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Design of a mechatronic system to relief search and rescue of victims after an earthquake disaster

Thesis

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BY

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In Partial Fulfillment of the requirements for the degree of Master of Science in Mechatronics

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Declaration of Autorship

I, Gabriela Alejandra Contreras-Moreno, declare that this thesis, ”Design of a mechatronic system to relief search and rescue of victims after an earthquake disaster”, is the result of my own work. Any part of this dissertation has not been previously submitted, in part or whole, to any university or institution for a degree or other qualification.

I confirm that all consulted work for others is attributed and the source is always given. Where the work is done with the help of others, these sources of help have been acknowledged.

Signed: ______________________________

Date: ______________________________

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I dedicate this work in memory of my cousin, Fernando Morales Moreno

Abstract

Immediately after an earthquake disaster, search and rescue activities are primordial in order to localize and relief victims. Time is a critical factor due that the survival probabilities of victims trapped under the rubble decrease with the increasing of the elapsed time. The use of technology for disaster relief activities is significantly helpful to reduce effort, risks and time of these operations. For this, the definition and conceptual design of a mechatronic system to relief search and rescue of victims after an earthquake disaster are presented in this Thesis.

The methodology used for the development of the project is based on the V-Model for projects development and Pahl-Beitz design model. In a first approach, the main functions of: exploration, illumination, detection of victims and collection of environment data were defined for the system to be developed. To obtain a final concept an analysis of the system functions and the solutions principles were elaborated. The resulting concept consists on a mobile robot with continuous tracks, two mobile arms, illumination and sensor subsystems. The mobile robot has capabilities to surmount different obstacles and move over different terrains as those found in affected zones.

Kurzfassung

Unmittelbar nach einem Erdbeben, Lokalisieren und Erstehilfe für Erdbebenopfer ist die wichtigste Aufgabe der Such- und Rettungsaktivitäten (SAR). Zeit ist ein kritischer Faktor für die Überlebenswahrscheinlichkeit der Opfer welche unter den Tümmern eingeschlossen sind. Der Einsatz von techischen Hilfmitteln erhöht signifikant die Überlebenswahrscheinlichkeit der Opfer, und minimiert das Riesiko der Hilfsarbeiten. Diese Abschlussarbeit befasst sich mit der Definition und dem Konzepdesign eines Mechtronischen Systems zur Suche und Ortung von Erdbebenopfern.

Die angewante Methodig zu Planung dieses Projektes basiert auf dem V-Model zur Projektentwicklung und dem Pahl-Beitz als design Modell. In einer ersten Annährung an das zu entwickelden Projekt wurden die zu implenetierenden Basisfunktionen definiert. Das resultierende Konzept besteht aus einer mobilen Plattform die auf Raupen oder Gleisketten, die Sensorik und Beleuchtungs Subsysteme trägt. Dieser mobile roboter hat die Fähigkeit Hindernisse zu um- oder überfahren.

Resumen

Inmediatamente después de un sismo, las actividades de búsqueda y rescate son primordiales para la localización y asistencia de víctimas. El tiempo es un factor crítico debido a que las probabilidades de supervivencia de las víctimas atrapadas bajo el escombro, se reducen con el transcurso del tiempo. El uso de tecnología para las actividades de apoyo de desastre es significativamente útil para reducir el esfuerzo, riesgo y tiempo de estas operaciones. Por ello, la definición y diseño conceptual de un sistema mecatrónico para apoyar la búsqueda y rescate de víctimas después de un desastre por sismo, son presentados en esta Tesis.

La metodología utilizada para el desarrollo del proyecto se basa en el V-Model para desarrollo de proyectos y en el modelo de diseño de Pahl-Beitz. En un primer enfoque, las funciones principales de: explración, iluminación, detección de vícttimas y recolección de datos del ambiente fueron definidas para el sistema a desarrollar. Para obtener un concepto final, un análisis de las funciones del sistema y los principios de solucion fueron elaborados. El concepto resultante consiste en un robot móvil con orugas, dos brazos móviles, subsistema de iluminación y sensores. El robot móvil tiene las capacidades de superar diferentes obstáculos y moverse sobre diferentes terrenos como aquellos que se encuentran en las zonas afectadas.

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Acronyms

CAD Computer-aided design

CCD Charge-Coupled Device

CO_2 Carbone Dioxide

ConOps Concepts of Operations

DOF Degrees of Freedom

EMAG Institute of Innovative Technologies

FOV Field of View

FR Functional Requirements

GPS Global Positioning System

GUI Graphic User Interface

HDMI High Definition Multimedia Interface

HLR High Level Requirements

IMU Inertial Measurement Unit

IoT Internet of things

IR Infrared

LED Light-Emitting Diode

$LiFePO_4$ lithium iron phosphate

LoRa Long-Range

LPG Liquefied Petroleum Gas

LPWAN Low Power Wide Area Networks

NIST National Institute of Standards and Technology

NFR Non-Functional Requirements

PIAP Industrial Research Institute for Automation and Measurement

PWM Pulse Width Modulation

SBC Single Board Computer

TOF Time of Flight

UGV Unmanned Ground Vehicle

USAR Urban Search and Rescue

USB Universal Serial Bus

WMR Warwick Mobile Robotics

Chapter 1

Introduction

It is estimated that there are 500,000 detectable earthquakes in the world each year. 100,000 of those can be felt, and 100 of them cause damage. About 90% of the earthquakes in the world occur in the so-called “Ring of Fire” which is the zone surrounding the Pacific Ocean [1].

The effects of an earthquake can destroy settlements collapsing buildings, disrupting communication and transportation links, and killing or injuring people who got trapped under the rubble. Smaller earthquakes and tremor that follow the main quake, called aftershocks, can cause additional damage to the area.

Mexico is one of the countries that are part of the ”Ring of fire” and almost all of Mexican territory is highly exposed to earthquake risk. On average, Mexico experiences more than 90 earthquakes per year with a magnitude of 4.0 or above on the Richter scale [2], that is between those that can be felt and those that can cause damage.

After an earthquake, it is primordial to localize people under rubble and rescue them. This is done by cutting and removing the debris in the affected zone and exploring the area, which is a hard labor and take too many time for a human being. As it can be observed in Figure 1.1, the survival probability decrease with the elapsed time so in this case, time is a critical factor.

