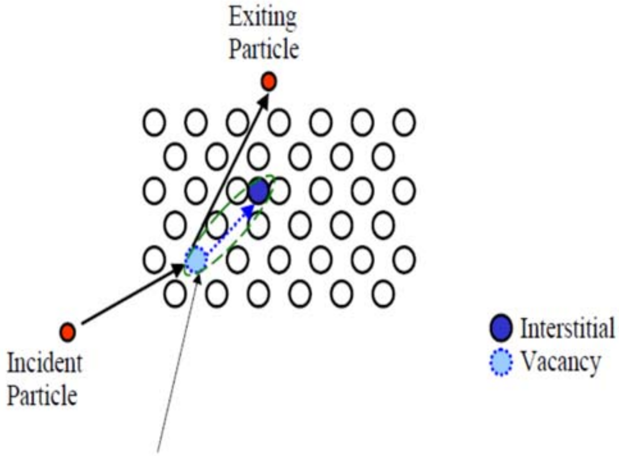

Figure 2.1 Displacement Damage (Holbert, 2013)

Impurity damage due to the introduction of foreign atoms (like nuclear transmutation) causes damage to the metal crystal structure by the introduction of foreign atoms (Thompson, 1974.). At high temperatures, helium is produced in metals because of radiations. Helium diffuses at the grain boundaries and can cause damage to the metals (Zinkle & Was, 2013). Transmutation reactions are generally observed in metals when the energy of the incident radiation is above several MeV (Vladimirov & Bouffard, 2008).

Significant changes in the properties of metals are induced by the displacement of atoms from their lattice sites (Kinchin & Pease, 1955). Austenitic stainless steel is one of the most important structural materials that can be used to make many structural components of a robot. In an environment of gamma radiation at 400 C it was found that austenitic stainless steel (of a pressurized water reactor) undergoes damage at the rate of 1dpa/ year. (Duysen, Todeschini, & Zacharie, 1993).

Metallic bonds are least affected by the ionization radiation (Holbert, 2013). However, indirect consequences of ionization in metals are: (i) the displacement of atoms which can lead to material defects (Holbert, 2013) and (ii) grain boundary failure. The materials exposed to radiations start losing their ductility rapidly at temperatures above 550°C to 600°C with increasing amount of grain boundary failures (Rowcliffe, Carpenter, Merrick, & Nicholson, 1967). In another study conducted regarding the effect of radiation on the engineering materials, it was found that irradiation leads to a decrease in the ductility of materials, above temperatures of 600°C (Irvin, & Bement, 1967).

From the above discussion it can be concluded that metals can be damaged by radiations. However, the damage to metals occur when: (a) energy of an incident radiation is high (usually above several MeV) and (b) the temperature is high (usually above 400°C). For these reasons, this thesis had not put attention on radiation damage to mechanical components.

2.2 Effect of radiations on electronics and communications

Electronic components form the communication and operational backbone of a robot. Radiations can adversely affect the functions of electronic components. The operations of semiconductor-based electronic devices are progressively degraded by radiation, ultimately leading to their failure (Casse, 2011).

The radiation damage mechanism in the electronic components can be divided into two classes: (a) surface damage and (b) bulk damage. In surface damage, the passage of ionizing radiation causes the build-up of trapped positive charge in the dielectric layer (usually SiO_2) that covers the silicon detectors. Surface damage to electronic components can occur at low radiation exposure (Cocca & Koepp-Baker, 1965). In bulk damage, illustrated in Figure 2.2, the radiation impinging on the silicon crystal can cause point-like defects (a single silicon atom displaced from its lattice position) or *cluster* defects (a high concentration of damaged crystal in a volume with a radius between 10 nm and 200 nm), depending on the radiation particle energy and type (Casse, 2011). Electrons having an energy of 260 keV can remove a silicon atom from its position in the crystal lattice. Further 5 keV of recoil energy is needed by silicon atom to displace other silicon atoms to create cluster defects (Meroli, 2012). For details, see Appendix D.

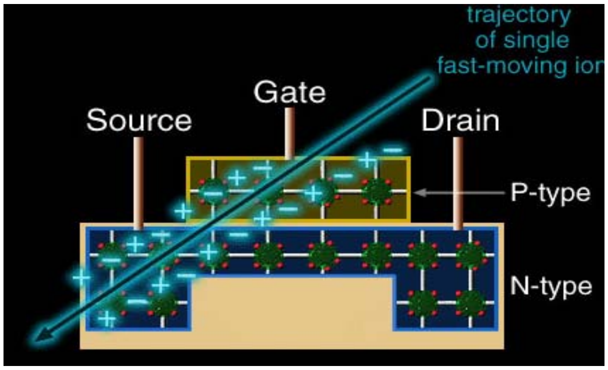

Figure 2.2 Bulk damage due to radiations.

(http://www.windows2universe.org/. Retrieved February 2, 2016)

Diodes are an important part of any electronic circuit and are used in communication equipment and rectifiers. In a study conducted by Ohyama et al. (2009) it was found that radiations can adversely affect the functioning of a diode. In a study, effects of radiation on electronic devices in VLSI (very large scale integration) was investigated and it was found that the damage to VLSI devices due to radiations can be either permanent or temporary (Fetahovi, Pejovic, & Vujisc, 2013).

The effect of radiations on electronic components can be observed at all temperatures. It was observed that gamma radiations affected the characteristics of transistors at cryogenic temperatures (Citterio, Kierstead & Rescia, 1996). This shows that electronic components functioning at even low temperatures can be affected by radiations.

From the discussion in this section it can be concluded that radiations affect the function of electronic components. Unlike mechanical components, radiations (even at low doses) can damage the electronic components even at low temperatures. For this reason, the primary focus of this thesis was on the radiation protection of electronic components of a robot.

2.3 Design of rescue robots

From the discussion in Section 2.1 and 2.2, it can be determined that the electronic components of a rescue robot are vulnerable to radiations. Therefore, to mitigate the effects of radiation on the electronic components of a robot, different manufacturing processes are used (Houssay, 2000). Some techniques that can be used to extend the life of the robotic and electronic system in an irradiated environment without using any complex radiation hardening work are: (1) split technique, (2) biasing and (3) annealing (Bostock & Sias, 1994; Houssay, 2000).

In the split technique, electronic components of a robot are removed from those areas which are exposed to high doses of radiations. The mechanical parts are exposed to radiations with the associated electronic parts protected in an area where there is low radiation exposure. The two parts (electronic part and mechanical part) can be connected by means of wires and cables. However, complex robotic systems cannot utilize this method of radiation protection. This is because a large number of sensors are used in complex robotic systems to make the robot more autonomous (Houssay, 2000), thereby making this technique unfeasible.

A biased device has a much shorter lifespan than an unbiased device in an irradiated environment. However, a device needs to be biased for it to be in operation. To mitigate this problem, two similar electronic systems installed in a parallel configuration can be used in a rescue robot. One system is used at a time while the other system remains out of operation. After a specified time, the two systems switch their states and this cycle can be repeated indefinitely (Houssay, 2000). An annealing process can also be used in a robotic system to increase the life of its electronic devices. A resistor can be glued to the device along with a thermistor and temperature sensor to regulate heat to the electronic device. It is noted that when the electronic device is heated up to 100^{o}C, the effects of radiation can be partially reversed (Mandal, 1994).

2.4 Conclusion from literature review

From the above study, it can be concluded that radiations affect metals, electronics and communication components. Radiations change the physical properties of the metals by (a) increasing brittleness, (b) reducing ductility and (c) reducing strength. However, changes in the properties of metals are witnessed at temperatures above 400^{o}C and at high radiation energies. Therefore, changes in the properties of metals will not affect the rescue robots as they are expected to operate at normal room temperatures. In the case of electronic and communication components, radiations reduce the full depletion voltage, reverse current, and truncate the communication signals. Radiations can also generate false logics and false states in electronic circuits as well as change the physical properties of semiconductor components. The effects of radiations (even at a very low dose) on electronics can even occur at low temperatures. Therefore, the function of rescue robots in an irradiated environment can be affected by the effects of radiation on the robot's electronic components.

Furthermore, it can be concluded from the literature review that the methods used for protection of rescue robots (see the discussion in Section 2.3) can only work for specialized type of robots used for rescuing operations in an irradiated environment. Such specialized type of robots cannot be used for any other purpose, so these robots stand-by when there is no accident of radiation exposure.

In conclusion, the proposed research objectives in Chapter 1 are important and pioneering work. With an increasing interest in nuclear energy worldwide, development of robust technology for rescue robots in an irradiated environment is timely.

CHAPTER 3

CLASSIFICATION OF RESCUE ROBOTS

This chapter provides the classification of rescue robots that have been used at nuclear disaster sites. Section 3.1 gives an overview of robots used at the Fukushima nuclear disaster site. Section 3.2 provides the classification of rescue robots based on their architecture and environment of operation. Section 3.3 provides the conclusion. It is noted that the Fukushima nuclear disaster has been made to be a reference event for this research, as the use of robots in some other nuclear disasters such as Three Mile Island nuclear disaster (1979) and a Chernobyl nuclear disaster (1986) was not reported.

3.1 Rescue robots used at the Fukushima nuclear disaster site

The Fukushima nuclear power plant consisted of six General Electric (GE) light water boiling reactors with a combined power production capacity of 4.7 Gigawatts (GW), making it one of the world's largest nuclear power plants (Fukushima: Background on reactors, 2012). On March 11, 2011, a 9.0 magnitude earthquake struck the Eastern coast of Japan. The earthquake caused a tsunami with waves having run-up heights of up to 39 meters (Oskin, 2015). The waves overwhelmed the plant's seawall and flooded emergency diesel generator rooms, which subsequently shut down diesel generators. This resulted in loss of the power to the critical coolant water pumps. Insufficient cooling of the reactors eventually led to the meltdown of multiple reactors at the Fukushima nuclear power plant. There were a number of hydrogen-air chemical explosions reported between March 12th and March 15th (Fukushima timeline, n.d.).

Due to the meltdown of multiple reactors and high risk of radiation emissions, it was decided that the best way to conduct surveillance at the disaster struck power plant was to send reconnaissance robots to the power plant to investigate the damages to the plant, to measure the radiation intensity and to perform any special physical tasks like opening and closing of valves or welding. The robots which were sent to the nuclear power plant in Fukushima are listed in Table 3.1. Their functions or roles will be discussed later in this chapter.

Table 3.1 List of rescue robots used at the Fukushima nuclear power plant

	Name of Robot
1	Quince (Figure 3.1)
2	Warrior Bot (Figure 3.2)
3	Frigo MA (Figure 3.3)
4	Rosemary (Figure 3.4)
5	Packbot (Figure 3.5)
6	Sakura (Figure 3.6)
7	Quadruped Robot (Figure 3.7)
8	Surface Boat (Figure 3.8)

Figure 3.1 Quince

(http://web-japan.org/trends/09_sci-tech/sci100909.html. Retrieved November 3, 2016)

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Figure 3.2 Warrior Robot

(http://www.fukuleaks.org/web/?p=12647. Retrieved November 3, 2016)

Figure 3.3 Frigo MA

(http://www.fukuleaks.org/web/?p=8417. Retrieved November 3, 2016)

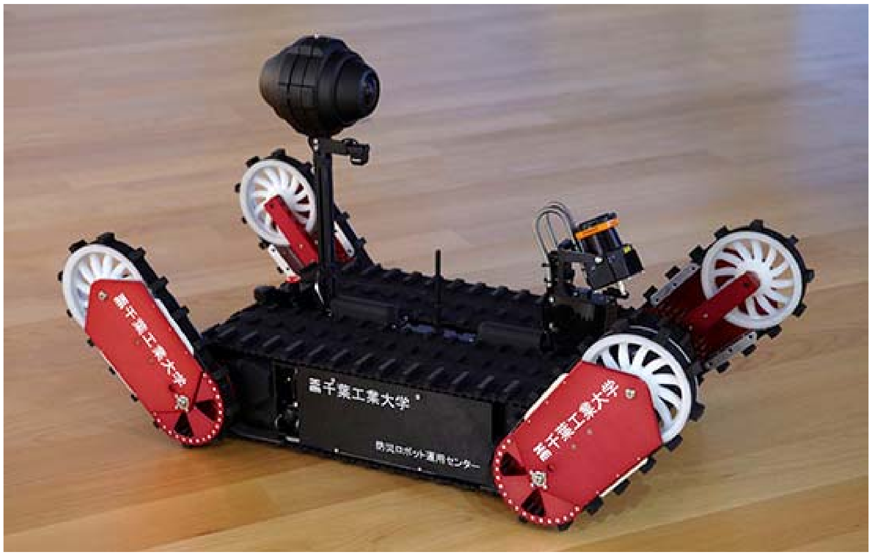

Figure 3.4 Rosemary

(http://furo.org/en/works/rosemary.html. Retrieved November 3, 2016)

Figure 3.5 Packbot

(http://www.sciencebuddies.org/science-fair

projects/project_ideas/Robotics_p015.shtml#background. Retrieved November 3, 2016)

Figure 3.6 Sakura

(https://spectra.mhi.com/robots_to_the_rescue. Retrieved November 3, 2016)

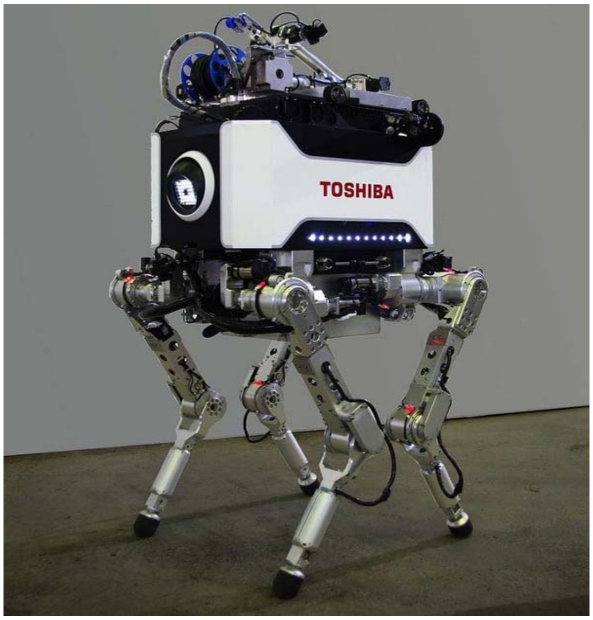

Figure 3.7 Quadruped Robot

(http://newatlas.com/toshiba-four-legged-nuclear-inspection-robot/25120/. Retrieved November 3, 2016)

Figure 3.8 Surface Boat

(http://ex-skf.blogspot.ca/2013/11/fukushima-i-nuke-plant-reactor-1.html. Retrieved November 3, 2016)

3.2 Classification of rescue robots

According to Meriam dictionary (Classification, n.d.) classification is the act or process of putting people or things into groups based on the way they are alike. Classification involves the orderly and systematic assignment of each entity to one and only one class within a system of mutually exclusive and non-overlapping classes. It is a tool which is created for the purpose of establishing a meaningful organization (Jacob, 2004).

Classification involves the ordering and sorting of objects into groups and classes on the basis of their similarities (Mayr & Bock, 2002). Classification will be based on (a) robot's architecture and (b) robot's working environment. This process is important for better cognition (Boundless, 2016) and organization of data. In this case, classification will help in the better understanding of a rescue robot. This improved understanding will provide basis to achieve the primary objective of this thesis, i.e., to design clothes for a rescue robot, which do not compromise any of its core functions.

3.2.1 Classification based on architecture

Architecture of a rescue robot has two important aspects, namely its function and the working principle to achieve the function (Zhang, 2016). To design clothes for a rescue robot, architecture of the robot has to be evaluated and studied. Therefore, classification of a rescue robot will be based on the robot's function and the working principle (or mechanism) that a robot's structure is built upon, respectively.

3.2.1.1 Classification based on the function

A robot is composed of mechanical, electrical and electronic components. Any system has a certain use, and the usefulness of a system is case sensitive (Zhang, Lin & Sinha, 2005). For example, a crank-slider mechanism can be used to generate a force on the end of its slider such that the needle attached on the slider can punch the clothes with the upper thread (in the context of a sewing machine). The crank-slider mechanism can also be used for compressing gas when its slider is used as a piston in a cylinder where the gas lies (Zhang, Lin & Sinha, 2005). In both cases, the mechanism is the same but their use is different due to different contexts.

Robots also perform a variety of tasks or functions. Generally, rescue robots are designed to perform the following functions:

- Mobility at site (F1). Mobility is an important aspect of a mobile rescue platform. The rescue operation in a disaster environment has two inherent problems: the complexity of the environment and unpredictable dangers (Jinguo, Yuechao, Bin & Shugen, 2007). Movement on terrain requires a system of motion with stability and sufficient friction to the ground, and a certain amount of acceleration. To be able to move on terrain is a necessary condition for any rescue robot, and the robot of this kind may be called an automated mobile platform.
- Survey (F2). Survey is an act of collecting data for the analysis of some aspect of a group or an area (Survey, n.d.). Rescue robots are supposed to provide the first-hand

information about a disaster-stricken area. These robots are usually equipped with a camera, video and image capture for the automated navigation of robots to a target site and for analysis of data. In addition to a camera, a rescue robot may also be equipped with a temperature sensor to measure the temperature of the environment of the site. Furthermore, a range scanner (typically a laser range scanner) may be mounted on a robot to measure distances of the robot with various different objects for a more accurate determination of the location of the robot in the disaster area. The robots performing the task of surveying may be called the surveying robot.

- Radiation measurement (F3). In a nuclear disaster, the major problem a human rescuer or surveyor faces is exposure to nuclear radiations. Therefore, rescue robots working in a nuclear disaster environment are equipped with a radiation measurement device, known as a dosimeter. This device helps humans to analyze the level of radiations and to ascertain if the area is safe for humans to enter, particularly in reference to exposure to nuclear radiations. Seven of the eight rescue robots mentioned before perform the task of radiation measurements except for Warriorbot (see Table 3.2).
- Physical work performing (F4). There were robots at the Fukushima disaster site, which performed a variety of physical work; for example, Warriorbot and Sakura have the capability of utilizing their robotic arm to perform tasks such as welding, opening and closing of valves and to remove debris (Quick, 2012). Warriorbot and Sakura are the only rescue robots which have the ability to perform physical work (see Table 3.2).

The classification of rescue robots based on their functions is listed in Table 3.2, where the first column is the robot and the right four columns represent the four functions as mentioned before.

Table 3.2 Classification of rescue robots on the basis of their functions

	Robot	Functions			
		F1	F2	F3	F4
1	Quince	Yes	Yes	Yes	No
2	Warrior Bot	Yes	Yes	No	Yes
3	Frigo MA	Yes	Yes	Yes	No
4	Rosemary	Yes	Yes	Yes	No
5	Packbot	Yes	Yes	Yes	No
6	Sakura	Yes	Yes	Yes	Yes
7	Quadruped Robot	Yes	Yes	Yes	No
8	Surface Boat	Yes	Yes	Yes	No

3.2.1.2 Classification based on the working principle

In the context of this research the overall task for a robot is to do reconnaissance missions inside a nuclear disaster zone and in some special cases to perform some specific physical work such as clearing debris and picking up objects. Information regarding the working principle of rescue robots will provide an in-depth view of a robotic system, as the structure of a robot will be built upon the working principle (Zhang and Wang, 2016).

Classification of rescue robots based on the working principle for the four functions (F1, F2, F3 and F4) is shown as follows.

With regard to the F1 (mobility), one working principle is based on a track and pulley mechanism for locomotion, called the track-and-pulley principle. The track based mobility system provides good traction, good power efficiency and stability in movement on rough terrain. The six robots (Quince, Rosemary, Packbot, Warriorbot, Frigo MA and Sakura) are based on this principle. The second working principle is based on the walking with legs (with links and joints), called the leg principle. Toshiba Quadruped is built based on this principle (Falconer, 2012, Li et al., 2016). The third principle is based on the concept of a propeller (screw) as a drive mechanism for mobility operating in water. The Surface boat has a propeller (screw) as its drive mechanism. Classification based on the working principle of rescue robots for the mobility function is shown in Table 3.3.