It is well known that the better way to attack the problem is to prevent the damage caused by an earthquake by setting up buildings against them and other precautionary methods. Nevertheless since this is a reality, disaster relief systems are required. Technology for Urban Search and Rescue (USAR) labor has significant application potentials during the rescue and recovery operations of recent disaster events. In general, the overall goal of a USAR mission is to explore unknown cluttered disaster scenes while searching for victims [4]. The use of technology for rescuing people and perform other necessary tasks during the rescuing labor such as cut, remove

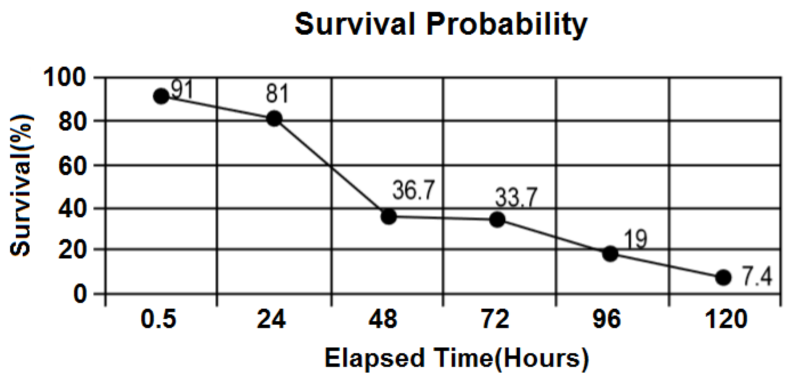


Figure 1.1: Survival probability vs. elapsed time in hours. Taken from [3].

and transport the rubble is significantly helpful to reduce effort and time, however, the majority of rescue technology used in Mexico need to be controlled by an external user. In order to minimize the workload of the system operator and increase efficiency in time-critical disaster scenes, recent efforts have been made to equip these systems with some level of autonomy [4].

The present Master project for the German-Mexican Master program will focus in the definition and conceptual design of a mechatronic system able to relief search and rescue of victims after an earthquake disaster by performing at least one of the following functions considered: debris cutting, debris removing, debris transportation, scene mapping and exploring, victims search, gear transportation and providing, or any other additional function important to rescue people or relief in this kind of disasters, in a more efficient way that is done at the time with the conventional methods and equipment.

1.1 Motivation

Structural damage to buildings, bridges and highways, fires, initiation of slope failures and aftershocks are some of the consequences that can be found after an earthquake. The main problem are the deaths and injuries caused by building collapse.

Earthquakes have claimed millions of lives in the last 100 years. In Mexico, at least 369 people die during a magnitude 7.1 earthquake. It follows a more powerful but less deadly earthquake, the most powerful to hit the country in a century, and improvements in technology have only slightly reduced the death toll [5].

USAR is a challenging yet promising research and development area which has significant application potentials. Systems able to reduce the search and rescue operation time are strongly needed in disaster situations to increase the survival probability of the victims while keeping rescuers safe and decreasing the overall effort.

Usually, approaches of the CIDESI-CONACYT are dedicated to develop solutions for industry applications. Nevertheless, this project focus to a problem whose solution will not just have a technological or scientific impact, but a big social one.

For this project, it was necessary to put into practice inventive capacity and creativity for a practical and useful mechatronic system design. At the same time, mechatronics principles and knowledge are required such as: project and system development, motion mechanisms, sensors and actuators, human-machine interfaces among others.

Applying engineering and mechatronic knowledge beyond industrial applications to develop USAR system is our strongest motivation to face this endeavor.

1.2 Hypothesis

As this project has been developed to achieve a Master degree in science of mechatronics, a formal hypothesis was established.

"A mechatronic system to perform one or more tasks of the rescuing process in a more efficient way than conventional methods to relief search and rescue for victims after an earthquake disaster could be designed applying state of the art and engineering techniques."

1.3 Justification

A great part of Mexican territory corresponds to seismic zones. Recently, eight states of the country have been significantly affected [6]. Dozens of buildings have collapsed, hundreds of human lives have been lost and others got trapped under rubble. Therefore, it is proposed the use of specialized machinery to increase the possibility of rescuing people by performing one or more tasks of the rescuing process such as debris cutting, debris removal, debris transport, exploring and mapping, searching for victims, among others.

Existent heavy machinery need to be manually controlled by external personal for a careful debris removal. This leads to slow times and hard work. On the other hand, rescue labor presents a danger for the people due to possible aftershocks or ignorance of the area to inspect. Urban disaster environments have been known to be very difficult to access by rescue workers due to the potential presence of asbestos, dust, poisonous gases, hazardous materials, radiation or extreme temperatures [4].

Actual technology allows the design and construction of specialized machinery with characteristics to support this labor. At the same time the use and production of technology is necessary in Mexico taking countries as Germany as an example, where exists a great variety of machinery and equipment for a lot of specific tasks.

1.4 Objectives

In this section the main objective of the Master Thesis is established as well as specific objectives. These objectives are Specific, Measurable, Achievable, Realistic and Time-Bounded, following the SMART criteria.

1.4.1 General objective

Approach, define and design the concept of a mechatronic system to relief search and rescue of victims after an earthquake disaster. The system functions shall justified its development, acquisition and practical use. This system shall be carried out within four months with a full-time schedule.

1.4.2 Specific objectives

The specific objectives in a chronological order are listed below. The time bounded criteria for each of these objectives is shown in the chronogram of activities in Appendix A.

1. **Thesis protocol.** Initial formal thesis definition document.
2. **Review of the state of art and concept exploration** of commercial products and existent machines technologies for rescue and search labor in articles, books and internet.
3. **Co-write the concept of operations and high level requirements.**
4. **Realize a concept design** of the mechatronic system.
5. **Select the essential components** for the system.
6. **Create a preliminary model**.
7. **Thesis manuscript.**
8. **Thesis dissertation.**

1.5 Methodology

The selected methodology was based in the V-model represented in Fig. 1.2. The scope of the project will cover the predevelopment phase that goes from the problem statement, the necessity and the motivation to the concept exploration. In this particular case the feasibility study is not necessary to be performed. It will also cover the first stages of the development phase, which are the definition subphase and the beginning of the design subphase. The definition subphase consists on the establishment of the concept of operations and the system requirements. The design subphase begins with the system concept which is a general design of the system giving solution concepts that satisfy the established requirements.

Pahl-Beitz design process model shown in Fig.1.3, was selected to be used to complement the main steps taken from the V-model for being a reasonably complete model, in order to obtain a more detailed methodology for the project development.