Table 3.3 Classification based on working principle for rescue robots for mobility at site

	Rescue robots	Working principle of mobility
1	Quince	Track and pulley
2	Sakura	Track and pulley
3	Warriorbot	Track and pulley
4	Packbot	Track and puller
5	Rosemary	Track and pulley
6	Frigo MA	Track and pulley
7	Quadruped robot	Legs
8	Surface boat	Propeller

Further, mobility encompasses the number of ways a robot can move in any environment. This is called degree of freedom (DOF) of the system. DOF of the cited rescue robot’s locomotion are shown in Table 3.4.

Table 3.4 DOF of rescue robots

	Rescue robots	DOF
1	Quince	4
2	Sakura	4
3	Warriorbot	4
4	Packbot	4
5	Rosemary	4
6	Frigo MA	4
7	Quadruped robot	4
8	Surface boat	6

The working principle for the mobility of a rescue robot can be further elaborated in terms of the kinematic structure or mechanism. The architectural structure of mechanisms can have three levels (Zhang, 2016). Level 1 focuses on only the component type. Level 2 focuses on the number of components along with component type. Level 3 focuses on the type and number of components along with joint types and their numbers (Zhang, 2016). Table 3.5 shows the classification of rescue robots based on the mechanism.

Table 3.5 Architectural level 1, 2 and 3 information regarding each robot's drive mechanism

		Level 1	Level 2	Level 3	
	Robots	Type of components	No. of components	Type of joints	No. of joints
1	Quince	Tracks	6	Revolute joint	12
		Pulleys	12		
2	Warriorbot	Tracks	4	Revolute joint	8
		Pulleys	8		
3	Frigo MA	Tracks	6	Revolute joint	12
		Pulleys	12		
4	Rosemary	Tracks	6	Revolute joint	12
		Pulleys	12		
5	Packbot	Tracks	4	Revolute joint	8
		Pulleys	8		
6	Sakura	Tracks	6	Revolute joint	12
		Pulleys	12		
7	Quadruped	Bars (Links)	8	Revolute joint	8
8	Surface Boat	Screw	1	Revolute joint	3
		Propeller	1		
		Rudder	1		

Furthermore, rescue robots with the track and pulley drive mechanism can be further classified according to the number of pairs of tracks and pulleys to form the drive mechanism as shown in Figure 3.9.

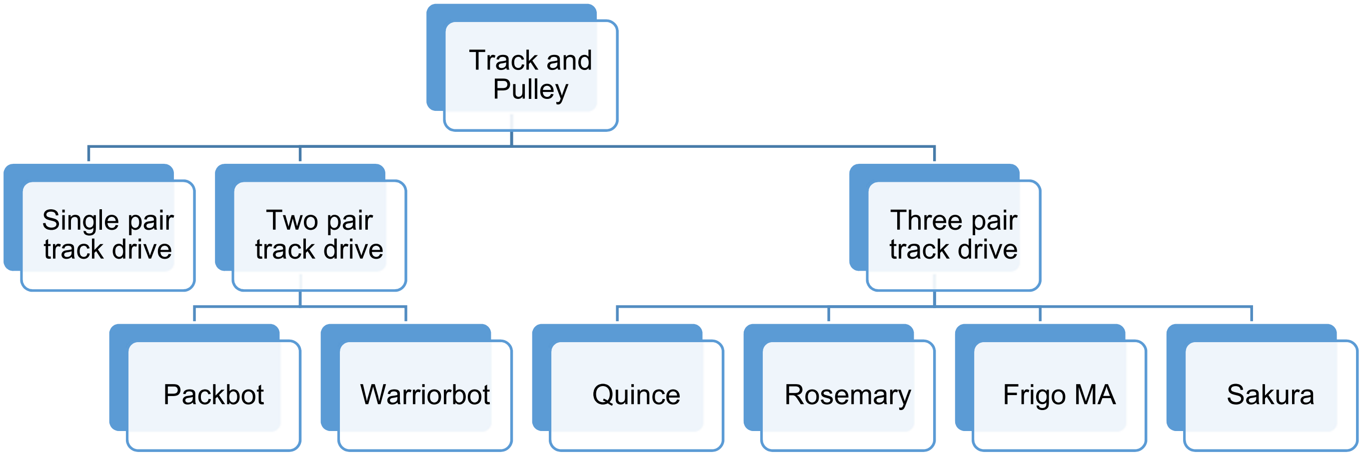

Figure 3.9 Classification of rescue robots with track and pulley drive mechanism

Physical work is one of the important tasks a rescue robot has to carry out at a disaster site. Physical work can consist of opening and closing of valves, clearing of debris or picking up samples for examination. A rescue robot performs physical work by using a robotic manipulator. Upon analysis of rescue robots used at the Fukushima nuclear plant disaster, it is observed that two rescue robots use arms or robotic manipulators to perform physical tasks. The physical work which the rescue robots can perform are: welding, clearing of debris and picking up of objects. Furthermore, Packbot also has a manipulator arm. However, Packbot has a camera mounted on its manipulator and cannot perform any physical task. Degree of freedom of manipulator arm of Warriorbot, Sakura and Packbot is shown in Table 3.6.

Table 3.6 DOF of manipulator arm of rescue robots

	Name of rescue robot	DOF
1	Warriorbot	4
2	Sakura	6
3	Packbot	5

DOF provides the number of ways a manipulator arm can move in XYZ plane. However, DOF does not provide any information regarding the mechanism of the manipulator of a rescue robot. Information regarding the architecture of mechanism is important because it can provide an in-depth view of a rescue robot. Architecture of mechanism has three levels. Table 3.7 shows the architectural levels 1, 2 and 3 of the structure of manipulator mechanism, where each of the three robots have similar type of components constituting their respective mechanism. Furthermore, each of the three robots have similar kind of joints. The differentiating factors between these robots is the number of components and the number of joints. Another differentiating factor is the purpose of these mechanisms. Sakura and Warriorbot use their manipulator to perform physical tasks. Packbot aims to produce better surveillance results by mounting a camera on its manipulator arm.

Table 3.7 Architecture level 1, 2 and 3 of links and manipulator mechanism

		Name of rescue robots		
Architectural Levels	Description	Packbot	Sakura	Warriorbot
Level 1	Type of components	Bars/ Links	Bars/ Links	Bars/ Links
Level 2	Number of components	3	4	2
Level 3	Type of joints	Revolute	Revolute	Revolute
	Number of joints	5	6	4

With regards to the working principle for survey, it was established earlier in this chapter that all eight rescue robots cited in this chapter perform the function of surveying. Various devices are employed by a rescue robot to perform the function of surveying. The surveying devices are used individually and as a part of a system to provide an accurate picture to the human controller concerning the situation inside a disaster area. Surveying devices utilized by a rescue robot are (a) visual recording or relaying device, (b) distance measurement device, (c) explosive gas measurement device, and (d) temperature measurement device. Surveying devices and their respective working principle are shown in Table 3.8. The surveying functions of rescue robots are shown in Table 3.9, where the devices are installed on each rescue robot.

Table 3.8 Surveying devices of a rescue robot and their respective working principles

	Surveying device	Working principle
a	Visual recording and relaying device	Light capture
b	Distance measurement device	Light's time of flight
c	Explosive gas measurement device	Resistance proportional to heat
d	Temperature measurement device	Thermo-junction voltage generation, thermography

Table 3.9 Physical surveying device of rescue robots

	Physical Measuring Devices				
	Name of Robot	Visual Instrument	Range measuring sensor	Explosive measurement sensor	Temperature measurement sensor
1	Quince	✓	✓	✓	✓
2	Warrior Bot	✓	X	X	✓
3	Frigo MA	✓	X	X	✓
4	Rosemary	✓	✓	X	X
5	Packbot	✓	X	X	✓
6	Sakura	✓	✓	X	X
7	Quadruped Robot	✓	✓	X	X
8	Surface Boat	✓	✓	X	X

For the convenience of classifying the rescue robots based on surveying, the robots further are divided into the following groups (Table 3.10):

1) Class I (Robots having any one of the four surveying functions)
2) Class II (Robots having any two of the four surveying functions)
3) Class III (Robots having any three of the four surveying functions)
4) Class IV (Robots having all four surveying functions)

Table 3.10 Classification of rescue robots with respect to surveying functions

Class I	Class II	Class III	Class IV
	Rosemary		Quince
	Sakura		
	Packbot		
	Frigo MA		
	Quadruped Robot		
	Surface Boat		
	Warriobot		

With regards to the working principle for radiation measurement. A dosimeter is used to measure radiation intensity and dosage. There are two types of dosimeters: passive dosimeters and active dosimeters. All rescue robot employ an active dosimeter (also called electronic dosimeter) to perform the function of measuring radiation intensity and dosage. An active dosimeter performs real-time measurement of radiation intensity and dosage. The radiation measurements of intensity and dosage are then relayed to the human controller. An active dosimeter is composed of Geiger-Muller (GM) counter (Introduction to dosimetry, 2012). A Geiger-Muller counter consists of two electrodes surrounded by either helium or argon. The radiation enters the Geiger-Muller counter and ionizes the gas. These ions are attracted towards the electrode and these ions produce electric pulses. A scaler counts these electric pulses and obtains a count whenever radiation ionizes the gas inside the GM counter (Introduction to Geiger counters, n.d.).

3.2.2 Classification based on the operation environment

Classification of a rescue robot based on its operating environment is important. Environment based classification will provide information regarding the environment where the rescue robots are intended to be deployed. Seven out of the eight rescue robots cited in this chapter are land-based robots. These seven rescue robots are being used to carry out functions (F1, F2, F3 and F4) at the Fukushima nuclear disaster site. However, Surface Boat is being used for water-based operations. It is being employed to carry out surveillance of submerged areas (Raven, 2013). Classification of rescue robots based on operation environment is shown in Table 3.11.

Table 3.11 Classification of rescue robots based on operation environment

	Rescue robots	Operation environment
1	Quince	Land
2	Warriorbot	Land
3	Frigo MA	Land
4	Sakura	Land
5	Rosemary	Land
6	Packbot	Land
7	Quadruped robot	Land
8	Surface boat	Water

3.3 Conclusion

In this chapter, the classification of rescue robots used at the Fukushima nuclear disaster site was provided. The rescue robots were classified according to their architecture and operation environment. This chapter provided the important information regarding a rescue robot and helped in the development of the clothing concept for a rescue robot (Chapter 4) in a systematical way. In particular, it helped the generality of the clothing concept for all kinds of rescue robots.

CHAPTER 4

CLOTHING RESCUE ROBOTS

This chapter provides the general architecture of clothing for a rescue robot and explains the material selection process for clothing. Section 4.1 presents the architecture of clothing for a rescue robot based on the classification of rescue robots in Chapter 3, because I believe that these robots cover most of the general-purpose robots that can be used for rescue operations in an irradiated environment. Section 4.2 provides details regarding the architectural parameters that can be instantiated to make the clothing for a particular rescue robot. Section 4.3 presents the criteria upon which materials of the clothing are selected. Section 4.4 gives a conclusion for this chapter.

4.1 Architecture of clothes for a rescue robot

In this section the architecture of clothing for rescue robots is developed. Consideration is given to the rescue robots classified in Chapter 3 in order to make the architecture be general and to cover all rescue robots that are supposed to work in an irradiated environment. The architecture of clothing for rescue robots is composed of several patterns or templates which are characterized by a set of parameters.

4.1.1 Chassis

The chassis of a robot is its main structure. Chassis of a rescue robot has electronic devices installed in it. The locomotion mechanism of a rescue robot is attached to the chassis. The chassis of a rescue robot usually has six basic sides: (a) front, (b) back, (c) top, (d) bottom, (e) right side and (f) left side, as shown in Figure 4.1.

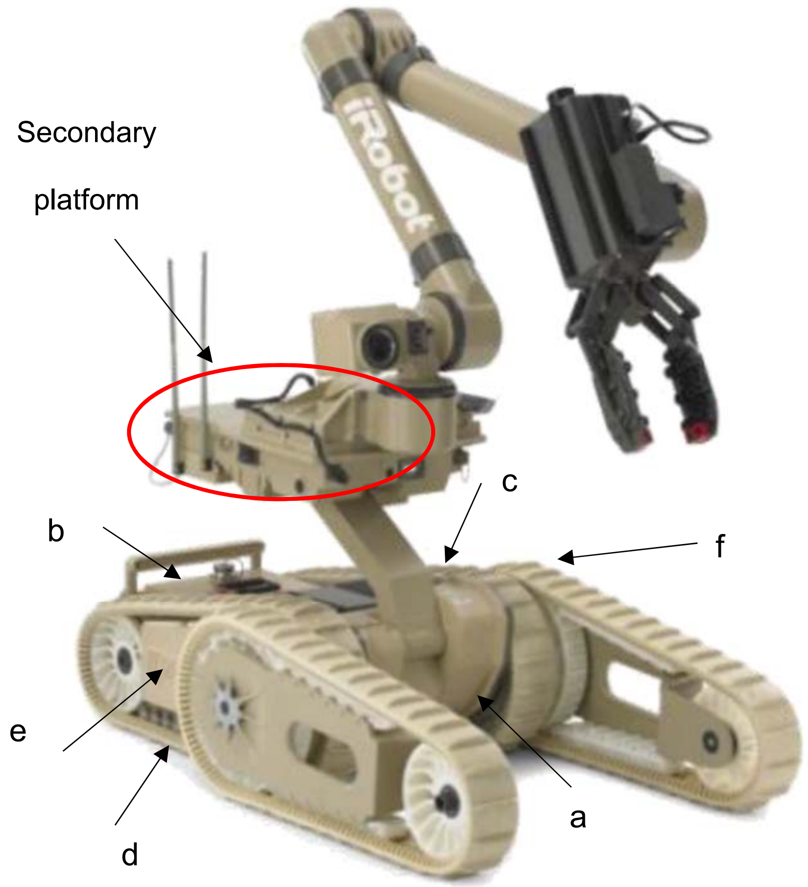

Figure 4.1 Six sides of chassis: (a) front, (b) back, (c) top, (d) bottom, (e) right side and (f) left side (Multi mission modular robot, 2014)

Front side. Clothing for the front side (a) will be attached to the clothing of the bottom side (d) of the rescue robot, which will be discussed later in this section.

Back side. Clothing for the back side (b) will be attached to the clothing of the bottom side (d) of the rescue robot, which will be discussed later in this section.

Top side. Clothing for the top side (c) of a robot can have a part with the rectangular shape (see Figure 4.2). This shape is described by the parameters (X, Y) which are discussed later in section 4.2.

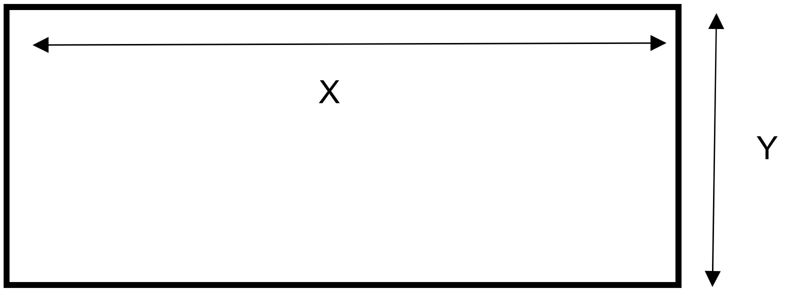

Figure 4.2 Clothing for the top side of the chassis

Bottom side. Clothing for the bottom side (d) of a robot can have a part with the rectangular shape. The clothing for the bottom side of a robot also has the clothing for the front (a) and back (b) sides of the robot attached to it (see Figure 4.3). The bottom part of the clothing will overlap the top side part (c) of clothing of a rescue robot which is discussed later in this section. The bottom side has four parameters (X, Y, K and I) that will be tailored to a particular robot and are discussed in section 4.2.

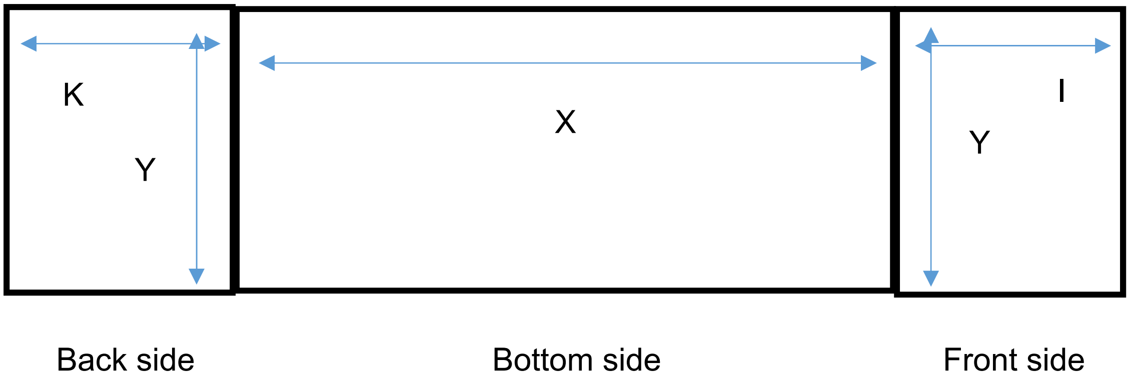

Figure 4.3 Clothing for the bottom side

Right side. Clothing for the right side (e) of a rescue robot can have a part with the shape as shown in Figure 4.4. Parameters (X, Y) associated with this part are shown in Figure 4.4 and are discussed later in section 4.2. The right side of clothing will be attached to the clothing of the bottom side (d).

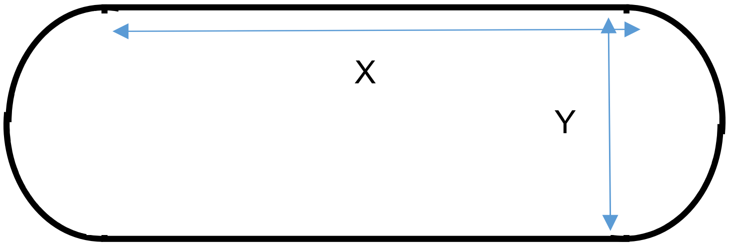

Figure 4.4 Architecture of clothing for right side

Left side. Clothing for the left side (f) of a rescue robot can have a part with the shape as shown in Figure 4.5. Parameters (X, Y) associated with this part are shown in Figure 4.5 and are discussed later in section 4.2. The left side of clothing will be attached to the clothing of the bottom side (d).

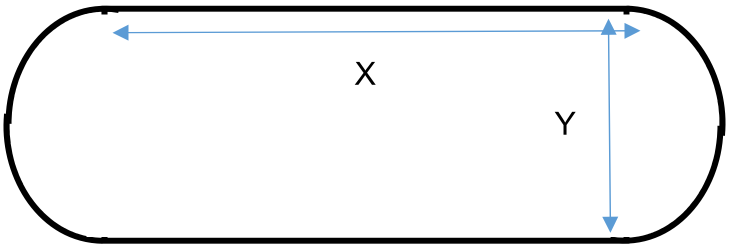

Figure 4.5 Clothing for the left side

4.1.2 Secondary platform and structure

The architecture of clothing for the secondary platform and structure of a rescue robot is designed by following a similar process to that of the chassis of rescue robot. An example of the secondary platform is shown in Figure 4.6 and Figure 4.7.

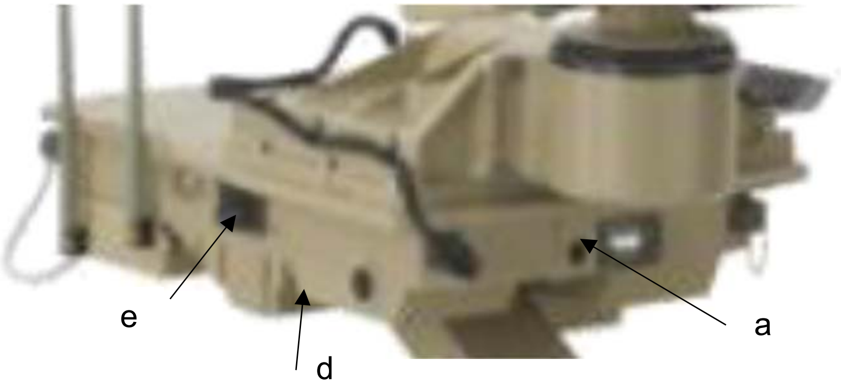

Figure 4.6 Secondary platform: (a) front, (d) bottom and (e) right side (Multi mission modular robot, 2014)

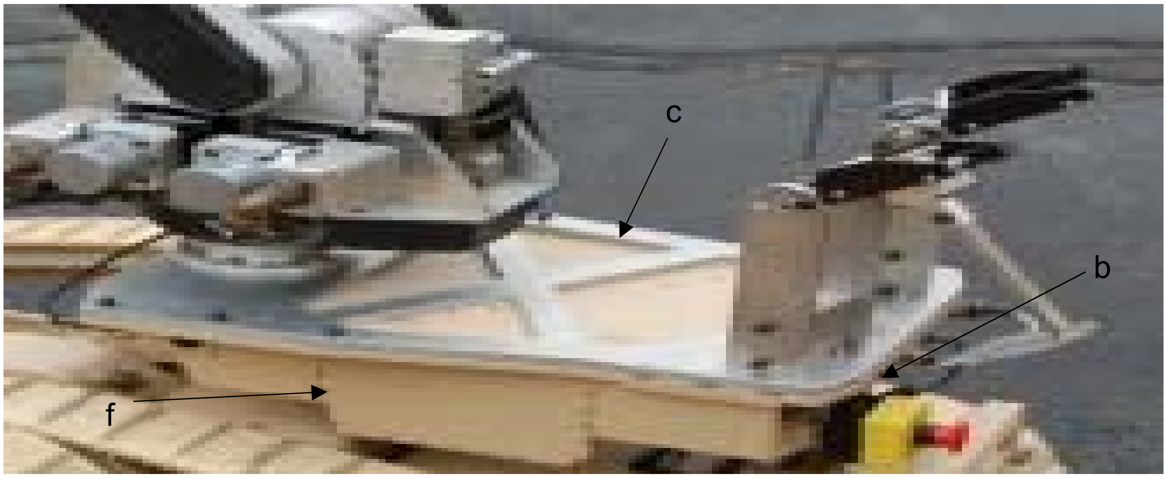

Figure 4.7 Secondary platform: (b) back, (c) top and (f) left side

(https://en.wikipedia.org/wiki/IRobot_Warrior. Retrieved February 21, 2017)

4.1.3 The manipulator arm

Figure 4.7 Manipulator arm of rescue robot (Multi mission modular robot, 2014)

A manipulator arm is shown in Figure 4.7. The architecture of clothing for a manipulator arm can have a part as shown in Figure 4.8. Parameters (X, Y, Y1) in Figure 4.8 will be discussed later in Section 4.2.

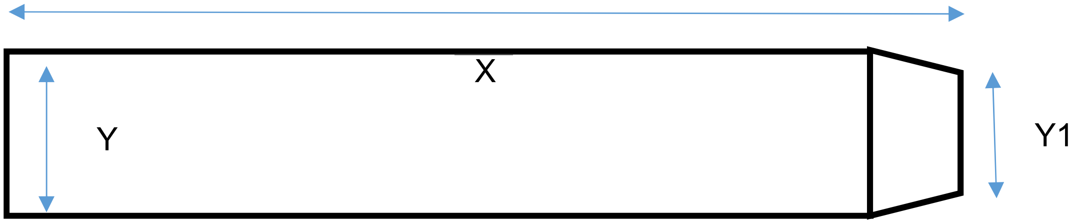

Figure 4.8 Clothing for the manipulator arm of a rescue robot

4.1.4 Special devices

- **Camera.** The architecture of clothing for a camera is shown in Figure 4.9. A special consideration has to be given to the clothing architecture of camera. This is because a camera functions on the principle of gathering light through its lens, therefore its lens cannot be covered by any opaque clothing material. Parameters associated with the clothing of camera are shown in Figure 4.9 and will be discussed in Section 4.2.

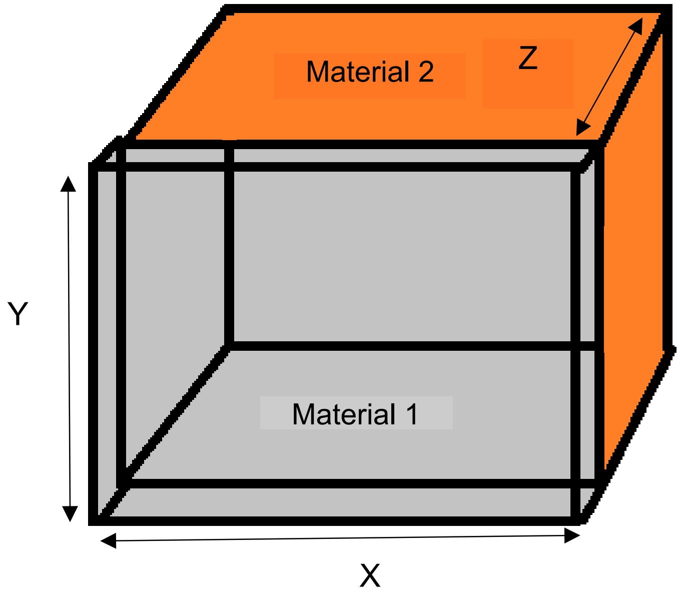

Figure 4.9 Clothing for a camera

- **Temperature measurement device.** A temperature measurement device typically functions based on two principles, namely: (a) thermo-junction voltage and (b) thermography. A temperature measurement device employing a thermojunction voltage principle does not have electronic components; therefore, the device does not require protection from radiations. However, a temperature measurement device working on the principle of thermography (see Figure 4.10) employs electronic components. Therefore, a temperature measurement device working on the thermography principle requires protection from radiations. The architecture of clothing for a temperature measurement device is shown in Figure 4.11. A particular piece of clothes can be tailored to fit a particular device by changing parameters shown in Figure 4.11 and discussed later in Section 4.2.

Figure 4.10 A typical thermo-graphic camera

(http://www.ir-thermalimagingcamera.com/sale-3420283-portable-fixed-infrared-thermography-camera-cctv-camera-surveillance-systems.html. Retrieved February 13, 2017)

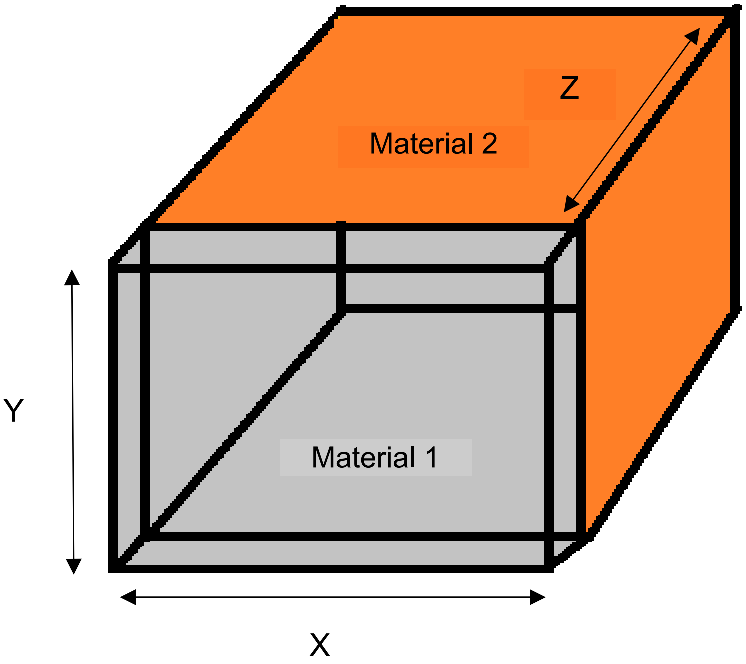

Figure 4.11 Clothing for thermography camera

4.1.5 Interfacing and arrangements of clothing components

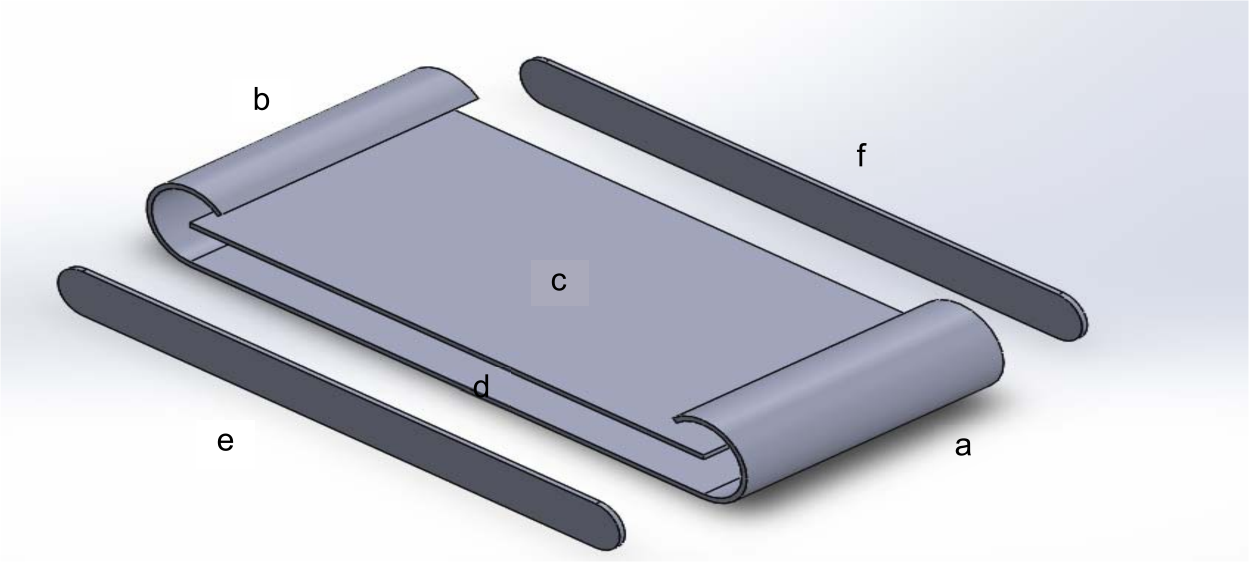

Figure 4.12 Exploded view of clothing of a rescue robot

Clothing components which may constitute the clothing architecture for the chassis of a rescue robot are shown in Figure 4.12. Arrangement of clothing components relative to each other is also shown (see Figure 4.12). Clothing for the top side (c) is being overlapped by clothing of the front side (a) and clothing of the back side (b). The front side clothing (a) and the back side clothing (b) are attached to the bottom side clothing (d). The lower part of the right side clothing (e) can be joined to the bottom side clothing (d), the front side clothing (a) and the back side clothing (b). The upper part of the right side clothing (e) can be joined to the top side clothing (a) by means of temporary joints (for instance buttons, zip or Velcro). Interface arrangement similar to the right side clothing (e) is applicable for the left side clothing (f).

4.2 Architectural parameters

In Section 4.1 a general architecture of clothing for rescue robot is developed. A particular piece of clothes is made by instantiating the architectural parameters to meet a particular robot. However, there are two issues. The first issue is regarding the measurement on a part of the robot and the second issue is regarding the treatment of clothing for some special parts of a robot.

4.2.1 Measurements

Every rescue robot has its own specific dimensions. By using the dimensions of a robot, the patterns or templates of the clothing (or architectural parameters), that are developed in Section 4.1 can be made to fit a particular rescue robot. The dimensions that need to be measured of a rescue robot for clothing are elucidated below:

- **Chassis length**. Measurement of the chassis length is required for creating the template of the top side clothing, the bottom side clothing, the right side clothing and the left side clothing.
- **Chassis width.** Measurement of the chassis width is required for creating the template of the top side clothing, the bottom side clothing, the front clothing and the back clothing.
- **Chassis height.** Measurement of the chassis is required for creating the template of the right side clothing, the left side clothing, the front clothing and the back clothing.
- **Length of the secondary platform.** Measurement of the secondary platform length is required for creating the template of the top side clothing, the bottom side clothing, the right side and the left side clothing.
- **Width of secondary platform**. Measurement of the secondary platform width is required for creating the template of the top side clothing, the bottom side clothing, the front clothing and the back clothing.
- **Height of secondary platform.** Measurement of the secondary platform height is required for creating the template of the right side, the left side clothing, the front clothing and the back clothing.
- **Joint to joint length of manipulator arm.** Measurement of the joint-to-joint length of the manipulator arm is required for creating the template of clothing for the manipulator arm.

- **Circumference of the manipulator arm.** Measurement of the manipulator arm's circumference is required for creating the template of clothing for the manipulator arm

Clothing can be made to fit the parts of rescue robots by changing the dimensional parameters of the clothing architecture as explained below:

- **Chassis**

Top side. The dimensional parameters (X and Y) of the top side clothing (see Figure 4.2) can be changed to fit a particular robot.

Bottom side. The dimensional parameters (X, Y, I and K) of the bottom side clothing (see Figure 4.4) can be changed to fit a particular robot. The clothing for the bottom side of the rescue robot also has the front and back side of the clothing attached to it.

Right side. The dimensional parameters (X and Y) of the right side clothing (see Figure 4.5,) can be changed to fit a particular robot.

Left side. The dimensional parameters (X and Y) of the left side clothing (see Figure 4.6, page 5) can be changed to fit a particular robot.

- **Secondary platform and structure**

Architectural parameters related to dimensions can be changed in case of clothing for the secondary platform of a rescue robot. These changes follow a similar scheme with the chassis of a rescue robot, as explained above.

- **Manipulator arm**

Clothing for a manipulator arm (see Figure 4.8) can be made to fit a particular robot by changing the architectural parameter related to dimensions (X, Y and Y1). It is important to note that “X” parameter is the length from one joint to the next joint of a manipulator arm. “Y” and “Y1” parameters are the circumference of the manipulator arm.

- **Camera**

Clothing for camera (see Figure 4.9) can be made to fit a particular camera by changing the architectural parameter related to dimensions (X, Y and Z).

- **Temperature measurement device**

Clothing for the temperature measurement device (see Figure 4.11) and more specifically, a thermo-graphic camera can be made to fit a particular thermo-graphic camera by changing the architectural parameters related to dimensions (X, Y and Z).

It is important to note that an ease allowance of one inch must be added to the actual size in the patterns. The ease allowance is required for the sewing and fitting purposes. Ease allowance may be added to the side seams of each pattern.

4.2.2 Clothing for the special requirements of a rescue robot

Some features of a rescue robot require special arrangements made in the clothing to accommodate them. The arrangements may be arm holes made in the clothes or a change of material. The specific features of rescue robot may include (1) locomotion mechanism, (2) manipulator arm, (3) instruments mounted on robot and (4) lens of cameras.

- **Locomotion mechanism of a rescue robot**

Mobility at site is one of the most important functions of a rescue robot. Clothes for a robot have to be designed keeping in consideration that functions of a rescue robot are not hindered. It was discussed in Chapter 3 that rescue robots achieve mobility at site by means of (a) track and pulley mechanism (b) legs or (c) a propeller. All the three mechanisms are mechanical in nature. Furthermore, it was noted in Chapter 2 that mechanical components are not affected by radiations. Therefore, these components do not require shielding from radiations. Hence, no clothing is required to cover them. However, arrangements may be required in the clothing to accommodate these mechanisms; for instance, armholes (see Figure 4.13) can be made to accommodate robot designs having legs or a propeller (see Figure 4.14).

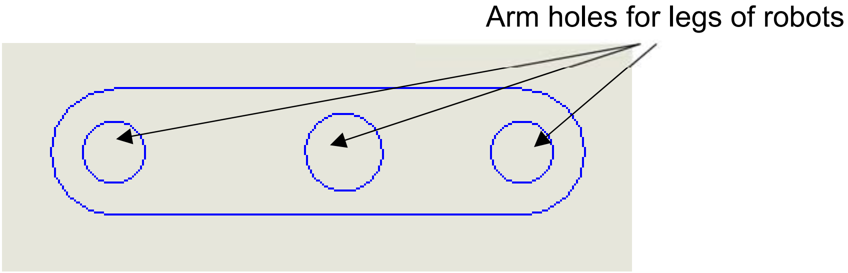

Figure 4.13 Side clothing with arm holes for legs of robot

Figure 4.14 Robot with legs

(https://www.engadget.com/2012/07/30/x-rhex-lite-robot-grows-a-tail/. Retrieved February 21, 2017)

- **Manipulator arm, secondary platform and structure, or equipment.**

Rescue robots employ robotic manipulators to perform physical work. Clothes of a rescue robot require features incorporated into them to accommodate manipulator arms or secondary platforms and structures. The features incorporated into clothing can be armholes (see Figure 4.15) in clothes of chassis or secondary platform for the accommodation of manipulator arms (see Figure 4.16).

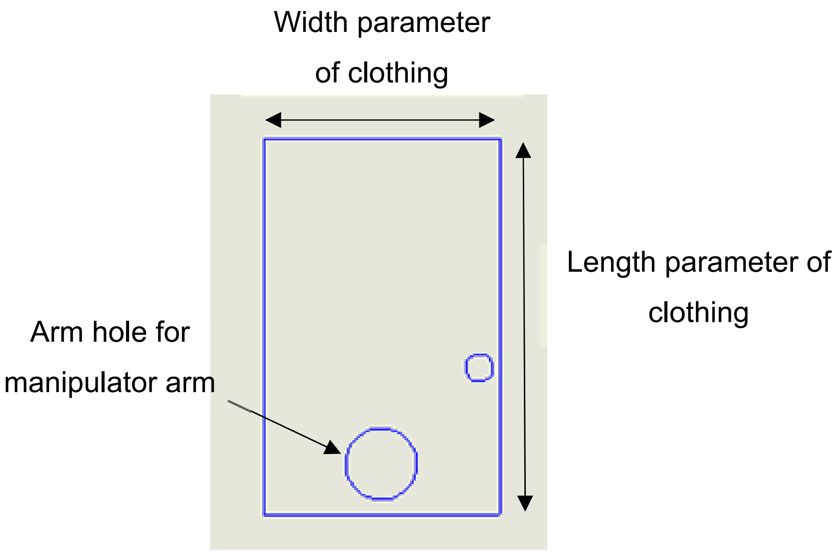

Figure 4.16 Top side clothing with arm hole to accommodate manipulator arm

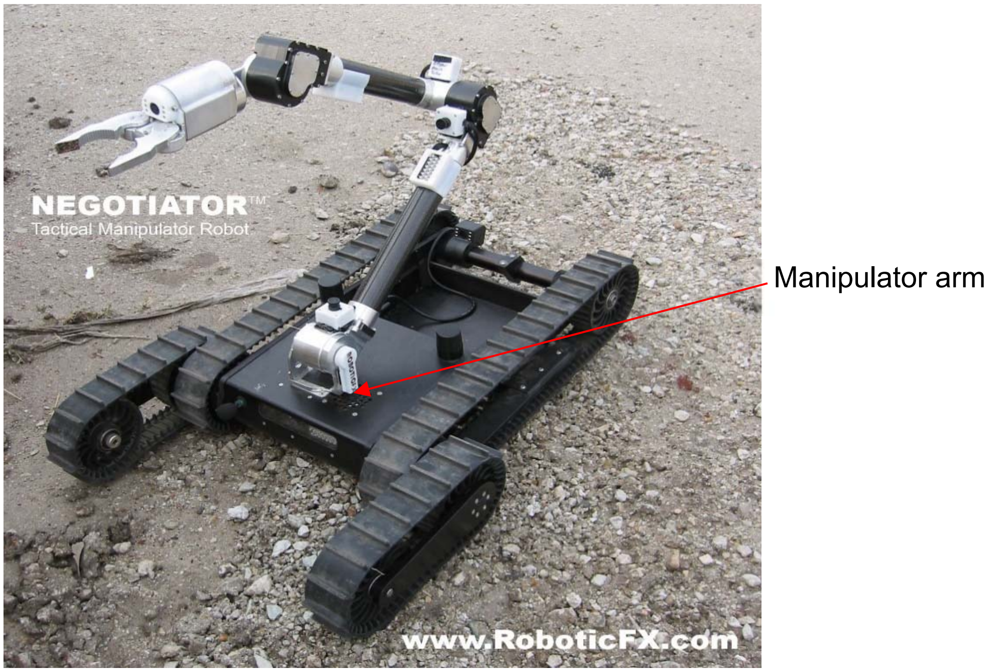

Figure 4.15 Rescue robot with manipulator arm

(http://www.prweb.com/releases/2007/06/prweb533822.htm. Retrieved February 21, 2017)

- **Equipment installed on rescue robots.**

Various instruments and components are installed in a rescue robot. Some of them require interactions with their surroundings. These may include an explosive gas measurement device, GPS device and radio antennas. Special features have to be incorporated in the clothing of rescue robots to accommodate the instruments and components that require interaction with their surroundings. Nevertheless, consideration has to be given to the working principle of the instruments. For instance, a radio antenna works on the principle of transmission and reception of radio waves. Therefore, radio antenna cannot be covered by a clothing material as that would hinder the antennas from functioning. Consequently, a small eye hole may be cut in clothing material to accommodate radio antennas and preserve their functioning.