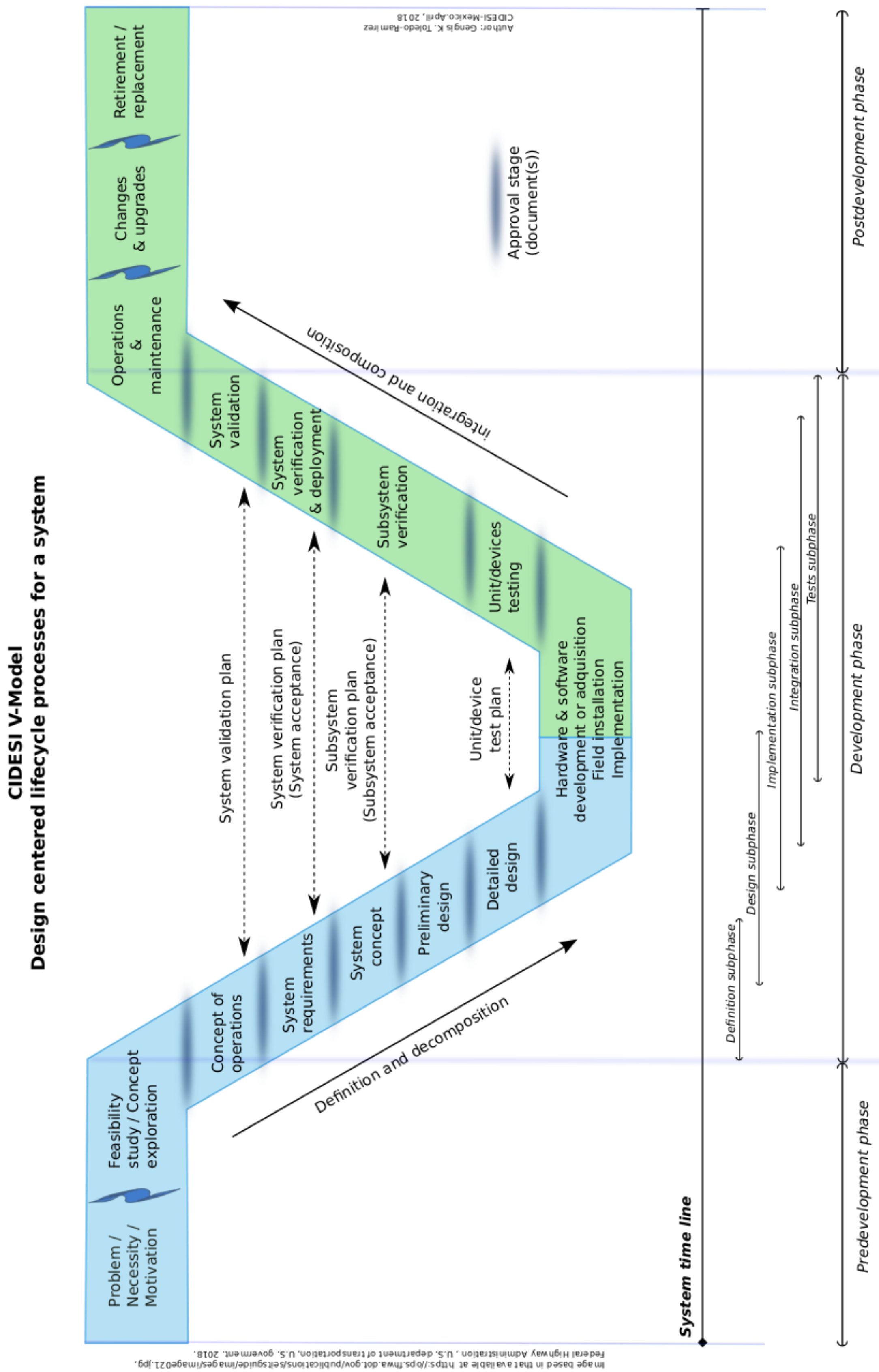


Figure 1.2: V-Model for Systems Engineering adapted for CIDESI. Taken from [7].

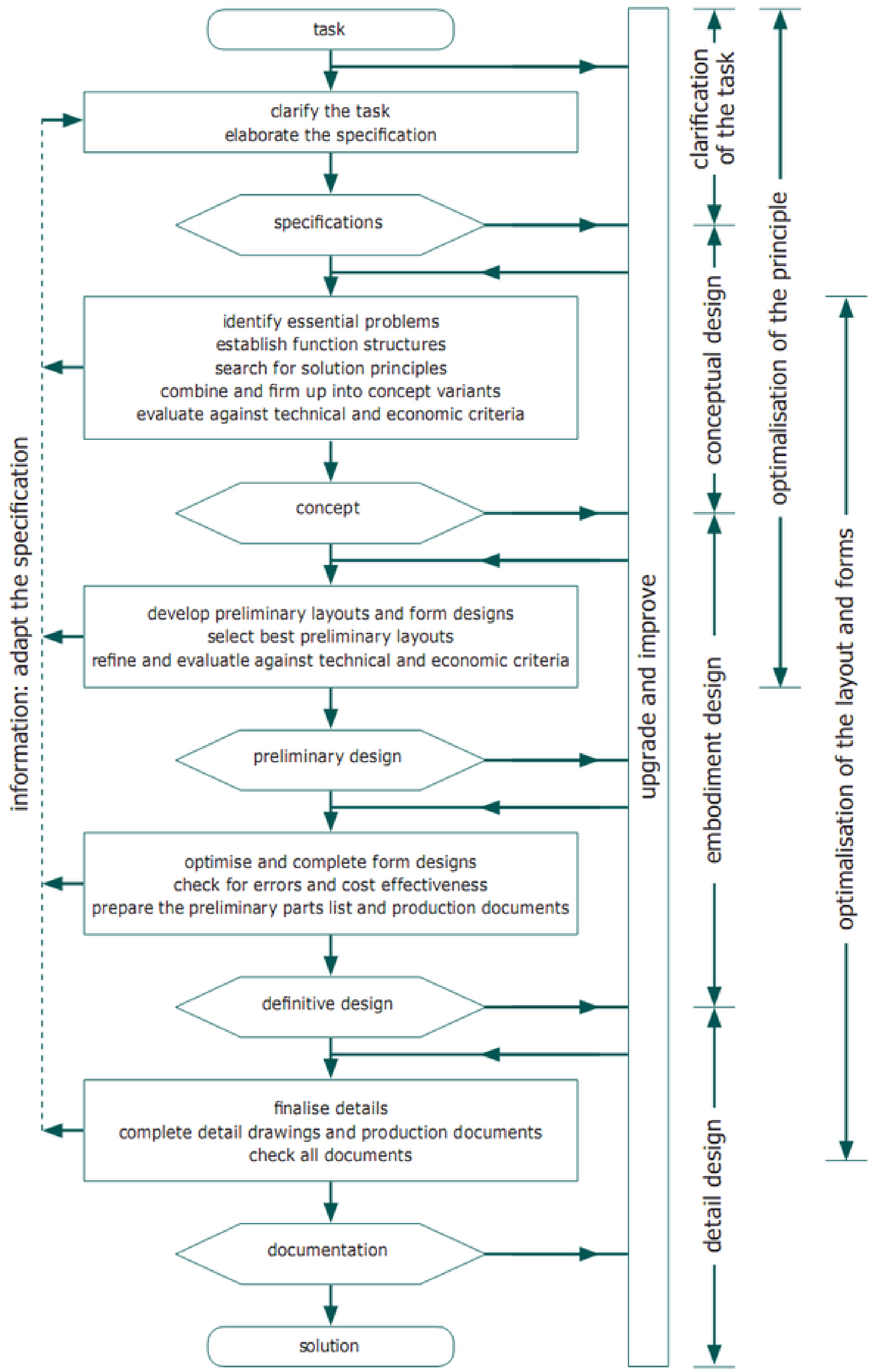


Figure 1.3: Pahl-Beitz design model. Taken from [8].

The resulting methodology is listed below. As it was mentioned before, it is pretended to cover up to the Concept Design. Therefore, steps from 26 to 31 were omitted from the methodology.