- **Lens of cameras**

Covering the lens of a camera with an opaque clothing material will render the camera dysfunctional. It can be seen from Figure 4.9 and Figure 4.11 that Material 1 covers the lens of visual and thermo-graphic cameras. The Material 1 has to be transparent, thus ensuring the functioning of the cameras. The Material 2 is similar to the material used for clothing the remaining parts of a rescue robot.

It is important to note that communication cables are the medium through which communication between various components in a robot is carried out. A study conducted by Ott (2002), notes that radiations have minimal effect on communication signals, for instance there is 15-decibel signal attenuation for a 1 Kilometer cable exposed to a total dose of 1 Million rad.

4.3 Material selection

The material selection process for clothing is rationalized first by classifying radiation environments at a nuclear disaster site. Then, the classification of the radiation shielding material is performed based on the classification of radiation environments. A material selection process is then developed. Finally, radiation attenuation property of the selected materials is discussed.

4.3.1 Classification of environments based on nuclear radiations

Studies were conducted by Steinhauser, Brandl & Johnson (2014) and Koo, Yang & Song (2014) regarding major components of fission reaction, which were responsible for alpha, beta and gamma radiations in Fukushima nuclear disaster. It was noted that isotopes of Cesium (Cs-134 and Cs-137), Tellurium (Te-132), Xenon (Xe-133), Iodine (I-131) and Strontium (Sr-90) are major producers of gamma and beta radiations (Steinhauser, Brandl & Johnson, 2014). Cadmium (Cd-109) is a gamma emitter that can exist in a nuclear disaster area as it is present in the neutron absorbers of a nuclear reactor (Cross, Green & Adsley, 2012). Alpha particles are produced by isotopes of Uranium (U-236 and U-238) and Plutonium (Pu-238, Pu-239, Pu-240, Pu-241 and Pu-242) (Koo, Yang & Song, 2014).

For this research, radiation environments can be classified into (a) environment with alpha, beta and gamma radiations and (b) environment with alpha and beta radiations.

- **Environment with alpha, beta and gamma radiations.** In a nuclear disaster environment, there can be alpha, beta, and gamma radiations. These radiations have varying intensities depending on their sources. As discussed earlier, fission reaction creates isotopes of various elements, which may emit any of the alpha, beta and gamma radiations.
- **Environment with alpha and beta radiations.** For this research an environment is assumed that has alpha and beta radiations. As discussed earlier, isotopes of different elements can emit alpha and beta radiations of varying intensities.

The classification of radiation environments helps in providing a basis on which material can be selected for the clothing of rescue robots potentially working in the above classified environments.

4.3.2 Classification of radiation shielding materials

Classification of radiation shielding materials is based on the radiation environments defined in Section 4.3.1. Based on the classification of radiation environments, radiation shielding materials can be classified into two groups: (a) radiation shielding material for alpha, beta and gamma radiations and (b) radiation shielding material for alpha and beta radiations.

Alpha, beta and gamma radiations have their specific properties. Alpha particles are energetic nuclei of helium atom. Alpha particles can heavily ionize matter. However, alpha particles quickly dissipate their kinetic energy to its surrounding. Thereby, alpha particles have short ranges of effects, for instance the range of a 5 MeV alpha particle is 3.5 cm in air (shielding of ionizing radiations, n.d.).

Beta particles are energetic electrons. Ionizing power of beta radiations is less than the ionization power of alpha radiations. However, beta radiations have a higher kinetic energy, and thus beta radiations have a longer range of effects. For instance, 1 MeV of beta radiations can travel 3.5 meters in air (Beta radiation, n.d.).

Gamma radiations possess high energy photons. Gamma radiations do not have an electrical charge; therefore, gamma radiations do not ionize the matter directly. Gamma radiations indirectly ionize the matter through the photoelectric effect, Compton scattering, and pair production (Shielding of ionizing radiations, n.d.) (see Appendix B and C for details). Gamma radiations are the most penetrating of all the radiations. For instance, around 10 cm of lead is required to absorb gamma radiations with the energy of 1 MeV (Ionizing power and penetrating power, 2017).

It is observed from the above discussion that alpha, beta and gamma radiations are different. Therefore, the shielding requirement and material selection for alpha, beta and gamma radiations is also different (Radiation shielding requirements, n.d.).

Alpha, beta and gamma radiations have different shielding requirements. In an environment where there are alpha, beta and gamma radiations, the material selected should satisfy the shielding demands of all the three type of radiations. Alpha radiations can be stopped by the shielding material as common as a piece of paper. Materials that have a low atomic number (Z) are required to shield against beta radiations. This is because beta radiations produce bremsstrahlung radiations (secondary radiations) in the form of X-rays while passing through materials that have high atomic numbers, for instance lead and tungsten (Radiation properties, n.d.). On the other hand, gamma radiations are most penetrating. Gamma radiations have to be shielded by materials that have high density and high atomic numbers (Radiation shielding requirements, n.d.).

There are several narrative guidelines of materials selection.

- **Radiation shielding material for alpha, beta and gamma radiations.** From the above discussion, it can be inferred that for alpha radiations, any material can provide shielding. Therefore, shielding materials which are used for beta and gamma radiations are sufficient to shield against alpha radiations. However, conflict arises while selecting materials for shielding against beta and gamma radiations. As discussed previously, beta radiations are shielded by materials that have low atomic number, for instance plastic, aluminum, acrylic and polyethylene. Using the material of low atomic numbers prevents the production of bremsstrahlung radiations. On the other hand, shielding materials required for gamma radiations need to have higher atomic number and density, for instance lead, tungsten and depleted uranium. Therefore, a combination of materials is required for shielding against both beta and gamma radiations. A study conducted by Van Pelt & Drzyzga (2007) showed that using material with lower atomic numbers before the material with higher atomic number provided effective shielding against beta and gamma radiations. It is important to note that the required thickness of shielding material is directly proportional to the energy of radiations.

- **Radiation shielding material for alpha and beta radiation.** Material requirement for shielding against alpha and beta radiations, is simpler compared to the case of material requirement for shielding against alpha, beta and gamma radiations. Shielding material used for alpha and beta radiations need to have a low atomic number (Z) to prevent the production of bremsstrahlung radiations because of beta radiations. Required thickness of shielding material is directly proportional to the energy of radiations. Plastic, aluminum, acrylic and polyethylene may be used for shielding against alpha and beta radiations.

4.3.3 Selection of material for architecture of clothing

Classification performed in Sections 4.3.1 and 4.3.2 help in determining the materials that can be used for shielding against alpha, beta and gamma radiations. The determination of suitable materials required for shielding against radiations depends on the properties of materials. The properties of materials can be called the functional requirements.

Functional requirements (FR)

The functional requirements are the properties of materials that can provide the desired performance (Lee & Suh, 2006). The primary objective is to find materials for developing the architecture of clothing for a rescue robot, which will protect the rescue robot from radiations. This primary objective can be called the overall functional requirement (FR-OV). The overall functional requirement can be further decomposed into sub-requirements based on the required properties of materials. The sub-requirements are:

- **Shielding against alpha, beta and gamma radiations (FR-1).** As discussed earlier, every material cannot be used to shield against alpha, beta and gamma radiations. Therefore, material or combination of materials is required to protect against alpha, beta and gamma radiations.
- **Formability of materials into clothes (FR-2)**. Ability of a shielding material to be formed into clothes is important. As discussed earlier, a variety of materials are available, which can be used for radiation shielding. However, not all of the shielding materials can be formed into a clothing product.
- **Type of joints applicable (FR-3).** One more important factor for the selection of materials is the type of joints, which can be easily applied to materials. In any architecture of clothing, there may be two kind of joints: (1) permanent joints (FR-3.1) and (2) temporary joints (FR-3.2).
- **Environment-friendly (FR-4).** Handling and disposing of materials are an important aspect of any material selection process. Materials affect the environment and the health of humans who handle them.

- **Transparency (FR-5).** Transparency of materials is a particular requirement necessary for covering the lens of visual cameras or thermographic cameras (see discussion in Section 4.2).

The general notation of functional requirement can be noted as FR-i,j. The numbers indicate the required function identity (the magnitude of the number indicates the sequence of selection).

Design parameters (DP)

The Design parameters (DP) are the material that can satisfy the functional requirements (FR) (Suh, 1990). There are several materials which can fulfill the FR-OV. These materials can be called the overall design parameters (DP-OV). The materials, which may be selected, are aluminum, polyethylene, Demron, acrylic and lead. The design parameters corresponding to each of the above-mentioned functional requirements are:

- **DP-1.** Materials have to be selected, that can be used to protect against alpha, beta and gamma radiations (DP-1).
- **DP-2.** Materials have to be selected, which have malleability and can be formed into clothing for rescue robot (DP-2).
- **DP-3.** Permanent joints in clothing materials for radiation protection can be made by laser welding (DP-3.1). Laser welding of clothing materials is a process, in which a thin layer of fabric melts without affecting the outer surfaces of the material (Dammaco, Turco & Glogar, n.d.). Therefore, joints made by laser welding blocks

any radiations from entering from the joint. Temporary joints may also be used in the architecture of clothing. Type of temporary joints for radiation protection clothing can be zips and Velcro. Zips (DP-3.2.1) and Velcro (DP-3.2.2) provide temporary joints that have a minimum permeability.

- **DP-4.** Materials selected need to be environment-friendly and non-toxic for humans.
- **DP-5.** Materials selected for covering the lens of camera or temperature measurement devices need to be transparent.

The general notation for design parameters can be noted as DP-i,j. The numbers indicate the required design parameter identity (the magnitude of the number indicates the sequence of selection). Based on the above-mentioned material and design parameters, a matrix can be created to facilitate the selection process of materials, as shown in Table 4.1.

Table 4.1 Material selection matrix

Design Parameters (DP)	Material				
	Lead	Demron	Polyethylene	Aluminum	Acrylic
DP-1	No	Yes	Yes	Yes	No
DP-2	Yes	Yes	Yes	Yes	No
DP-3.1	Yes	Yes	Yes	Yes	Yes
DP-3.2.1	Yes	Yes	Yes	Yes	No
DP-3.2.2	Yes	Yes	Yes	Yes	No
DP-4	No	Yes	No	Yes	Yes
DP-5	No	No	No	No	Yes

Table 4.1 shows that lead is not suitable to use for protection against alpha, beta and gamma radiations as it has high atomic numbers; hence there is a high probability that bremsstrahlung radiations may be produced by its interaction with beta radiations. Acrylic on its own cannot be used to protect against gamma radiations as it is completely transparent to it. Temporary joints (zip and Velcro) can be applied to all the materials. However, lead, polyethylene, acrylic and aluminum need to be encapsulated in a clothing material. Moreover, lead and polyethylene are not environment-friendly materials. Particularly, lead is a toxic material requiring special arrangements for handling and disposal. Lead is especially toxic to humans and can damage human organs (Tong, Schirnding & Prapamontol, 2000) Also, polyethylene is highly resistant to biodegradation; hence it creates a disposal problem (Stevens, 2001).

Therefore, based on Table 4.1, it can be inferred that Demron and aluminum are the most suitable materials for developing radiation protection clothing for a rescue robot. Furthermore, acrylic can be used for lens covering of visual and thermo-graphic cameras. This is because acrylic is transparent and can shield against alpha and beta radiations. However, acrylic alone cannot shield against gamma radiations. Therefore, a combination of acrylic and lead acrylic can be used to shield against alpha, beta and gamma radiations. In this combination, acrylic will be placed before lead acrylic. Acrylic will attenuate the beta radiations and lead acrylic will attenuate the gamma radiations.

4.3.4 Radiation attenuation property of selected materials

In this section radiation attenuation property of (a) Demron (b) acrylic and (c) lead acrylic with respect to beta and gamma radiations will be discussed. Demron will be used for the clothing of rescue robot. A combination of acrylic and lead acrylic will be used for covering the lens of visual camera and clothing architecture of temperature measurement camera. Hence, beta and gamma radiation dosage is considered for Demron, acrylic and lead acrylic. It was explained earlier that alpha radiations can be shielded by a piece of paper. Therefore, materials for shielding from beta and gamma radiations are also sufficient to shield from alpha radiations.

- **Demron**

Demron is a proprietary material developed for making clothes for radiation protection. It is a fabric which is more flexible and malleable than lead (Friedman & Singh, 2003). It can significantly reduce the beta radiation and also have a limited impact on gamma radiations. It has a surface density of 0.12 g/cm^2 (Friedman & Singh, 2003). Furthermore, it is a non-toxic material easy to handle and with no special arrangement required for its disposal (Friedman & Singh, 2003).

Demron fabric provides protection from beta radiations and a limited protection from gamma radiations (Friedman & Singh, 2003). Figure 4.17 shows dose transmission graph for beta radiations emitted from Strontium-90 and Yttrium-90. Additionally, Figure 4.18 shows the graph of dose transmission of gamma radiations emitted from Cadmium-109. In Figure 4.17, Demron samples are indicated as Mat 1 and Mat 2. Taking Mat 2 as reference, it can be inferred from the figure that for a thickness of 0.38 mm (1 layer of Mat 2), beta dose transmission can be reduced by almost 75 percent. If the layer is doubled to 0.76 mm, beta dose transmission can be reduced by approximately 85 percent. For instance, a Strontium-90 source has a specific radioactivity of 5.21 TBq/g (Delacroix et al., 2002). This source is 1 meter from the rescue robot. The dose rate calculated (using online Radpro calculator, see Appendix A) is 5.81 Gy/ hr. This means that robot working in the disaster area for 8 hours near this source will be exposed to a total dose of 46.5 Gy without the use of shielding fabric. A single layer of Demron reduces the total dose to 11.6 Gy in an eight-hour shift.

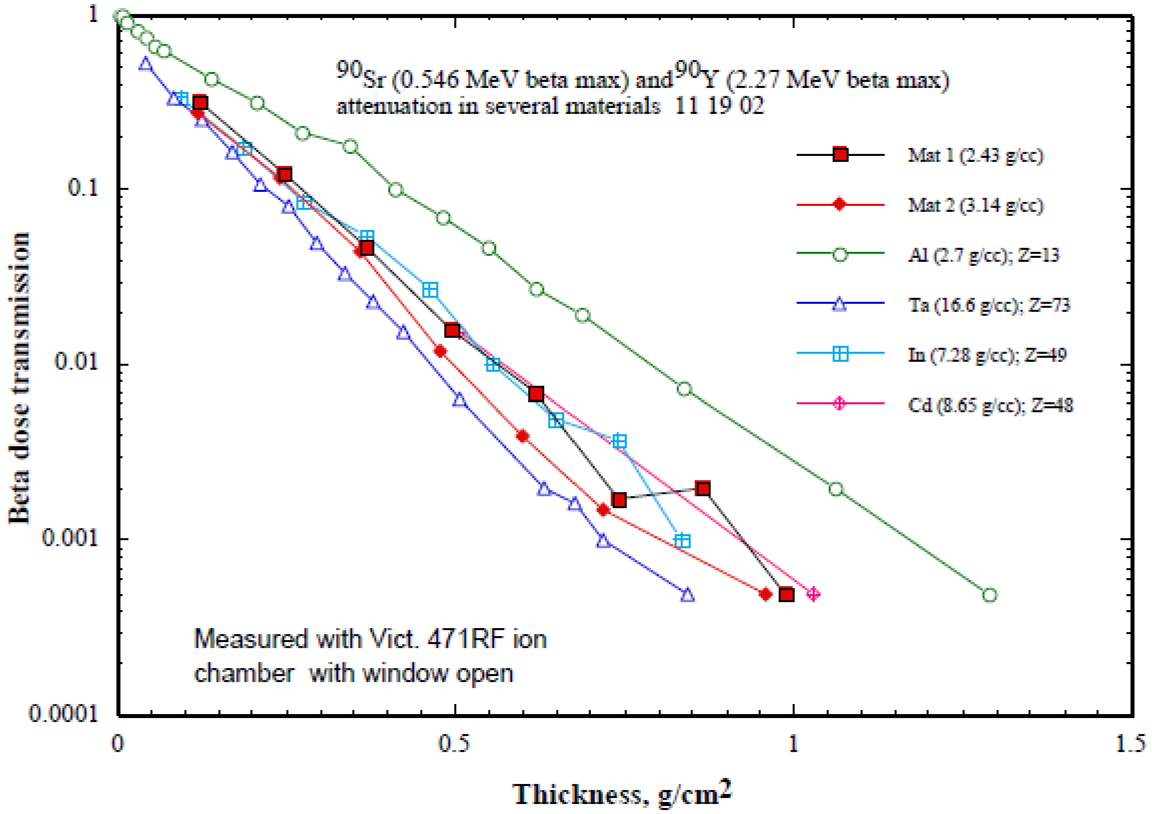

Figure 4.17 Transmission of beta radiations through several materials (Friedman & Singh, 2003)

Yttrium-90 is a daughter isotope of Strontium-90 having an energy of 2.28 MeV. It has specific radioactivity of 19900 TBq/g (Delacroix et al., 2002). We assume Yttrium-90 source to be 1 meters from the rescue robot. The dose rate calculated (using online Radpro calculator, see Appendix A for details) is 170,244 Gy/ hr without using the shielding fabric. A single layer of Demron reduces the total dose to 42,561 Gy/ hr.

It can be observed in Figure 4.17 that Demron is a better material than aluminum to shield against beta radiations that are emitted from Strontium-90 and Yttrium-90.

Demron can provide reasonable protection from low energy gamma radiations and limited protection from medium and high energy gamma radiations. For example, a source of Cadmium-109 (gamma emitter) is at 1 meter from rescue robot. Specific radioactivity of Cadmium-109 (Cd-109) is 9.58 x 10^7 MBq/g (Delacroix et al., 2002). Dose rate calculated (using online Radpro calculator, see Appendix A for details) is 4.24 Gy/ hr. Single layer of shielding fabric will provide dose transmission attenuation of 90 percent (see Figure 4.18). Therefore, the dose rate transmitted to rescue robot will be around 0.424 Gy/ hr after using a single layer of Demron.

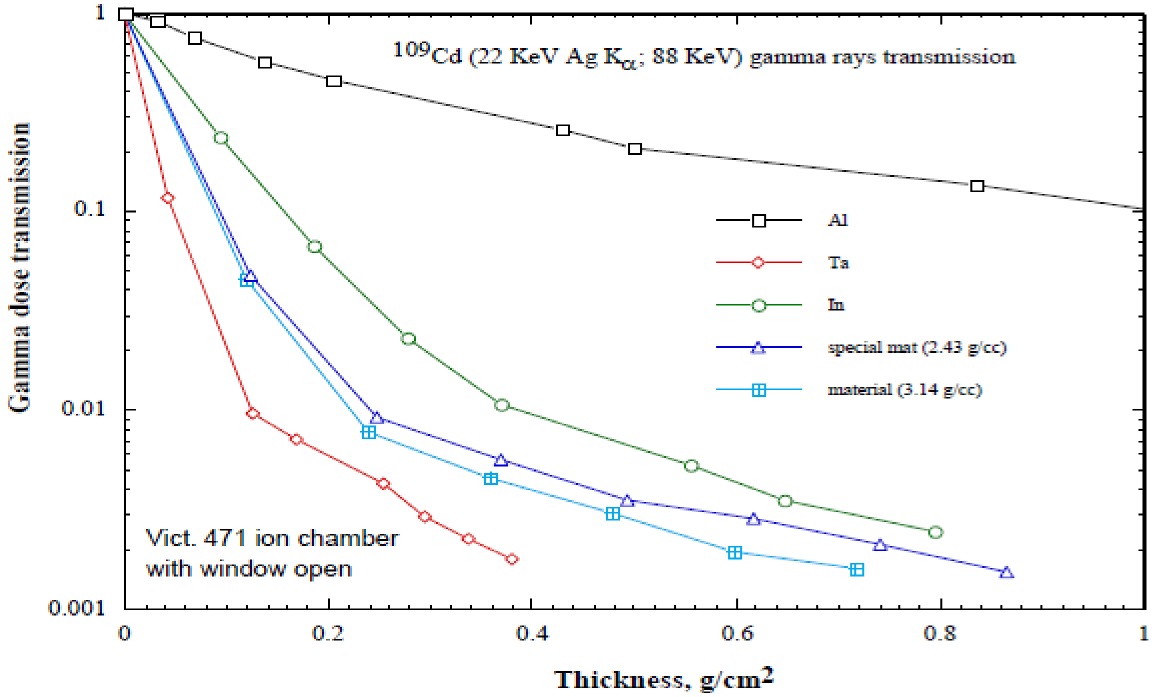

Figure 4.18 Transmission of gamma radiations through several materials (Friedman & Singh, 2003)

- **Acrylic**

A combination of acrylic and lead acrylic are the proposed materials that can be used for covering the lens of a visual and LWIR cameras. Acrylic will be used to shield against beta radiations while lead acrylic will be used to shield against gamma radiations.

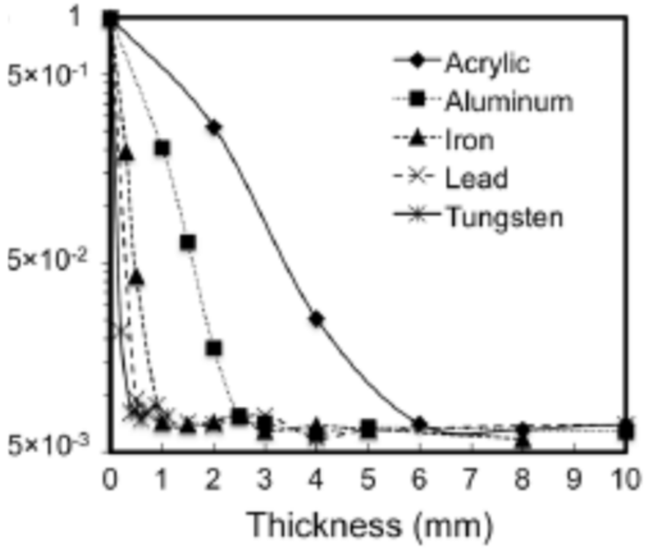

Figure 4.19 Shielding ability of different material from beta radiations emitted from Y-90 (Murata et al., 2014)

Acrylic can provide protection against beta radiations while it is transparent to gamma radiations. Half an inch of acrylic can provide complete protection from beta radiations emitted from Strontium-90 (Strontium-90/ Yttrium-90, n.d.). An acrylic sheet of 4-mm thickness can attenuate beta radiation emitted from Yttrium-90 by almost 97 percent (see Figure 4.19). Yttrium-90 source (decayed from Strontium-90) has specific radioactivity of 19900 TBq/g (Delacroix et al., 2002). For instance, a point source of Yttrium-90 is assumed to be 1 meter from the rescue robot. The dose rate calculated (using online Radpro calculator, see Appendix A for details) without shielding is 170,244 Gy/ hr. After using a 4-mm thick acrylic sheet for radiation protection, the dose rate is reduced to 5107 Gy/hr.

- **Lead acrylic**

Lead acrylic is a material that contains 30 percent lead by weight and the rest of the material composition is acrylic. Lead acrylic can be used for the protection against gamma radiation but not for shielding against beta radiations (Lead acrylic gamma L-block shields, 2015). Therefore, acrylic can be used before lead acrylic to attenuate beta radiations. Table 4.2 provides lead acrylic thickness and its corresponding lead equivalency.

Table 4.2 Lead acrylic thickness and its corresponding lead equivalency (Lead acrylic, n.d.)

	Lead acrylic thickness (in mm)	Lead equivalency (in mm)
1	8	0.3
2	12	0.5
3	18	0.8
4	22	1.0
5	35	1.5
6	46	2.0
7	70	3.0

For instance, a source of Cadmium-109 (gamma emitter) is at 1 meter from rescue robot. Specific radioactivity of Cadmium-109 (Cd-109) is 9.58 x 10^7 MBq/g (Delacroix et al., 2002). Dose rate calculated (using online Radpro calculator, see Appendix A) is 4.24 Gy/hr. According to a study conducted by Smith & Stabin (2012), 0.03-mm thickness of lead is required to attenuate gamma radiations emitted by Cd-109 by 90 percent. An 8-mm thick lead acrylic sheet (having lead equivalency of 0.3-mm) will reduce the dose rate to 0.007 Gy/hr (calculated using online Radpro calculator, see Appendix A for details).

The disadvantage of using a transparent cover for the protection of cameras is that each transparent covering material has its own refractive index. Therefore, the functionality of the cameras and its accuracy may be affected by the use of transparent cover. To mitigate this problem a calibration algorithm may have to be used (Jordt-sedlazeck & Koch, n.d.).

4.4 Conclusion

In this chapter, the general architecture of clothing for a rescue robot is presented along with the architecture of clothing of its special equipment. The architectural parameters were also discussed, which enables the clothing to fit a particular rescue robot. Furthermore, the material selection procedure was discussed. Then, based on the Axiomatic Design Theory (ADT), a methodology for materials selection was developed, which can be used for development of radiation protection clothes for a rescue robot. By using the methodology for materials selection, Demron, acrylic and lead acrylic were the materials selected to be used for the clothing for radiation protection of rescue robots.

This chapter is the basis on which the case study will be presented in the next chapter (Chapter 5).

CHAPTER 5

CASE STUDY

Chapter 5 establishes the feasibility of the concept of clothing for radiation protection for rescue robots. In Section 5.1, information is provided regarding the rescue robot that is used to demonstrate the concept of clothing for radiation protection. In Section 5.2, design of clothing for a selected rescue robot called ‘Packbot’ is presented. In Section 5.3, materials are selected for that robot. In Section 5.4, it is shown that the clothing does not hinder the motion of that robot. Finally, in Section 5.4, a conclusion is given.

5.1 Introduction to the case of rescue robots

In this section, the scope of case study is first defined, particularly (i) the type of nuclear radiations against which the shielding needs to be provided and (ii) the regulation that is followed. Then, a brief introduction is given to a particular rescue robot (Packbot) used for the case study.

5.1.1 Scope of case study

The primary objective of this research is to protect the vulnerable electronic components of a rescue robot from radiations by applying the concept of clothing to the rescue robot.

There is a regulation for radiation protections from international organizations or particular countries. In this case study, a regulation established by the governments of the United States of America (ALARA, 2016) and Canada (Codification, 2016) called ALARA (as low as reasonably achievable) was followed. The important factors in ALARA are the state of materials technology, economics of the technology, the economics of health benefits and other societal and socioeconomic considerations (Nuclear & Commission, 2004).

The major beta radiation emitters considered for this case study are Strontium-90 (0.546 MeV) and Yttrium-90 (2.28 MeV) (Delacroix et al., 2002; Nabeshi et al., 2015; Assessment for Sr-90, 2014). The major alpha radiation emitters considered for this case study are Uranium (U-236 and U-238) (Koo, Yang & Song, 2014). The gamma radiation emitter considered for this case study is Cadmium-109 (88 keV). The conditions for operation of Packbot are stated in Table 5.1.

Table 5.1 Conditions for the operation of Packbot

	Conditions	Specification of conditions
1	Radiations	
	– Alpha	U-236, U-238
	– Beta	Sr-90, Y-90
	– Gamma	Cd-109
2	Functions	
	– Locomotion	Track & pulley mechanism
	– Camera	Visual camera

	– Radiation measurement	Dosimeter
	– Temperature measurement	Thermography camera

5.1.2 The description of Packbot

Packbot (see Figure 5.1) is a rescue robot that carries out a range of functions in a disaster environment, such as bomb disposal, explosive detection and surveillance/ reconnaissance. Packbot can accommodate a wide variety of interchangeable payloads that enable a wide variety of missions (One robot, unlimited possibilities, n.d.). From Figure 5.1, it is observed that Packbot has a chassis with a single manipulator arm mounted on it. Packbot has two pairs of tracks on its right side and left side, respectively. It was discussed in Chapter 4 that most of the electronic components of a robot are installed inside the robot's chassis. Packbot has (1) on-board computer, (2) accelerometers, (3) inclinometers, and (4) compass, and all of them are installed inside its chassis (One robot, unlimited possibilities, n.d.). In addition to the above, Packbot also has two radio antennas mounted on its front side, a visual camera and a temperature measurement camera mounted on its manipulator arm (One robot, unlimited possibilities, n.d.). Packbot measures 27" (68.6 cm) in length (with flippers stowed) and 16" (40.6 cm) in width (without flippers). Additionally, the height of Packbot is 7" (17.8 cm) without including the manipulator arm (One robot, unlimited possibilities, n.d.). It was stated in Chapter 3 that Packbot used at the Fukushima nuclear disaster site performed three basic functions namely, (a) mobility at site, (b) survey and (c) radiation measurement.

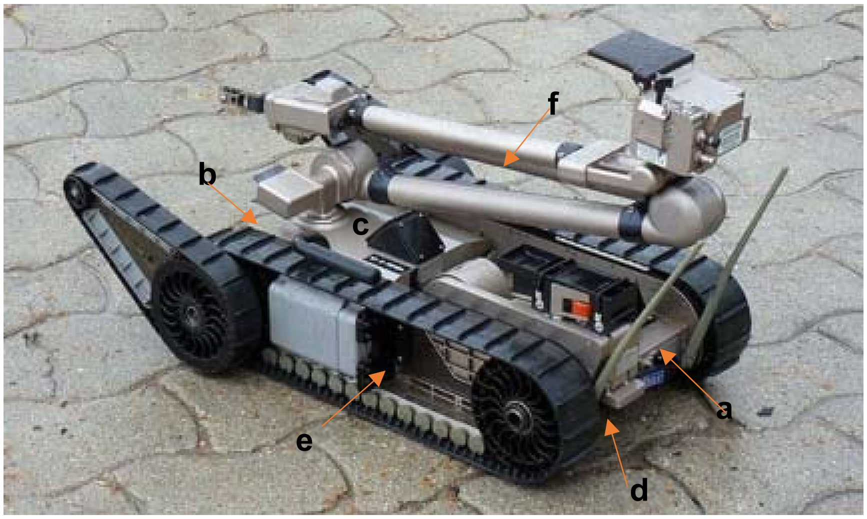

Figure 5.1 Packbot: (a) front, (b) back, (c) top, (d) bottom, (e) right side and (f) left side

(http://www.sciencebuddies.org/science-fair projects/project_ideas/Robotics_p015.shtml#background. Retrieved November 3, 2016)

5.2 Design of the clothes for Packbot

A specific clothing architecture was developed for Packbot based on the discussion in Chapter 4. The parameters defined in Section 4.2 are applied to this architecture. Clothing was also developed for the special instruments such as the camera and temperature measurement device of Packbot. Clothing for Packbot was developed as per the following scheme:

5.2.1 Clothing for chassis

Packbot has a rectangular chassis having six sides: (a) front side, (b) back side, (c) top side, (d) bottom side, (e) right side and (f) left side. The design of clothing for the six sides is as follows:

- **Clothing for the front side.** The clothing for the front side (a) of Packbot is attached to the clothing of the bottom side (d) (see Figure 5.4).
- **Clothing for the back side.** The clothing for the back side (b) of Packbot is attached to the clothing of its bottom side (d) (see Figure 5.4).
- **Clothing for the top side.** The clothing for the top side of Packbot is shown in Figure 5.2. The features incorporated in the top side clothing for Packbot are shown in Table 5.2. Table 5.3 shows the measurement of the dimensional parameters that is mentioned in Figure 5.2. Figure 5.3 shows the top side clothing applied on the chassis of Packbot.

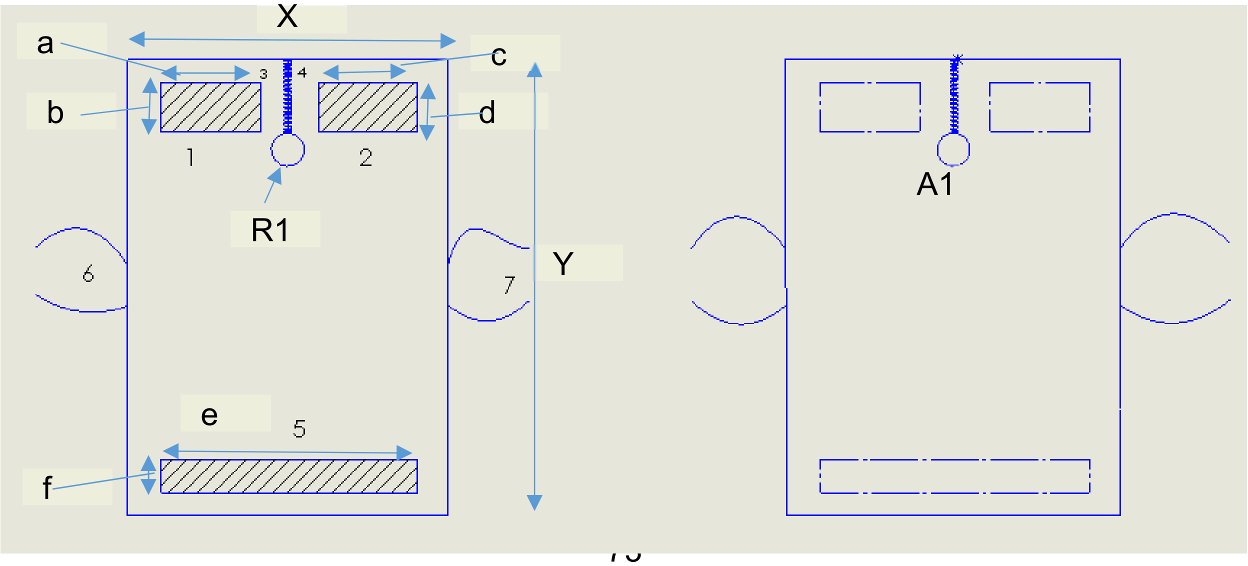

Figure 5.2 Top side clothing: (a) top view (b) bottom view

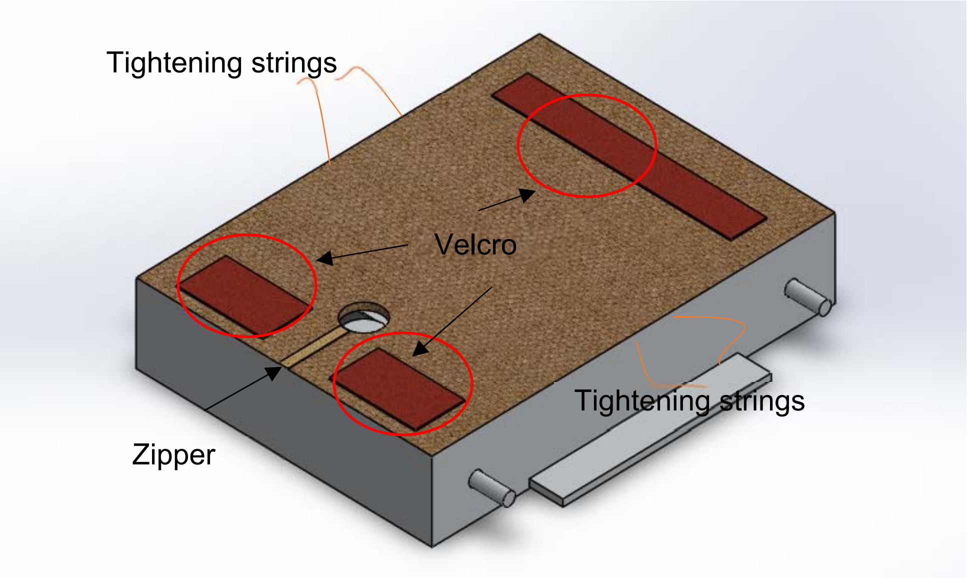

Figure 5.3 Top side clothing applied on the Packbot chassis

Table 5.2 Components of the top side clothing

	Name of components	Identity Number
1	Velcro	1
2	Velcro	2
3	Zip	3
4	Zip	4
5	Velcro	5
6	Tightening strings	6
7	Tightening strings	7
8	Armhole for manipulator	A1

Table 5.3 Measurement of the parameters shown in Figure 5.2

	Identification Tag	Measurement (in mm)
1	X	432
2	Y	711
3	A	50
4	B	25
5	C	50
6	D	25
7	E	390
8	F	25
9	R1	25

- **Clothing for the bottom side.** As discussed earlier in this section, the clothing for the bottom side of Packbot has the front and back side clothing attached to it (see Figure 5.4). The features incorporated in this piece of clothing for Packbot are shown in Table 5.4. Furthermore, Table 5.5 shows the measurement of the dimensional parameters that is mentioned in Figure 5.4.