1. Define the problem, necessity or motivation of the project.
2. Clarify the problem and elaborate the specification.
3. Prepare a list of the design objectives.
4. Order the list in objectives sets in high and low level of priority.
5. Draw a tree diagram of objectives that shows the hierarchical connections and interconnections.
6. Establishment of the functions.
7. Express the general function of the design in terms of conversion of inputs and outputs.
8. Separate the general function in a set of functions.
9. Draw a block diagram that shows the interactions between secondary functions.
10. Draw the system limits.
11. Look for the appropriate components to do the secondary functions and their interactions.
12. Meet the requirements and Concepts of Operations (ConOps) of the project.
13. Delineate design features, including warnings and instructions, that can be expected to eliminate the hazards.
14. Make a list of essential characteristics or functions for the system.
15. For each function, mention the medias which can be used to reach it.
16. Draw a diagram with all the possible secondary functions.
17. Identify the feasible combinations of secondary functions.
18. Generation of ideas.
19. Creation of concepts based on the ideas and analysis of the alternative concepts.
20. Evaluate the different concepts by technical and economical criteria.
21. Selection of a concept and elaboration of the concept design.
22. Make a list of the different components for the system and identify the function of each component.

23. Determine the values of the identified functions.
24. Determine costs of each component.
25. Selection of the necessary components for the system.
26. Development of preliminary design and form designs.
27. Evaluate the alternatives and selection of the best preliminary design by technical and economical criteria.
28. Optimize and complete the preliminary design.
29. Verify by making an analysis of the main parameters acting on the system.
30. Elaborate a detailed design of the system.
31. Finalize the details and complete all the drawings and documents.
32. Write the necessary documentation of the project.
33. Verify the documentation.

The established methodology was really useful for the development of the work, especially on the first steps of the process. Usually the first steps are the more complicated on the design process due that the ideas are not clear enough but with this methodology it was possible to have a starting point to clarify these ideas and then begin with the conceptualization. The methodology was adapted to the limitations of the project, for these reasons some steps were omitted or changed.

In the following chapters, the development of the project is presented as well as the conclusions of this work.

Chapter 2

State of the art and concept exploration

For the definition and conceptualization of a practical mechatronic system to relief search and rescue of victims after an earthquake disaster, it was necessary to make a review of the available projects, patents, papers, etc. to know and understand the state of the art and technique in these kind of applications.

The state of the art was divided in different tasks performed during a search and rescue labor such as debris cutting, debris removal, debris transport and exploration.

2.1 Debris Cutting

In this section, the best suitable machinery and technologies to cut debris from different materials resulting from buildings collapse such as metals and concrete, are presented.

2.1.1 Brokk 330D demolition machine

The Brokk 330D (Fig. 2.1) is one of the most powerful diesel-driven demolition machines available today. It outperforms conventional excavators several times heavier with both its breaking power and its ability to get into tight spaces.

With an impressive power-to-weight ratio, it has the muscle to tackle dense concrete structures. The powerful, environmental-friendly diesel engine makes it perfect for heavy-duty demolition in places that lack a power supply. It is also extremly effective for openspace work. For work in extreme environments, it can be ordered with stainless steel hood, heat resistant hoses, extra cylinder protection and an air-cooling system [9].

Figure 2.1: Brokk 330D demolition machine. Taken from [9].

2.1.2 KUKA robot with laser cutting effector

KUKA offers industrial robots in a wide range of versions with various payload capacities and reaches. It offers additional modules, as end effectors, for all payload categories, for full automation and human-robot collaboration [10].

Figure 2.2: DigiRob Laser DGRL270F. Taken from [11].

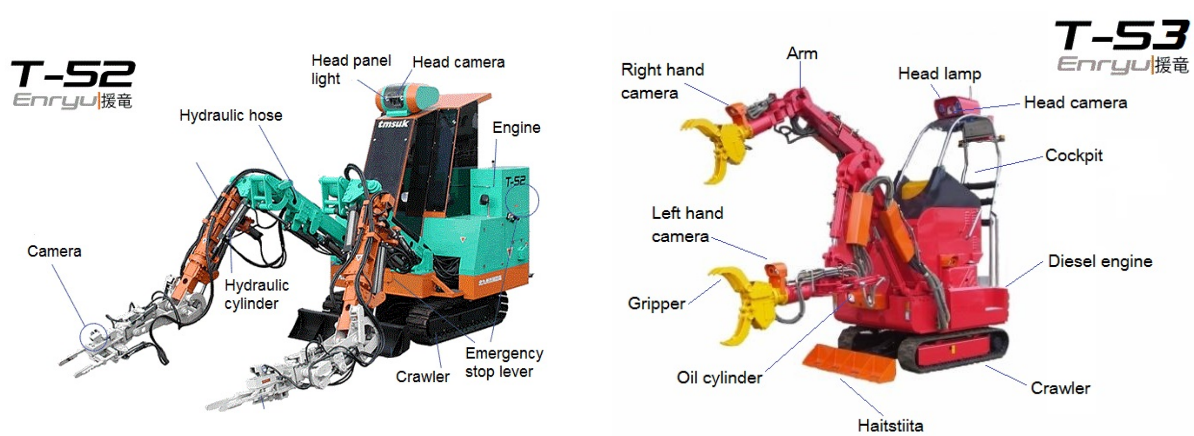
Digi Robotic Industries uses a KUKA QUANTEC robot series in combination with a Rofin Fiber Laser 1000Watt to create DigiRob Laser DGRL270F (Fig. 2.2) for laser cutting [11]. Laser cutting can be used for various cutting tasks. The thermal cutting process is suitable for metallic materials as well as for steel, ceramics, among others [10].

2.2 Debris Removal

The ability to manipulate and carry heavy payloads, and the capacity of easy movement on affected areas were considered for a debris removal system, and the technologies that better fit those characteristics with different grades of autonomy are the following.

2.2.1 Enryu rescue robots

The rescue robots called "T-52 Enryu" and "T-53 Enryu" (Fig. 2.3a and Fig. 2.3b) were developed to aim at the rescue operation in danger zone such as disaster district. The robots have two arms with eight Degrees of Freedom (DOF) for execution of various tasks, and they can be operated remotely in order to achieve the tasks such as removal, mining, and so on without sending the pilot to a dangerous place. Namely, the pilot had to understand the situation of surrounding of the robot from a few monitors that display the images of the cameras installed in the robot. Thus, because an assistance system to help the understanding of the positions of target objects was/had been necessary to improve the efficiency of the remote operation of the robot, a vision system that assists the pilot by tracking multiple targets and intelligibly presenting them was developed [12].



(a) Rescue robot: t-52 enryu.

(b) Rescue robot: t-53 enryu.

Figure 2.3: Enryu rescue robots. Taken from [12].

The system consists of a parallel stereo camera equipped on the gripper joint of the right arm and a laptop PC, and they were installed into the Enryus. Therefore, a fast executable stereo-vision system robust against vibration of the arm without using color information and easy to understand for the pilot is used.

2.2.2 ALACRANE: A mobile robotic assistance for rescue missions

ALACRANE (Fig. 2.4) is a mobile robot assistant for exploration and rescue missions with dexterous load manipulation capability. It is a fully hydraulic robot with two motorized outriggers to provide stability when lifting or manipulating weights. Hydraulic actuators provide a high power-to-size ratio for navigation and manipulation. The robot consists of three main parts: the mobile base, the main arm, and the LR-Arms dual manipulator.

This design is beneficial for exploration of unstructured environments, such as disaster areas, as well as dexterous manipulation in workspaces of difficult access. The system is equipped with Charge-Coupled Device (CCD) and Infrared (IR) cameras and a 3D-laser scanner for victim detection and environment perception and force/torque sensors [13].