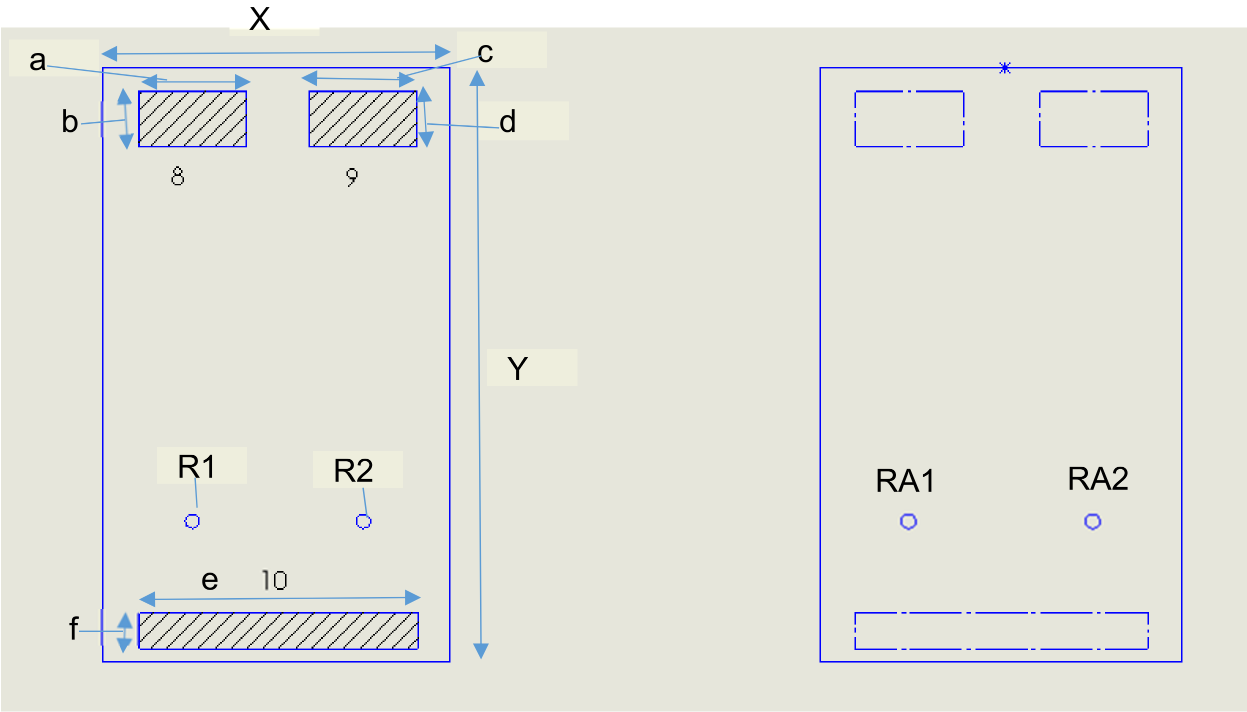

Figure 5.4 Bottom side clothing: (a) Top view (b) Bottom view

Table 5.4 Components of the bottom side clothing as shown in Figure 5.4

	Name of components	Identification number
1	Velcro	8
2	Velcro	9
3	Velcro	10
4	Eye for radio antenna 1	RA1
5	Eye for radio antenna 2	RA2

Table 5.5 Measurement of the dimensional parameters shown in Figure 5.4

	Identification tag	Measurement (in mm)
1	X	432
2	Y	1245
3	A	50
4	B	25
5	C	50
6	D	25
7	E	390
8	F	25
9	R1	10
10	R2	10

Table 5.6 and Figure 5.5 show the scheme of interfacing of the top side clothing components with the bottom side clothing components.

Table 5.6 Scheme of interfacing of the clothing components

	Component No-Component No	Component Name-Component Name
1	1-8	Velcro-Velcro
2	2-9	Velcro-Velcro
3	3-4	Zipper-Zipper
4	5-10	Velcro-Velcro

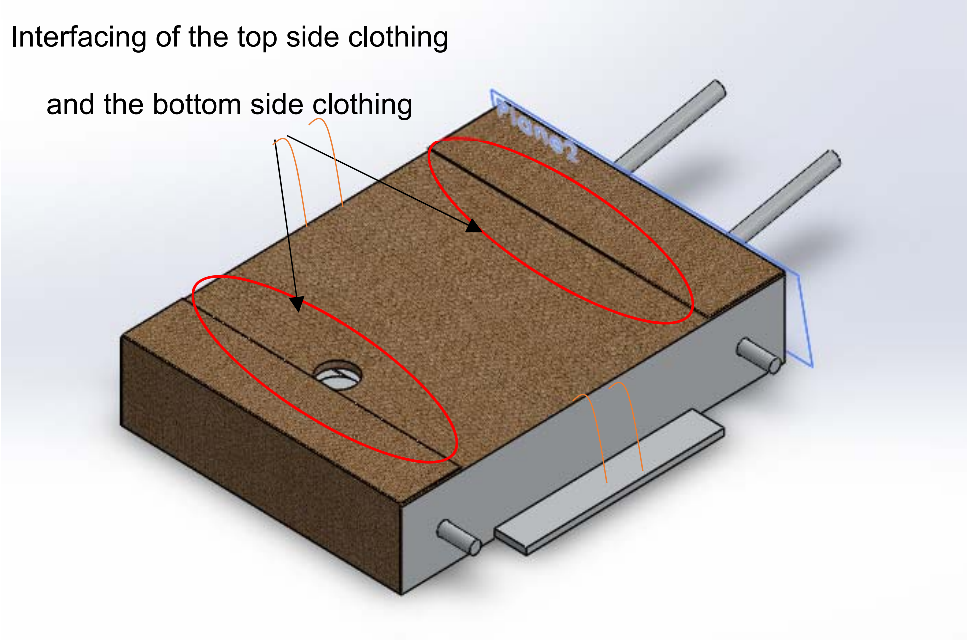

Figure 5.5 Interfacing of the top side and the bottom side clothing on the Packbot chassis

- **Clothing for the right side.** Packbot has a track and pulley system as its mechanism for locomotion (see Figure 5.1). The major consideration in the design of clothing for the right side of Packbot was to preserve the full functionality of its locomotion mechanism. The clothing architecture of Packbot ensures that: (a) the tracks of the Packbot do not become entangled in clothing and (b) the tracks are not covered by clothing. It was found in Chapter 2 that the mechanical components are not affected by the radiations. Also, the ALARA regulation allows for making judgments regarding design of shielding for radiation protection based on its practical significance (Keeping radiation exposure and doses "as low as reasonably achievable", 2004). Therefore, clothing material was not used for protection on the right side of Packbot. Furthermore, the structure of Packbot chassis is made of metals like aluminum or steel, which can also attenuate the radiation dosage.

- **Clothing for left side.** The reason explained for not having clothing on the right side of Packbot is also applicable for its left side.

5.2.2 Clothing for the manipulator arm

Packbot has a single manipulator arm (see Figure 5.1 and Figure 5.6). The equipment mounted on the manipulator arm are: (1) the visual camera, (2) the long width infrared (LWIR) camera and (3) the dosimeter (One robot, unlimited possibilities, n.d.). It can be observed from Figure 5.1 that there are no electronic components or communication cables exposed to the surrounding environment on the manipulator arm except the equipment mentioned above. Therefore, the clothing material was not used for the radiation protection of the manipulator arm of Packbot. This decision was in line with the ALARA regulation that allows for the design of shielding for radiation protection to be based on a practical significance and cost benefits (Keeping radiation exposure and doses "as low as reasonably achievable", 2004). However, the individual equipment can be wrapped in the clothing after considering the functions of the equipment (discussed later in this section).

It is important to note that the dosimeter cannot be covered in clothing. This is because the dosimeter's function is to measure the radiations. The dosimeter performs its function by interacting with its surrounding environment, therefore covering it with clothing will nullify its purpose.

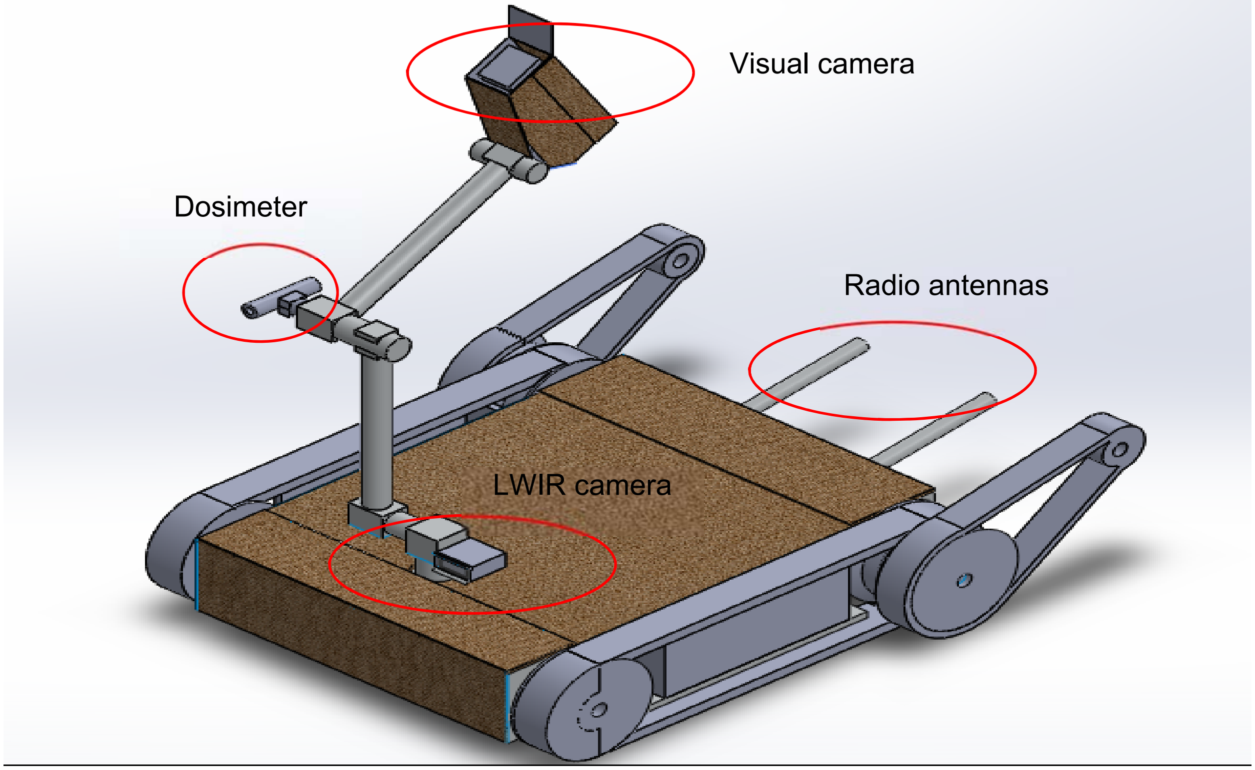

Figure 5.6 Clothing applied on Packbot

5.2.3 Clothing for the visual camera

Packbot has a single visual camera, mounted on its manipulator arm (see Figure 5.7). The clothing architecture consists of two materials (see Figure 5.7). Clothing for the visual camera consists of a string on the bottom. This string will facilitate in the closing and fastening of the visual camera’s clothing to the structure of the manipulator arm (see Figure 5.8). Additionally, Velcro (1) will attach to Velcro (2) as shown in Figure 5.8.

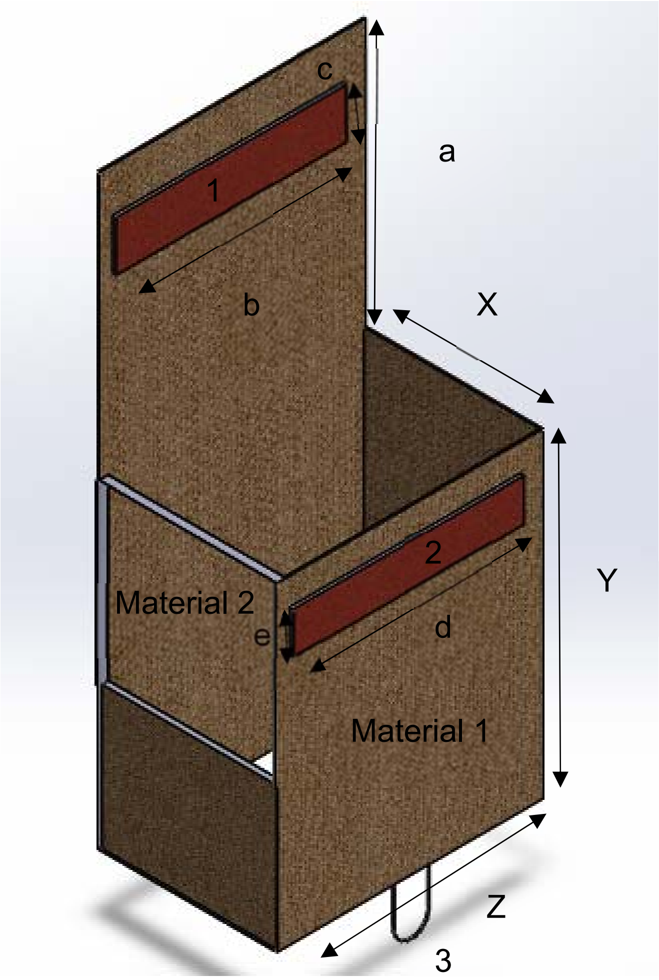

Figure 5.7 Clothing for the visual camera of Packbot

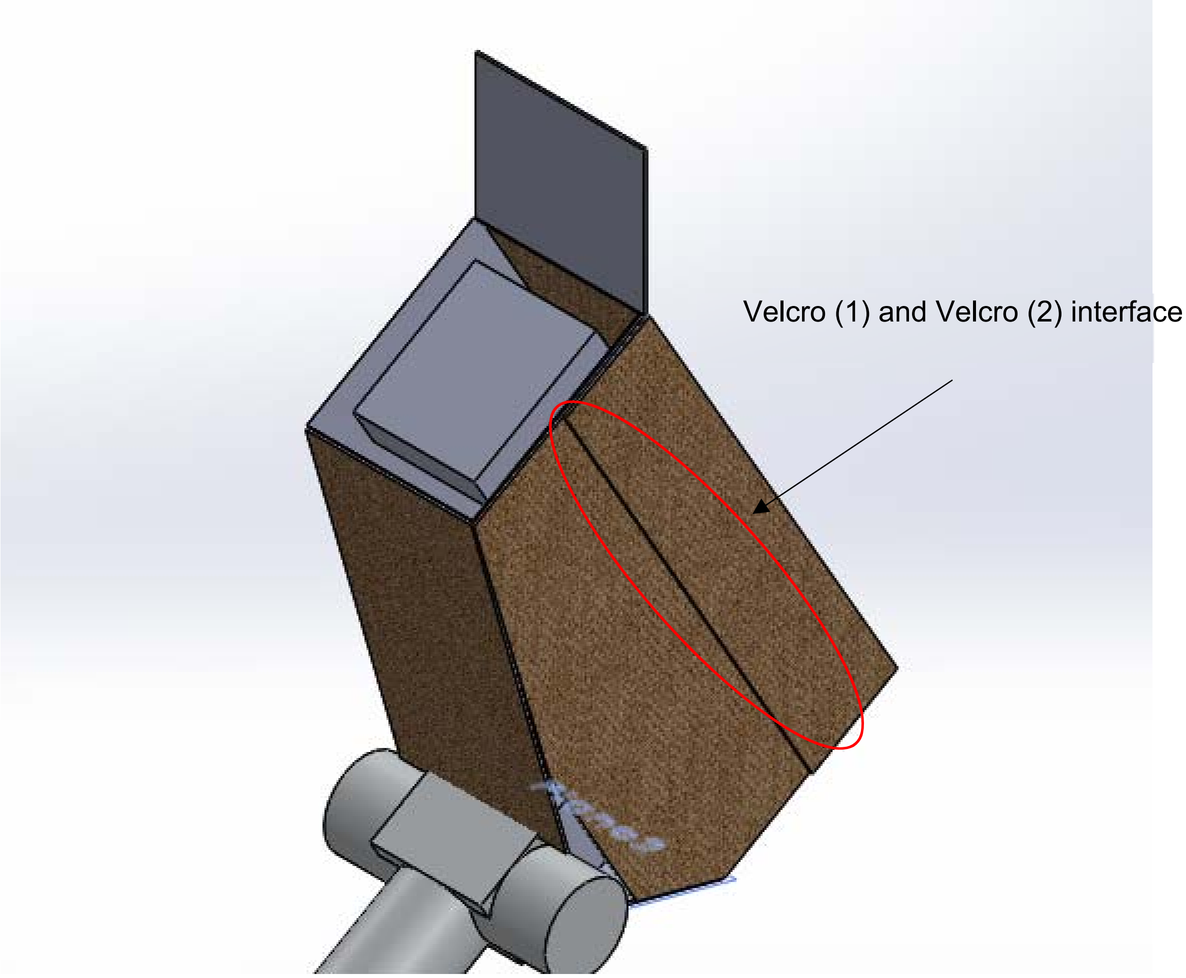

Figure 5.8 Visual camera with the clothing applied

The components of the clothing architecture of the visual camera are illustrated in Table 5.7. Velcro 1 and Velcro 2 will attach to each other. Tightening string is required to fasten the clothing of the visual camera on the manipulator arm. Material 1 is the same material that is used for clothing the body of Packbot. Material 2 is a transparent material or a combination of transparent materials that is required to cover the lens of the visual camera. The measurement of the dimensional parameters mentioned in Figure 5.7 is illustrated in Table 5.8. In Table 5.8, measurement of the different dimensional parameters is given. This will help in designing the clothing of visual camera.

Table 5.7 Components of clothing for the visual camera

	Component description	Identification tag
1	Velcro	1
2	Velcro	2
3	Tightening string	3
4	Shielding material	Material 1
5	Transparent shielding material	Material 2

Table 5.8 The measurement of dimensional parameters as shown in Figure 5.7

	Identification tag	Measurement (in mm)
1	X	80
2	Y	160
3	Z	160
4	A	110
5	B	150
6	C	12
7	D	150
8	E	12

5.2.4 Clothing for the LWIR camera

Packbot has a single long width infrared (LWIR) camera for temperature measurements. The LWIR camera is mounted near the manipulator arm’s base (see Figure 5.9). The architecture of clothing for the LWIR camera consists exclusively of transparent shielding materials (see Figure 5.10). It can be seen from Figure 5.10 that the architecture of clothing consists of five sides. This is because the LWIR camera is attached to the manipulator arm on one of its sides (see Figure 5.9). Therefore, the side attached to the manipulator arm is not exposed to the external environment, hence it is protected from the radiations. The measurement of dimensional parameters shown in Figure 5.10 is illustrated in Table 5.9.

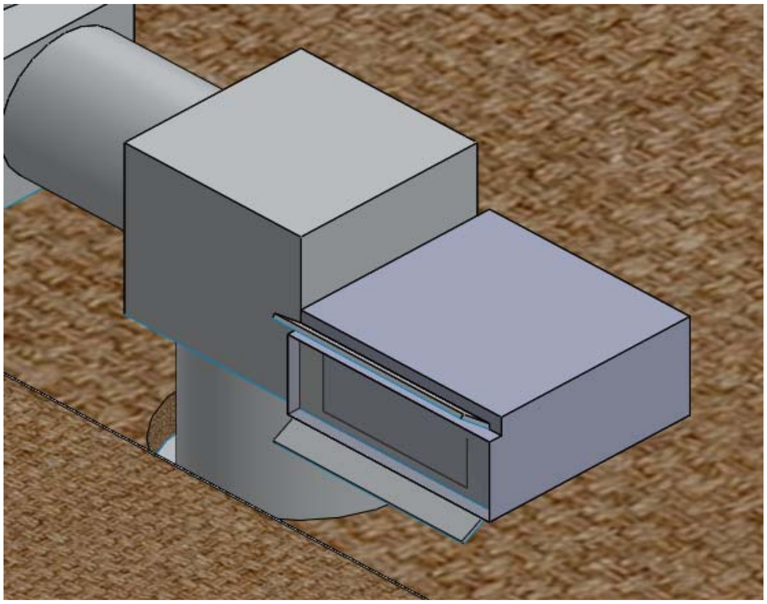

Figure 5.9 LWIR camera protected by clothing

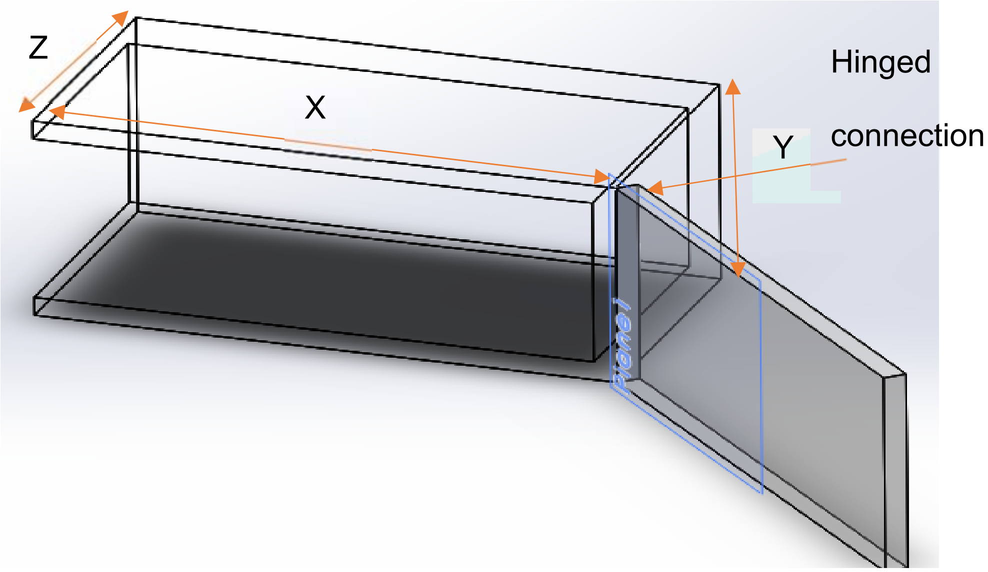

Figure 5.10 Clothing for the LWIR camera

Table 5.9 The measurement of dimensional parameters as shown in Figure 5.10

	Identification tag	Measurement (in mm)
1	X	80
2	Y	30
3	Z	30

5.3 Selection of the materials for Packbot

The materials for clothing of Packbot were selected based on the discussion in Section 4.4 and the ALARA principle with a particular attention to (a) covering its body and (b) covering the lens of visual and thermographic cameras.

5.3.1 Materials for the clothes for the body of Packbot

From the discussion in Section 4.4 it was found that Demron and aluminum were the most suitable materials for Packbot. Both aluminum and Demron are malleable materials that can be formed into clothes. They can shield against alpha, beta and gamma radiations and are environment-friendly.

However, it was shown in Chapter 4 that Demron has a better radiation protection capability than aluminum. From Figure 4.17, it can be seen that for a material density of 0.12 g/cm2, Demron is twice more effective in attenuating beta radiations than aluminum. Additionally, from Figure 4.18, it can be seen that for a material density of 0.12 g/cm2, Demron is four times more effective in attenuating gamma radiations than aluminum. Therefore, Demron was selected as the material for clothing the body of Packbot. Demron material of 0.38 mm thickness was used for Packbot. This can reduce the beta radiation dose emitted by Sr-90 and Yt-90 by 75 percent (see Figure 4.17) and gamma radiation dose emitted by Cd-109 by 85 percent (see Figure 4.18).

Specifically, Demron was used for developing the following parts of clothing of Packbot: (1) clothing for the top part of Packbot (See Figure 5.2 and Figure 5.3), (2) clothing for the bottom part of Packbot (See Figure 5.4 and Figure 5.5) and (3) parts of clothing for the visual camera (see Figure 5.7 and Figure 5.8).

5.3.2 Materials for clothes for the lens of visual and thermographic cameras

It was discussed in Chapter 4 that acrylic is a suitable material to cover the lens of cameras. This is because acrylic is a transparent material and can shield against alpha and beta radiations. However, acrylic is totally transparent to gamma radiations (Plexiglas, general information and physical properties, 2006). Therefore, a combination of acrylic and a special material called lead acrylic was used for protection against beta and gamma radiations respectively. A sheet of 4-mm acrylic was used before an 8-mm sheet of lead acrylic for the clothing design of specific parts of Packbot. This can reduce the beta radiation dose emitted by Y-90 by 97 percent (see Figure 4.19) and gamma radiation dose emitted by Cd-109 by more than 90 percent (Smith & Stabin, 2012). Specifically, the combination of acrylic and lead acrylic was used to develop the following parts of clothing for Packbot: (1) the lens of visual camera (see Figure 5.7) and (2) the clothing architecture of thermographic camera (see Figure 5.10)

5.4 Check of no obstacle to motion

The clothing for Packbot was designed to ensure its core functions. One of the core functions of Packbot is the physical motion of its various components. The components that perform important tasks by means of physical motion are: (a) the locomotion mechanism and (b) the manipulator arm.

5.4.1 The locomotion mechanism

In the design of clothing for Packbot, the full functionality of its locomotion mechanism was ensured. Therefore, the clothing material did not cover the right side and the left side of Packbot (see Figure 5.6). The two ways in which the clothing of Packbot could affect the functionality of its locomotion mechanism were: (1) by covering the track and pulley

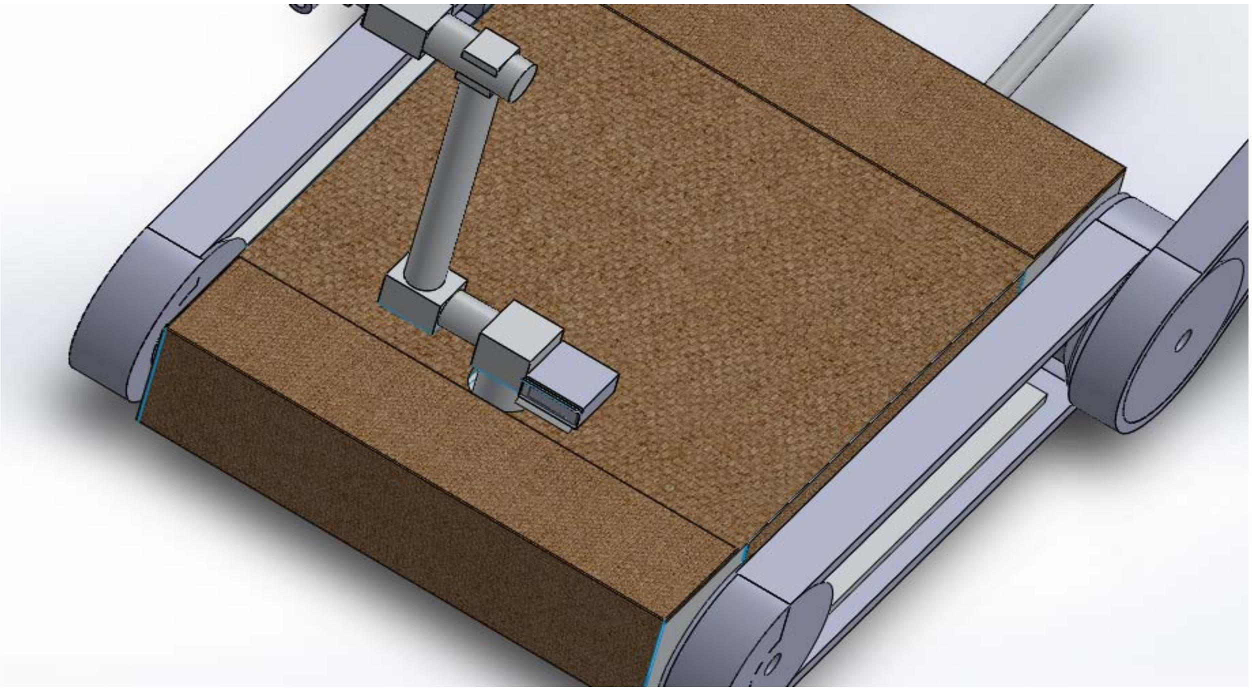

Figure 5.11 Locomotion mechanism and the manipulator arm of Packbot

mechanism and (2) by getting entangled with the track and pulley mechanism. Upon observing Figure 5.11 it is seen that the clothing of Packbot does not cover the locomotion mechanism and does not get entangled with it. Therefore, it can be concluded that the design of clothing does not hinder the function of the locomotion mechanism of Packbot.

5.4.2 The manipulator arm

It was shown in Section 5.2 that the manipulator arm of Packbot was not covered by clothing. However, clothing of the chassis could interact with the base of the manipulator arm (see Figure 5.11). This interaction could cause friction between clothing and the manipulator arm while the manipulator arm was in motion. This type of friction is known as Coulomb friction or kinetic friction. A study conducted by Braun & Preyrard (2011) found that Coulomb friction increases with the increase in velocity of a moving body.

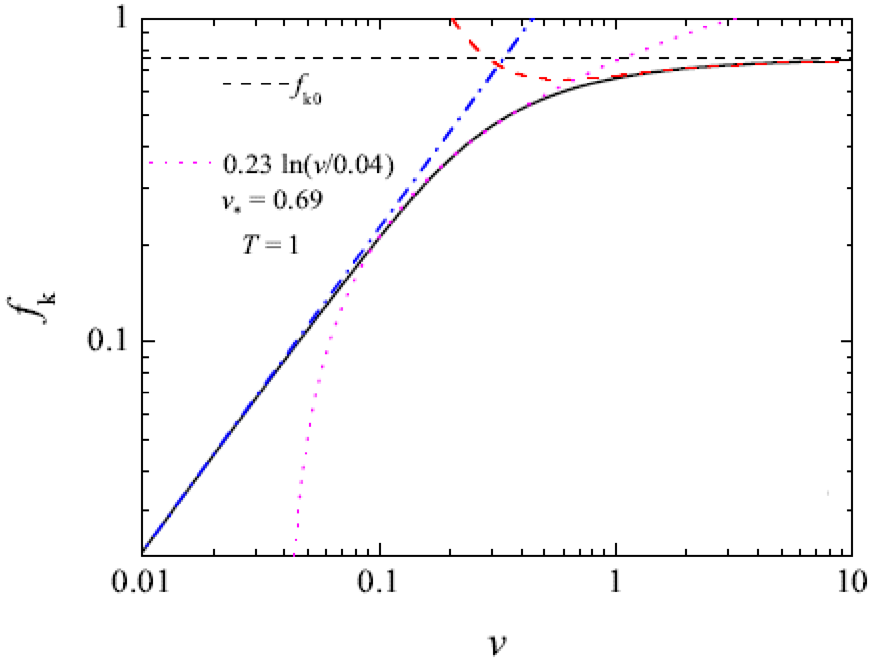

Figure 5.12 Blue and red lines show increase in kinetic friction with increase in velocity (Braun & Preyrard, 2011)

From Figure 5.12 it can be inferred that if the clothing material is impeding the motion of the manipulator arm of Packbot, then there will be a reduction in its angular velocity. From Figure 5.13, it can be observed that the angular velocity of the manipulator arm remains almost constant (blue line in Figure 5.13). This is because there is a minimal physical contact between the clothing material and the manipulator arm of Packbot. Therefore, it can be safely concluded that the clothing design does not impede the motion of the manipulator arm.

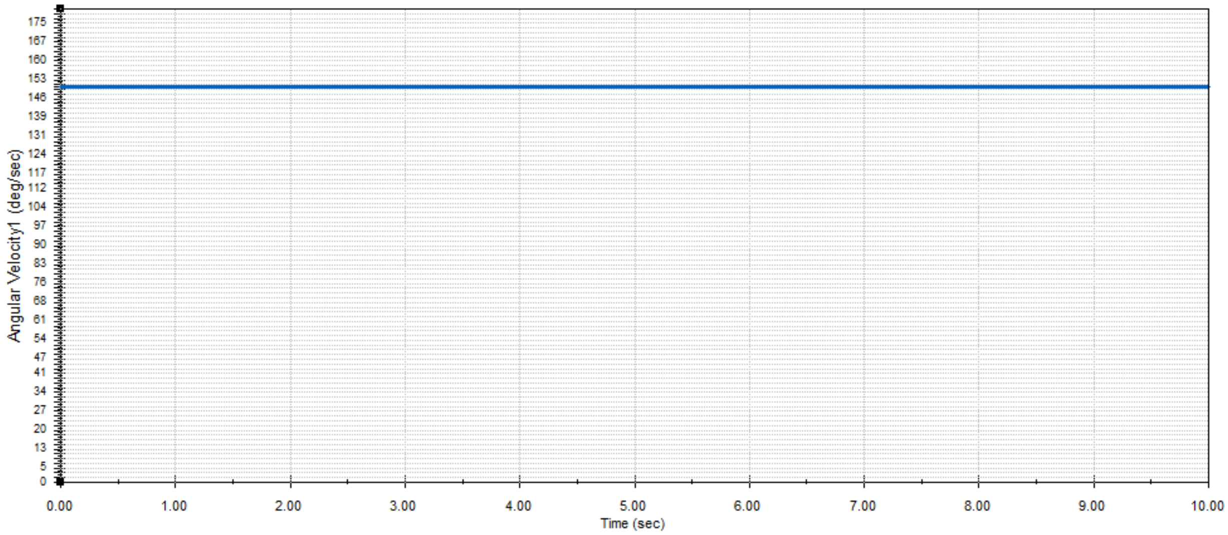

Figure 5.13 Angular velocity of manipulator arm

It is important to note that for Figure 5.13 there is an assumption that the motor disengages from the manipulator arm after providing a constant speed of 25 RPM (rotation per minute). This assumption was necessary to negate the power of the motor as the motor would always keep the angular velocity constant by overcoming the frictional force between the manipulator arm and the clothing material. Therefore, by using this assumption it can be seen that only the frictional force between the manipulator arm and the clothing material can affect the angular velocity of the manipulator arm.

5.5 Result of the case study

The result of the case study is summarized in Table 5.10. The table shows that there is 0.5 percent increase in the mass of Packbot because of the clothing material. Also, Demron reduces alpha radiation dose emitted by U-236 and U-238 by 100 percent, beta radiation emitted by Sr-90 and Y-90 by 75 percent and gamma radiation dose emitted by Cd-109 by 90 percent. Furthermore, 4 mm of acrylic reduces alpha radiation dose emitted by U-236 and U-238 by 100 percent and beta radiation emitted by Sr-90 and Y-90 by 97 percent. 8 mm of lead acrylic reduces gamma radiation emitted by Cd-109 by 90 percent. Also, it is mentioned in Table 5.10 that no function of Packbot is affected by the application of clothing.

Table 5.10 Result of the case study

	Specifications	Results
1	Mass of clothing	0.113 Kg (0.5 % increase in mass of robot because of clothing)
2	Radiation	
	– Alpha	100% reduction by Demron 100% reduction by acrylic
	– Beta	90% reduction by Demron (see Figure 4.17) 97% reduction by acrylic (see Figure 4.19)
	– Gamma	75% reduction by Demron (see Figure 4.18) 90% reduction by lead acrylic (see Table 4.2)
3	Functions	
	– Locomotion mechanism	No obstruction (see Figure 5.6)
	– Visual camera	No obstruction (see Figure 5.8)
	– Dosimeter	No obstruction (see Figure 5.6)
	– Thermography camera	No obstruction (see Figure 5.9)

5.6 Conclusion

In this chapter a case study was presented. A rescue robot was selected and the concept of clothing for radiation protection was applied to it. The material chosen for the clothing of the body of the rescue robot was Demron and the combination of materials chosen for the clothing of the lens of visual and thermographic camera was acrylic and lead acrylic. It was shown that the selected materials have the ability to protect the rescue robots from alpha, beta and gamma radiations. Furthermore, it was shown that the clothing of the rescue robot did not impede the motion of its components such as the locomotion mechanism and the manipulator arm. This case study provided validation to the concept of clothing for the radiation protection of rescue robot.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Overview and conclusions

This thesis presents the concept of using clothing for the protection of rescue robots from nuclear radiations. The study was motivated by the observation that the existing general purpose rescue robots do not have the required protection to shield them against nuclear radiations. Consequently, there is a possibility that these rescue robots may malfunction because of radiations inside a nuclear disaster zone. On the other hand, the special rescue robots with special coating materials are either costly from a point of view of their utilization or poor functionality (due to the constraint imposed on their design for the radiation protection purpose). The concept of clothing for radiation protection may provide a cost-effective solution for shielding against nuclear radiations for a rescue robot, as general-purpose robots may be employed for rescue mission in a radiation environment by wearing special clothes. This thesis manifests a pioneering effort on the clothing concept for rescue robots in a radiation environment. Two objectives were proposed for research to prove the concept of clothing for radiation protection for rescue robots, and the objectives are revisited below for the convenience of readers.

Specific Objective 1: Classify the current rescue robots which are expected to work in an irradiated environment in terms of their function as well as their conceptual structure or principle (Zhang, 2016). It is noted that in this thesis, study of effects of radiations on electronics and of materials for radiations protection were not investigated but the application of the knowledge relevant to radiations for developing a robotic clothing was focused. Furthermore, the design of rescue robots themselves and the management of operations of rescue robots were not studied.

Specific Objective 2: Develop a general architecture of the clothing system for rescue robots with consideration of classification performed in Specific Objective 1. This architecture should allow for the clothing to cover all the vulnerable parts of a rescue robot, which may be affected by the radiations. The selection of materials of clothes for radiations protection was focused, but any new material including its coating was considered to be out of the scope of this thesis. The clothing concept was proposed only for those robots which were classified in the Specific Objective 1.

The objectives stated above have been achieved, and the work related to the above objectives has been presented in detail in the preceding chapters. In particular, the comprehensive literature review presented in Chapter 2 provided a motivation and justification for the need to conduct this study. The literature review also identified the parts of rescue robots that needed to be focused for radiation protection. Chapter 3 presented the classification of rescue robots on the basis of their architecture and environment of operations. The rescue robots used at the Fukushima nuclear disaster were used for the purpose of classification. Chapter 4 presented the general architecture of clothing for a rescue robot and the material selection process. The architectural parameters that can be instantiated to make the clothing for a particular rescue robot were also presented in Chapter 4. Chapter 5 presented a case study by selecting one rescue robot from Chapter 3 and applying the concept of clothing on it to validate the concept of radiation protection clothing for a rescue robot.

The conclusions drawn from the work on this thesis are: (1) The existing general purpose rescue robots can work in an irradiated environment by using the concept of clothing for radiation protection. (2) The general architecture of clothing for radiation protection for rescue robots seems to work with the general functions of rescue robots, as classified in this thesis. (3) Special pieces of equipment mounted on rescue robots, for instance visual cameras and temperature measurement devices can also be protected by applying the concept of clothing.

6.2 Contributions

The contributions of this thesis are:

a) In the field of safety engineering, this thesis is perhaps the first to propose the idea of clothing of equipment to protect the equipment from harsh environment. The concept is promising in that equipment does not need to change itself in order to work in a different harsh environment (e.g., radiation, temperature, etc.) but just needs to wear a “cloth” for fire protection, radiation production and so forth.
b) In the field of robotics, the clothing concept for robots opens an entirely new dimension for robots, which is very promising in developing more intelligent robots in

the application situations where a harsh environment exists for robots or where human operators and the robot interacts with need to be protected. In the latter case, clothes for robots may be soft and compliant to humans and may be sensible to the accidental touching by humans, which may further harm humans.

6.3 Future work

There are several future works that are discussed below.

First, this thesis is concerned with the development of a general architecture of clothing for radiation protection for a rescue robot. Material selection is a component of this research. However, this research is not concerned with the synthesis and development of new materials that can provide protection from all types of nuclear radiations. Therefore, due to limitation in technology, this research only focused on protection from alpha, beta and low energy gamma radiations. Future work can be focused on development of clothing materials that can provide protection from all type of radiations.

Second, the idea of the radiation protection clothing can be expanded to the protection of rescue robots from other extreme conditions like heat from fire, extreme cold and aquatic environments.

Third, work can be done to develop clothing which is adaptable to different types and structures of rescue robots by introducing the concept of modularity to the clothing design.

Fourth, simulation can be performed to investigate the effect of clothing for radiation protection on a rescue robot. The simulation can include the calculation for radiation dosages and can explore the effect of clothing on the motion of various components of a rescue robot.