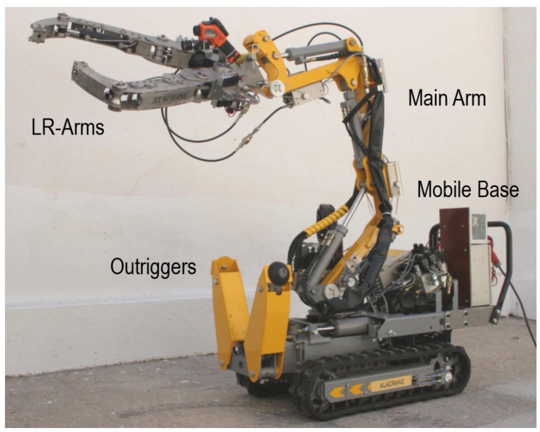


Figure 2.4: ALACRANE with LR-arms. Taken from [13].

2.3 Debris transport

Most of the existent technology for heavy payloads transportation are for industrial applications. For these reasons they are designed to move on flat surfaces and only a small part of them are able to move on different surfaces similarly to the affected zones in earthquake disasters. The systems that better resembles to what is intended are listed below.

2.3.1 Innok Heros transport robot

Innok Robotics has developed a transport robot called Innok Heros equipped with a trailer and/or carry boxes. Innok Heros becomes a transport robot that can automatically follow a person. It is able to transport various large and heavy payloads, e.g. wood, stones, soil, workpieces in a factory environment, among others [14].

2.3.2 WARTHOG UGV

Warthog (Fig. 2.5) is a large all-terrain UGV capable of traveling on land and in water. It can handle tough environments with its rugged build, low ground pressure, and traction tires.

Figure 2.5: WARTHOG amphibious UGV. Taken from [15].

Payload mounting plates and accessible power and communication ports allow Warthog to be easily customized with sensors, manipulators and other payloads to accommodate a wide variety of robotics applications in mining, agriculture and environmental monitoring. The powerful drive train of Warthog is capable of moving 272 kg of payload. The optional trailer hitch provides ample force for towing massive payloads and industry-standard implements with ease [15].

2.4 Exploration

Technology dedicated to explore inaccessible terrains for humans and search for victims, with different grades of autonomy and equipped with a variety of sensors as cameras, CO2 sensors and microphones, was considered. Some of the most prominent are mentioned in this section.

2.4.1 Ixnamiki olinki: search machine

Ixnamiki olinki is a rescue robot created with the finality of support for searching victims of an earthquake, landslides or buildings collapses. It is capable to handle 800 grams in the gripper.

This robot is equipped with low voltage three-phase motors and big batteries to obtain an autonomy of approximate 1 hour, the robot transmission consists in planetary boxes able to supply high starting force, additionally, it counts with a thermal cameras and a Carbone Dioxide (CO_2) sensor for people detecting [16].

2.4.2 ATLAS: Urban search and rescue robot

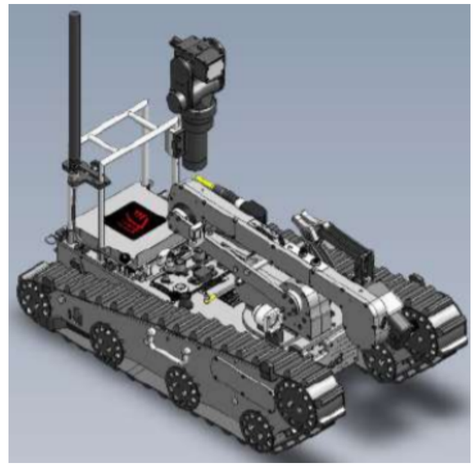
ATLAS (Fig. 2.6) is an urban search and rescue robot, created by Warwick Mobile Robotics (WMR), capable of locating and assisting the victims of disaster zones. ATLAS operation within disaster zones is: safer, more reliable and its deployment is faster. The robot is replaceable and easier to maintain than a human workforce as exhaustion is removed [17].

Figure 2.6: ATLAS USAR robot. Taken from [17].

2.4.3 ICARUS project: Search and rescue robots

ICARUS concentrates on the development of unmanned search and rescue technologies for detecting, locating and rescuing humans. Two main UGV platforms are being developed within the context of the project: a large UGV (Fig. 2.7a) which can be used as a mobile base, equipped with ample sensing capabilities, broadcasting the data it collects towards the field operators, as such increasing their situational awarenes; and a small UGV (Fig. 2.7b), which is used for entering small enclosures, while searching for human survivors [18].

(a) Large Unmanned Ground Vehicle.



(b) Small Unmanned Ground Vehicle.

Figure 2.7: ICARUS project search and rescue robots. Taken from [18].

2.4.4 Resquake: mobile rescue robot

Resquake (Fig. 2.8) is a robot with great capabilities in climbing obstacles in destructed areas. It can surmount uneven terrains with a relatively high stability, climb stairs and slopes up to 35°, search unreachable environments within a maximum distance of 50 meters from the operator station, broadcast thermal and visual data from the area and posses high reliability of hardware and electronic devices [19].

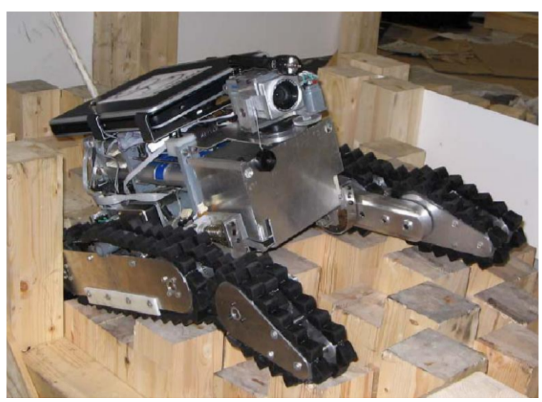


Figure 2.8: Resquake rescue robot. Taken from [19].

2.4.5 GMRI: Mobile inspective mining robot

Institute of Innovative Technologies (EMAG) and the Industrial Research Institute for Automation and Measurement (PIAP) elaborated a mobile inspective mining robot GMRI for working in explosive hazardous zones [20].

The robot, as a vehicle, is equipped with appropriate sensors for measurements of some gases concentration, cameras, transmission system, control and visualization systems as well as electrical accumulators [20].

Figure 2.9: Prototype fo GMRI, a mobile inspective mining robot. Taken from [20].

2.4.6 Pleurobot: A robotic salamander skeleton

Pleurobot is a salamander-like robot with 27 DOF that can emulate the walking and swimming gaits of a salamander. Its locomotion matches that of a real salamander, because the robot replays the sequence of animal postures.

In terms of robotics, an amphibious salamander-like robot capable of locomotion in different environments could find useful applications for inspection or search-and-rescue operations [21].