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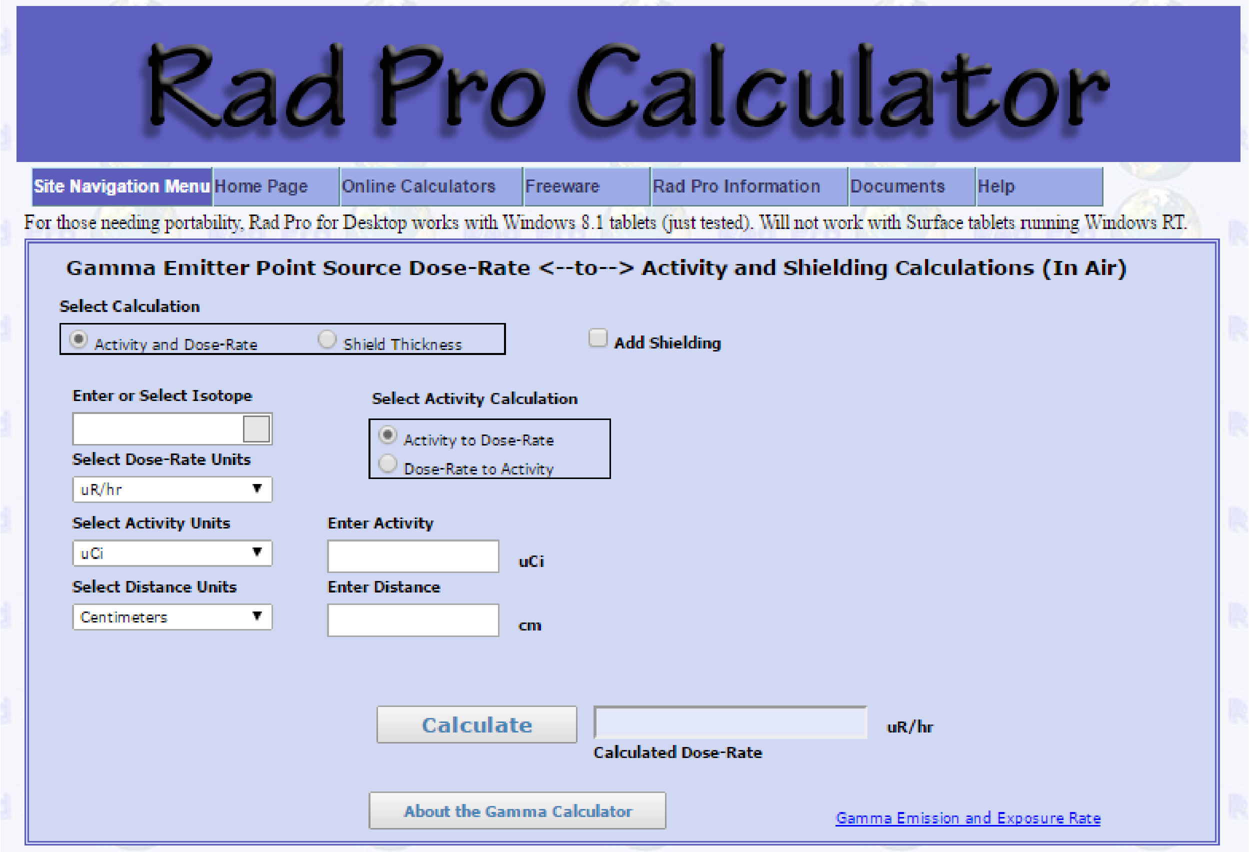
APPENDIX A RADPRO CALCULATOR

Radpro calculator is an online program that is used for the calculation of beta and gamma radiation dosages. The radiation dosage for beta and gamma radiations using Radpro is calculated as follows:

(1) select the isotope for which the radiation dosage is to be calculated,
(2) select the dose rate unit,
(3) select the specific radioactivity unit of the isotope,
(4) insert the value of specific radioactivity,
(5) select the unit of distance the object is from the radiation source, and
(6) insert the value of the distance.

The calculators for gamma (see Figure A.1) and beta (see Figure A.2) radiations are similar with one major difference: the gamma radiation calculator has the option to add shielding factor to the radiation dose rate calculation.



For those needing portability, Rad Pro for Desktop works with Windows 8.1 tablets (just tested). Will not work with Surface tablets running Windows RT.

Gamma Emitter Point Source Dose-Rate <--to--> Activity and Shielding Calculations (In Air)

Select Calculation: ● Activity and Dose-Rate ○ Shield Thickness

☐ Add Shielding

Enter or Select Isotope:

Select Activity Calculation: ● Activity to Dose-Rate ○ Dose-Rate to Activity

Select Dose-Rate Units: uR/hr

Select Activity Units: uCi

Enter Activity: uCi

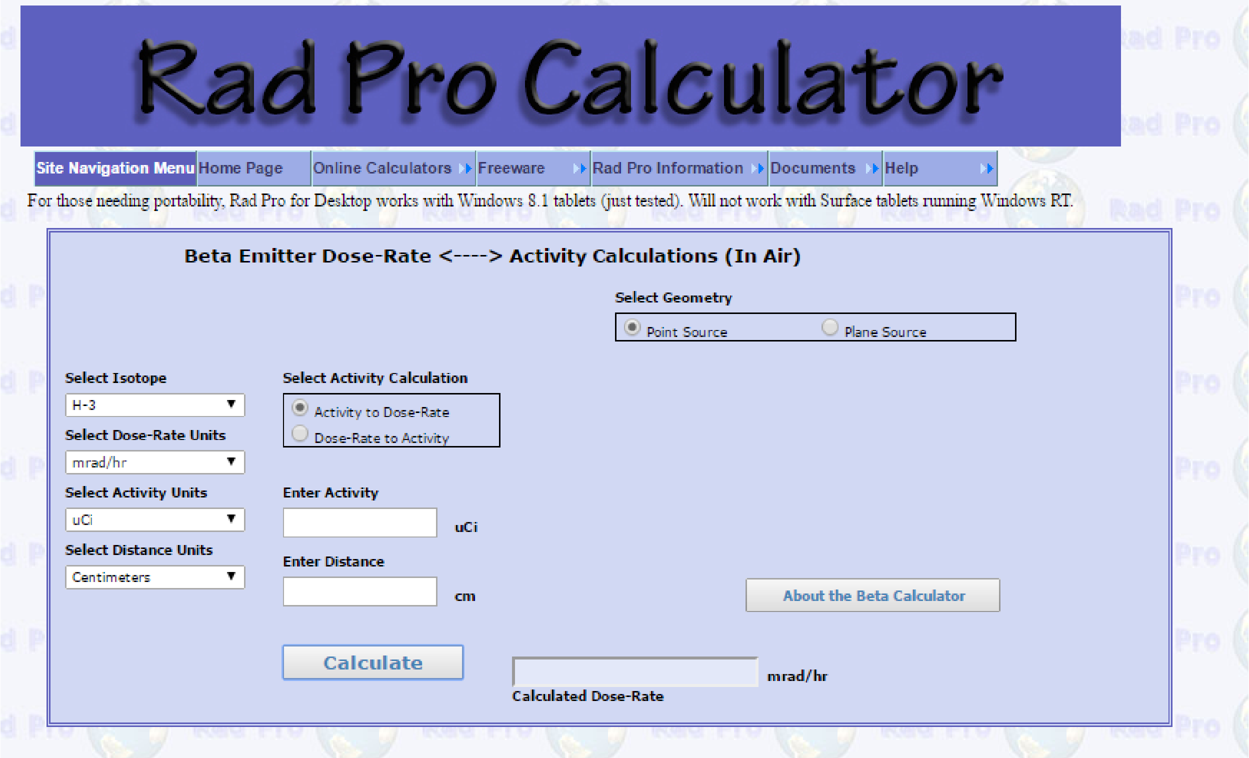
Select Distance Units: Centimeters

Enter Distance: cm

Calculated Dose-Rate: uR/hr

Figure A.1 Gamma radiation dose calculator.

(http://www.radprocalculator.com/Gamma.aspx. Retrieved March 25, 2017)



For those needing portability, Rad Pro for Desktop works with Windows 8.1 tablets (just tested). Will not work with Surface tablets running Windows RT.

Beta Emitter Dose-Rate <----> Activity Calculations (In Air)

Select Geometry
● Point Source ○ Plane Source

Select Isotope: H-3

Select Dose-Rate Units: mrad/hr

Select Activity Units: uCi

Select Distance Units: Centimeters

Select Activity Calculation
● Activity to Dose-Rate
○ Dose-Rate to Activity

Enter Activity: uCi

Enter Distance: cm

Calculated Dose-Rate: mrad/hr

Figure A.2 Beta radiation dose calculator.

(http://www.radprocalculator.com/Beta.aspx. Retrieved March 25, 2017)

APPENDIX B PHYSICS OF RADIATION

Radiation is the emission and transmission of energy through space or through a material medium (Weisstein, n.d.). This energy can be in the form of particles and waves (Radiation Basics, 2014). Electromagnetic waves, acoustic waves and particles are all different forms of radiation (Weisstein, n.d.). Radiations can be divided into two broad categories: ionizing radiations and non-ionizing radiations. The major difference between ionizing and non-ionizing radiations is that ionizing radiations carry enough energy to break bonds of materials and ionize them, while non-ionizing radiations do not have enough energy to break bonds of materials and ionize them (Nipun, 2015).

Ionizing radiations. Ionizing radiation is a radiation with enough energy that can remove tightly bound electrons from their atoms, causing the atom to become ionized (Nipun, 2015). Ionization radiations occur in two forms; waves and particles. For instance, alpha and beta radiations are in the form of particles while gamma radiation can be in the form waves.

- **Alpha radiations.** Alpha radiations are in the form of particles. Alpha radiation is a Helium nuclei that consist of two protons and two neutrons (Radioactivity, n.d.). Almost all naturally occurring alpha radiation emitters are heavy elements with atomic number exceeding 83 (Turner, 2007). Alpha radiation occurs when an atom undergoes radioactive decay, giving off the Helium nuclei (Radioactivity, n.d.). Alpha radiations interact strongly with matter because of their charge and mass and, therefore travel only a few centimeters in air (Alpha particles, n.d.). Alpha radiations are unable to penetrate a piece of paper or the outer layer of dead skin. However, alpha radiations can cause serious damage to the cells of living things if ingested in food or air (Types of ionizing radiation, n.d.).

- **Beta radiations.** Beta radiation is an electron emitted from the nucleus of a radioactive atom, along with an antineutrino. These particles are created at the moment of the nuclear decay (Turner, 2007). Due to the smaller mass of beta particle compared to alpha particle, it can travel up to a few meters in air. Beta radiations are effectively shielded by materials having low atomic numbers. This is because beta radiations when shielded by materials having higher atomic numbers, produce secondary radiations known as bremsstrahlung radiations in the form of photons (Beta particle, n.d.).

- **Gamma radiations.** Unlike alpha and beta radiations, gamma radiations do not consist of particles, instead gamma radiations are high-energy photons that are emitted from an unstable nucleus. Gamma radiations have no charge or mass; hence gamma radiations travel much farther in air than alpha and beta radiations. Gamma radiations can only be stopped by materials having high atomic number such as lead or depleted uranium (Types of ionizing radiation, n.d.). Gamma radiations interact with matter in three principle ways: (1) Photoelectric effect, (2) Compton scattering and (3) Pair production (Characteristics of gamma rays, n.d.).

1) **Photoelectric effect.** Photoelectric effect is the process in which, electromagnetic radiations can be used to push electrons from the surface of a solid (Elert, n.d.). The phenomenon of photoelectric effect is used in the field of radiation protection. This is done by transforming penetrating gamma radiations into electrons that are easy to stop (Photoelectric effect, n.d.).

2) **Compton scattering.** In Compton scattering, the incoming gamma radiation strikes an electron. This interaction of gamma radiation with electron, ejects the electron from its orbital position in the atom. Gamma radiation loses some of its energy by sharing it with the ejecting electron and continues to travel through the material in an altered path until it loses its energy by colliding with another electron (Gamma rays in matter, n.d.).

3) **Pair production.** When the energy of gamma radiation exceeds one million electronvolts (1 MeV), the gamma radiation interacts with the nucleus of an atom to produce an electron and positron (Gamma rays in matter, n.d.). The energy of gamma radiation is transformed into matter (Turner, 2007).

Non-ionizing radiations. Compared to the ionizing radiations, non-ionizing radiations have lower energies, that do not have the capability to ionize atoms or molecules (Nipun, 2015). Non-ionizing radiations are located at the lower end of the electromagnetic spectrum. Visible light, heat, radio waves, infrared radiations and lasers are all examples of non-ionizing radiations (Ronca, n.d.).

APPENDIX C GAMMA RADIATION ABSORBTION IN MATERIALS

Gamma radiations traveling through matter are absorbed in that medium. The gamma radiations are absorbed due to a number of processes, for instance; photoelectric effect, Compton scattering and pair production.

The linear attenuation coefficient for a substance is the ability of the substance to absorb gamma radiations (Absorption of gamma rays, n.d.). Gamma radiation absorption is a random process and is governed by the probability per unit distance traveled that a photon interacts by any of the three physical processes. This probability is called linear attenuation coefficient (Turner, 2007).

Gamma radiations are attenuated exponentially in a uniform material. Consider a narrow beam of gamma radiations (N_o) that are incident normally on a slab of material. As the beam penetrates the material, some gamma radiations are absorbed and some are scattered. Gamma radiations absorbed by the material can be denoted by N and the distance penetrated can be represented by x. The probability that gamma radiation is absorbed by the material is denoted by μ. Hence, the relation for gamma radiation absorption can be written in the form of Equation 1 (Turner, 2007).

$$N_o = Ne^{-\mu x} \qquad \text{(C-1)}$$

Linear attenuation coefficients of various materials is shown in Figure C.1.

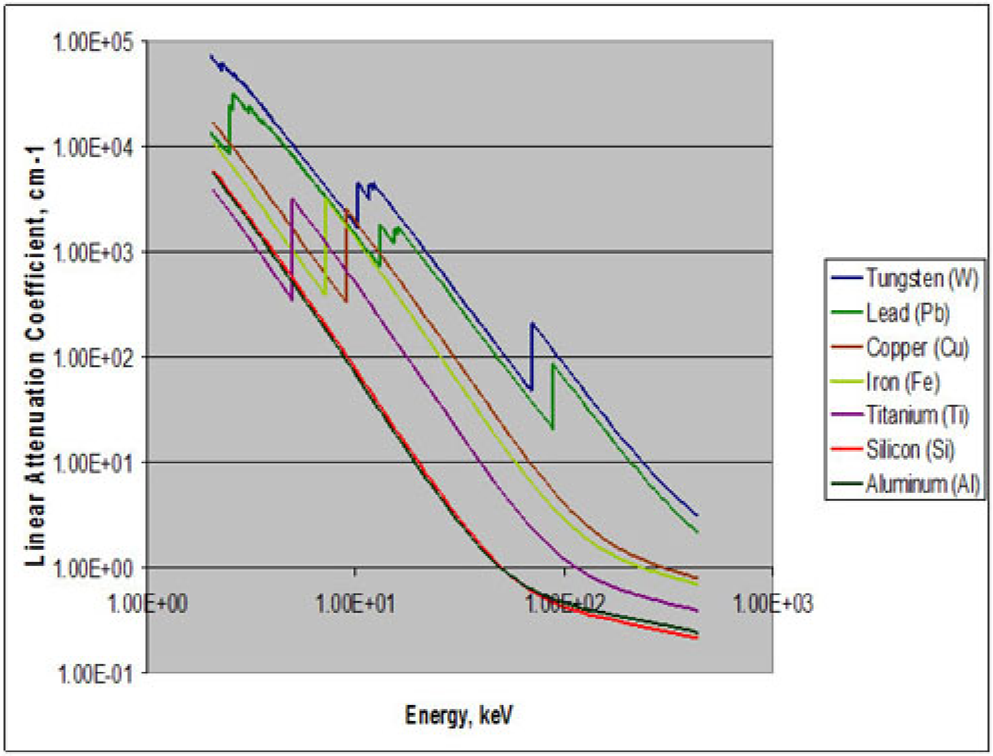


Figure C.1 Linear attenuation coefficients for various materials. (https://www.nde-ed.org/EducationResources/CommunityCollege/Radiography/Physics/attenuationCoef.htm. Retrieved on May 31, 2017)

APPENDIX D EFFECT OF RADIATIONS ON ELECTRONICS

Various type of damage can occur in electronic devices due to exposure to radiations. The damage to electronic devices can be categorized into, (1) effects due to ionizing radiations and (2) effects due to non-ionizing radiations.

- **Effects due to ionizing radiations**. Due to ionizing radiations there is an accumulation of free charges which can modify the properties of materials, and thus change the behavior of electronic components. Ionizing radiations cause the electronic devices to suffer from Total Ionizing Dose (TID) effect and Single Event Effects (SEE). TID is caused by the gradual accumulation of charges due to prolonged exposure to ionizing radiations. TID is also known as surface damage (Fiore, 2015).

  The term surface damage is used for all the defects in the overlaid dielectrics, for instance, the silicon oxide and the interface between the dielectric and the silicon (Meroli, 2012). The surface of silicon is sensitive to radiations. The damage caused by the ionizing radiations is primarily due to the trapping of the charge in SiO2 (Makowski, 2006). The ionizing radiation causes the creation of electron-hole pair in the oxide layer (Meroli, 2012). A small portion of the created electron-hole pairs quickly recombine. As the mobility of electrons is much higher than the mobility of holes, therefore only a small number of holes can move to silicon through the interface. Holes remaining in the insulator result in the charge build up in SiO2

(Makowski, 2006).

- **Effects due to non-ionizing radiations**. Non-ionizing radiations can displace atoms from the lattice sites and produce bulk damage effects. Bulk damage effects is also known as Displacement Damage Dose (DDD) effects (Fiore, 2015). To remove a silicon atom from its lattice position, an electron requires at least 260 keV, while protons and neutrons, due to their higher mass, require 190 eV. The single vacancy-interstitials are mostly created by electromagnetic radiations of low energies (Meroli, 2012).

APPENDIX E INTRODUCTION TO A ROBOT

A robot is a reprogrammable, multifunctional platform designed to perform various functions through variable programmed motions for the performance of these functions (Kapila, n.d.). A robot consists of four major parts: (a) actuators, (b) sensors, (c) mechanisms, and (d) controller (Introduction to Robotics, n.d.). These parts of a robot work together to perform specific functions.

- **Actuators.** Actuators are mechanical or electro-mechanical devices that provide controlled and sometimes limited movements. The actuators can be operated electrically, manually or by fluids such as air, oil or water. The actuators perform two basic motions namely, linear and rotary (Types of actuator, n.d.). Actuators of a robot are controlled by the controller which instructs the actuator to perform certain tasks in a controlled manner.

- **Sensors**. A sensor is a device that detects and responds to some type of input from the physical environment. The input can be in the form of motion, heat, light, pressure or any of the other environmental measures. The output provided by the sensor is usually in the form of electrical signals. These signals are then converted into human readable form or transmitted to the controller for further processing (Sensor, 2012). Cameras, temperature measurement devices, distance measurement devices are all different types of sensors.

- **Controller**. A controller is a device which takes one or more than one input and adjusts its output in a way that the connected device functions in a controlled manner (Controllers, 2017). The controller of a robot is responsible for processing all the information transmitted from the sensors. After processing the input from the sensors, the controller instructs the actuators of the robot to perform any function or set of functions.

- **Mechanisms**. A body that transfers motion and force.

There are various types of robots. The classification of robots can be done on two major criteria: (a) type of robots by application and (b) type of robots by locomotion (Type of robots, n.d.).

- **Type of robots by application**. Robots perform a variety of functions. In terms of application, robots can be divided into; (1) Industrial robots, (2) Household robots, (3) Medical robots, (4) Service robots, (5) Military robots and (6) Entertainment robots.

- **Type of robots by locomotion.** Robots can have various means of locomotion mechanisms. In terms of locomotion mechanism, robots can be divided into; (1) Stationary robots, (2) Wheeled robots, (3) Legged robots, (4) Swimming robots and (5) Flying robots.