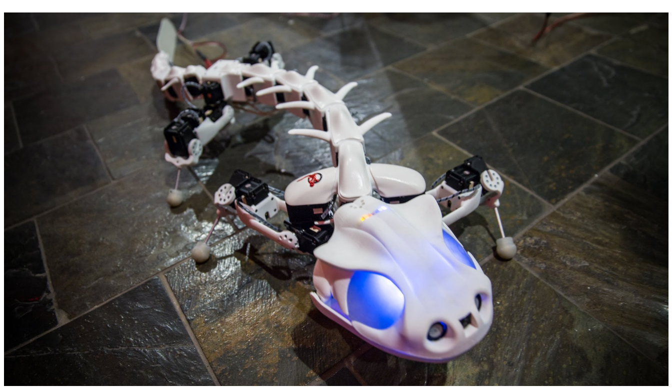


Figure 2.10: Pleurobot: an amphibious robot. Taken from [21].

2.5 Exploration and debris manipulation

There are systems able to perform more than one task. The main objective of the presented systems in this section is the exploration task. These systems were additionally equipped with manipulators for debris removal and interaction with other objects that could be present on their ways.

2.5.1 Mitsubishi MHI-HERCULeS

MHI-HERCULeS (Fig. 2.11) can ascend and descend stairs with inclinations up to 45 degrees as well as pivot and climb up narrow spaces such as stair landings with its manipulator folded and is outfitted with 4 cameras and 6 lighting, allowing operation in dark places.

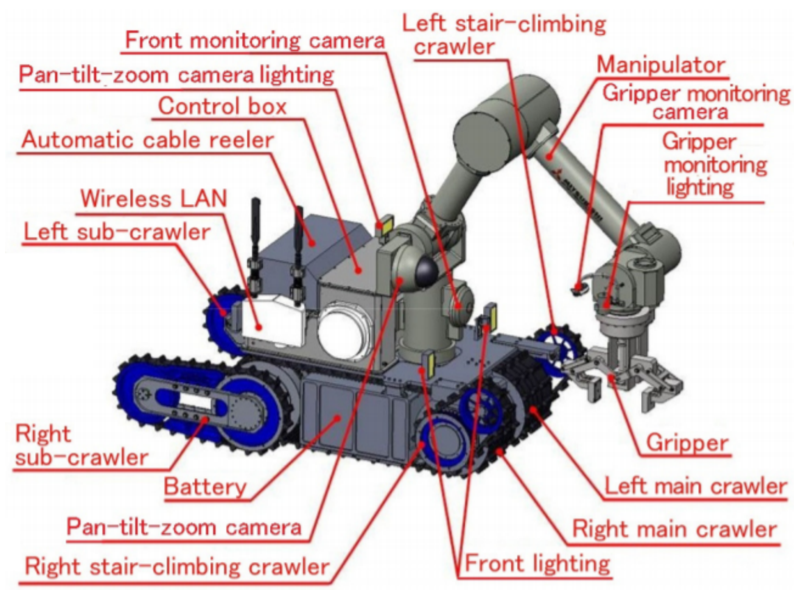


Figure 2.11: MHI-HERCULeS rescue robot. Taken from [22].

2.5.2 Jaguar V6 tracked mobile platform with arm

Jaguar V6 (Fig. 2.12) with Manipulator Arm Mobile Robotic Platform is designed for indoor and outdoor applications requiring robust maneuverability, terrain maneuverability and object manipulation. It integrates outdoor Global Positioning System (GPS) and 9 DOF Inertial Measurement Unit (IMU) (Gyro/Accelerometer/Compass) for autonomous navigation.

Figure 2.12: Jaguar V6 with Manipulator Arm Mobile Robotic Platform. Taken from [23].

Jaguar V6 is rugged, compact, weather and water resistant. It is designed for extreme terrains and capable of stair or vertical climbing up to 300 mm with ease. The 4 articulated arms could convert the robot into various optimal navigation configurations to overcome different terrain challenges. The integrated high resolution video/audio and optional laser scanner provide remote operator detail information of the surrounding [23].

2.5.3 Versatrax 450™ inspection crawler

Versatrax 450™ (Fig. 2.13) is designed specifically for applications in hazardous environments and is perfectly suited for a range of projects where remote handling and inspection are required. It allows to inspect, capture, and remove dangerous or lost materials quickly and easily. It counts with maneuverability in confined spaces and over obstacles.

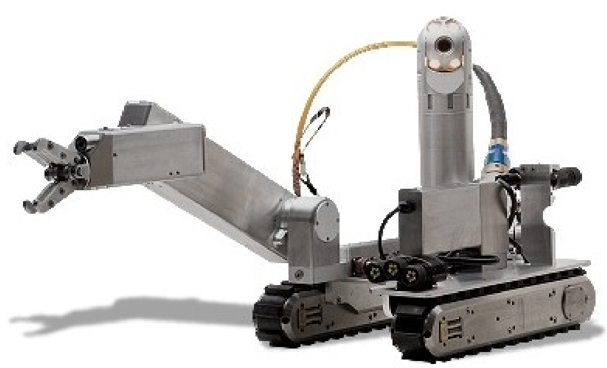


Figure 2.13: Versatrax 450™ Inspection Crawler. Taken from [24].

Versatrax 450™ possesses a camera which can be collapsed to navigate through tight spaces and lifted for a 360 degree view from an intuitive position; the four-function manipulator unfolds from the crawler for remote handling of articles and debris, and includes a second integrated camera allowing the user to closely monitor items during handling and forward and rear-facing LED auxiliary lights allow for high visibility in low light situations.

2.6 Exploration and illumination

The systems described in this section have the main purpose of exploration. They also are equipped with a light source for illumination of the area in case of being necessary, e.g. in dark places or at night.

2.6.1 CASTER: A Robot for Urban Search and Rescue

CASTER (Fig. 2.14) counts with high quality victim information, excellent maps and an intuitive user interface. The robot has two pairs of rubber tracks for locomotion, two motors provide enough torque to allow the robot to carry payloads of up to 40 kilograms and an internal battery pack provides a runtime of approximately 90 minutes. The sensors were chosen in order to satisfy three goals in mind: high quality 3D mapping, reliable victim identification and good situational awareness. It also carries high powered lighting, positioned so as to not shine directly into any of the cameras. It is able to operate in lighting conditions ranging from floodlit to complete darkness [25].

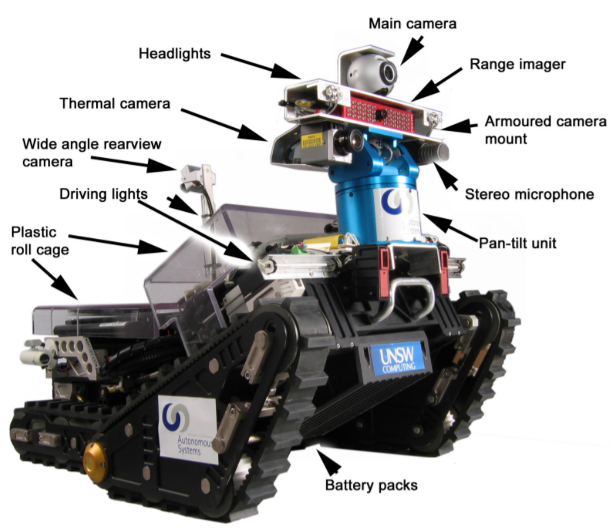


Figure 2.14: CASTER main parts. Taken from [25].

2.6.2 Mitsubishi Sakura II

Sakura II (Fig. 2.15) features wide crawlers, which avoid stranding, showing high traction performance even over punishing terrain such as stairs and debris. It uses a Li-ion battery lasting for about 4 hour and wireless LAN control with laptop PC and joypad.

It features a long wired communication performance of 1,000 m, which is the necessary length for remote control in tunnels where the transmission of electromagnetic waves can be interrupted. It is also equipped with light source at the front for operation in dark places.

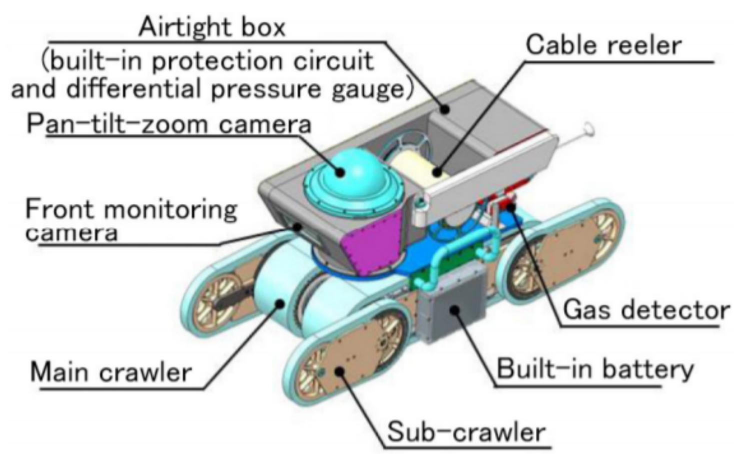


Figure 2.15: Mitsubishi rescue robots. Taken from [22].

2.6.3 QUINCE: mobile rescue robot

Quince (Fig. 2.16), is designed for practical use in search and rescue missions. It is waterproof and highly mobile over rough terrain. It used an AXIS212 PTZ camera that consists in a wide-angle lens combined with a three mega pixel sensor and realizes instant pan/tilt/zoom by clipping an image from the high-resolution image without any mechanical motion.

To obtain useful images when using the cameras in a dark environment, lighting was very important. Quince counts with two LED lights in front and back, along with extra IDX battery. The operation box for Quince is composed of two 15 inch touch-panel LCDs (liquid crystal displays), a game pad, and one PC (Aspire Revo: Acer, Atom, ION), packed in a pelican case (1700) [26].

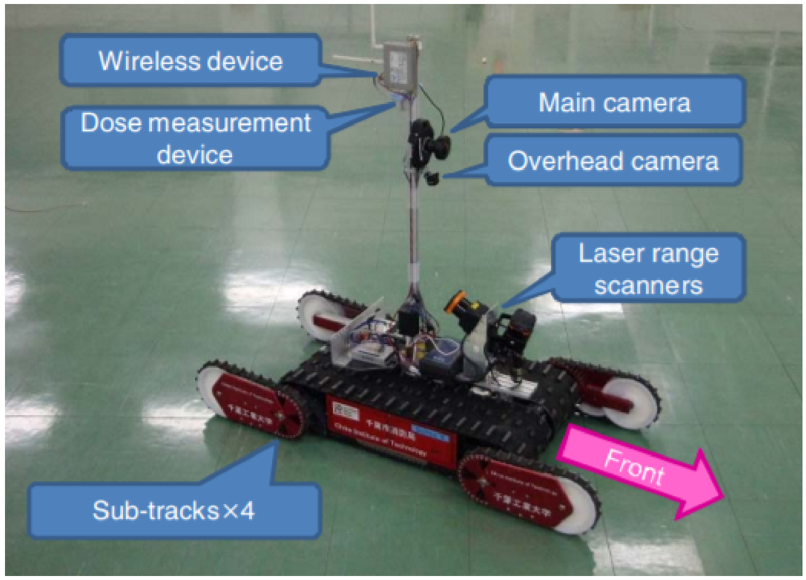


Figure 2.16: Quince exploration robot. Taken from [26].

2.6.4 Tehzeeb: a robot for rescue missions

Tehzeeb (Fig. 2.17) is a 30 kilogram mobile robot. The robot navigates by using information from a laser scanner, creates maps, finds victims and sends information about the locations of casualties to the station via wireless communication. The Tehzeeb robot is equipped with several sensors, i.e. Universal Serial Bus (USB) cameras, heat sensor, CO_2 detector, and microphone [27].

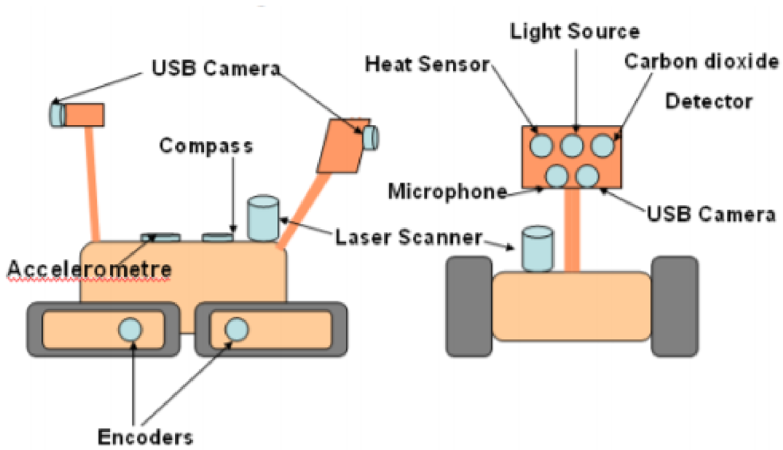


Figure 2.17: Tehzeeb hardware components. Taken from [27].

2.6.5 Modular Snake Robots

Snake robots (Fig. 2.18) can use their many internal DOF to thread through tightly packed volumes accessing locations that people and machinery otherwise cannot use [28]. Snakelike robots can locomote through rubble or tight spaces in ways that conventional robots cannot, enhancing the ability of the responder to locate and reach disaster victims.

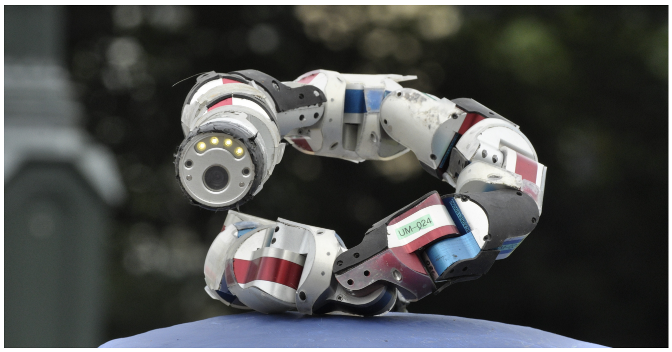


Figure 2.18: Modular Snake Robot. Taken from [28].

2.6.6 Trunk Snake Robot

The Trunk Snake robot (Fig. 2.19) is equipped with a camera to help locate victims, and can be outfitted with a two way speaker/microphone to enable communication with victims in a search and rescue environment [29].

Figure 2.19: Trunk Snake Robot. Taken from [29].

The reviewed works, patents, papers, etc. were used to give an idea of the existent systems used to relief search and rescue labor and act as a support for the system to be developed. The following sections contains the definition and conceptual design of the required system.

Chapter 3

Approach to the system to be developed

An important first step is to make an approach to the system to be developed to make clear which objectives or functionalities will be satisfied by the system to be designed.

For this, the problem statement and the system objectives for each proposed task, the concept of operations as a framework of several systems for earthquake disasters relief, the selection of which tasks will be performed by the system to be designed and the high level requirements that should be accomplished by those systems, are presented in the following sections.

3.1 Problem statement

From the general problem can be found particular problems which can be solved by the different tasks that can be performed for earthquake disasters relief.

The problem statement for each considered search and rescue task is presented in Table 3.1.

Table 3.1: Problem statement for each task.

Problem statement	**Task**
Buildings collapse is a common consequence from an earthquake disaster. With the level of destruction, it can be very difficult for rescue team to access the disaster area. Fallen buildings create mountains of rubble, impeding essential machinery and rescuers from moving to the spots where they are needed. Debris cutting address such problems, cutting pathways through the debris, allowing passage. Debris cutting should be performed in a carefully and strategically secure way to avoid injuring trapped survivors. In some occasions the debris to be cut is in a zone difficult or dangerous to access for the rescuers.	Debris cutting
When a disaster as an earthquake strikes a community, it is almost certain that some form of debris will be generated and that its removal will be required. Debris removal is a critical step in post disaster scenario because not only does it help in saving lives but also allows the relief operations to run unabated by clearing the way. It should be done carefully as it can have serious health and environmental consequences. Usually this process is done by handwork which takes too much time, or by using heavy machinery which is difficult to control in a carefully way. On the other hand, this can be a dangerous labor for the rescuers due to the hazards of the zones where the debris need to be removed.	Debris removal
Debris transportation includes the movement of debris during various stages of debris management activities. Normally, the debris is transferred twice; once from the accident area to a temporary stacking site and then from there to the final burial site. Certain regulatory controls should be formulated to enable efficient, effective and low risk debris transportation. Actual methods consist on the use of wheelbarrows or buckets to deposit the debris and transport it from the accident area to the temporary stacking, but these methods require a great effort.	Debris transport
Major sudden onset natural disasters, such as earthquakes, typically cause damage to the infrastructure, injury and sometimes massive loss of life, and trap people in debris. An immediate response is required to rescue those who are trapped, evacuate survivors and stabilize the zone. Search and rescue operations need to be performed very fast, by using specialized skills, and often need heavy or specialized technical equipment. The operational context may be extremely challenging, as rescuers work in debris fields and areas where public services and infrastructure are entirely disrupted, destroyed or unstable and the ignorance of these areas can be a risk for them.	Exploration

Problem statement	Task
Earthquakes and seismic activity cause structures to suffer substantial damage. To prevent the worsening of damage, shoring and other emergency reinforcements shall be applied. These allow temporary support to structures, providing stability and security to search and rescue operations. Shoring can be a hard work due to the complicated ways of placing the props depending on the scenario and the great effort needed to handle heavy props.	Shoring
During the search and rescue labor a good illumination is needed when searching through the debris at any hour of he day. This process can have a duration of many days and the search during the night is a fact that need to be handled. The existent sources of light need to be directed to the spot to be illuminated in a manually way and can have just one fixed intensity that could not be enough at certain levels of darkness.	Illumination

3.2 Objectives of the system to develop

In order to clarify the purpose of the system, a list of objectives classified in particular objectives for each of the proposed tasks, and general objectives which should be accomplished by any of them is presented in table 3.2.

Table 3.2: Particular and general objectives for the proposed tasks.

Function	**Particular objectives**	**General objectives**
Debris cutting	• Rod cutting of different sizes • Metal cutting different sizes • Concrete cutting • Access to high levels • Perform cuts in any plane	• Self energy supply • User friendly • Easy installation • Easy to operate • To be semi-automatic • Use of sensors • To be secure • Different environment resistance • Work in contamined environments • Work outdoors • Easy to transport • Adequate volume • Adequate complexity for its functionality • Light weight • Work on irregular terrains • To be viable
Debris removal	• Work with heavy payloads • Access to risk levels/zones • Handle different shapes of debris	
Debris transport	• Mobility on affected zones • Work with heavy payloads	
Exploration	• Mobility on affected zones • Move into small spaces • Move through rubble	
Shoring	• Mobility on affected zones • Work with heavy payloads • Able to handle props	
Illumination	• Mobility on affected zones • Illuminate at any hour • Adjust light intensity • Adjustable light direction	

Additionaly, for the easy organization of the relations and interconnections between main objectives and secondary objectives, a tree diagram of each considered task can be found in the Appendix B.

The particular objectives of each task are compared in Table 3.3 in order to identify common objectives between tasks besides the general objectives.

Table 3.3: Comparative table of proposed tasks particular objectives.

Objective	Debris cutting	Debris removal	Debris transport	Exploring	Shoring	Illuminate
Mobility			✓	✓	✓	✓
Heavy payload		✓	✓		✓	
Rod cut	✓					
Metal cut	✓					
Concrete cut	✓					
High levels	✓					
Risk levels		✓				
Handle diff. shapes		✓				
Illuminate at any hour						✓
Adjust light						✓
Intensity						✓
Handle props					✓	
Small spaces				✓		
Through rubble				✓		

It can be observed that some objectives from one task are similar to others from other tasks or does not affect their functionality, so it is possible to combine some tasks to form a new system able to perform both of them. Based on this analysis, there were obtained three combinations of tasks: Debris removal-transport, debris removal-shoring and exploration-illumination.

3.3 Concept of Operations for the system to develop

This chapter is aimed to describe the ConOps [30] for a relief machine able to aid rescue after an Earthquake disaster. The ConOps describe the expected functionality of a future or existence system in terms of its users. It supplies important information for the acquisition or development of the system to develop. It includes the current project situation, system stakeholders, concepts of the required system and important operational procedures for it. All of this as a framework of several systems of the type of those that meet any of the functions to earthquake disasters relief. The full version of the ”Concept of operations” document is included in Appendix D.

3.3.1 Current system status

During earthquake disasters several rescue, first response and associated techniques are used in order to find and rescue injured and trapped persons. Several types of equipment, tools and machinery are used. Most of these gear is generally used for workshop or industry work, so they are not designed specially for this kind of disasters, either for those specific tasks that are required to perform.

About machinery specifically designed to earthquake disaster relief, there are some projects in different entities across the world specially designed to aid search and rescue tasks. Nevertheless, they are not available in Mexico or other Latin American countries. So the importance to design and develop a system aimed to relief after-earthquake disasters. At the moment, any system or any related subsystem has not been developed yet in our group or institution.

3.3.2 Stakeholders

A preliminary stakeholders analysis is important in order to consider them during system development. Within the stakeholders there are those who require the development of the system or at least are direct beneficiaries of the existence of such system. In the opposite sense, there are people which the systems generate some among of damages, and so, they are potential detractors of the proposed system.

A list of the current envisioned stakeholders for the system which is required to be developed is as follow:

1. **Earthquake victims.** Every victim, related person or friend, rescuers and associations related to victims or rescuers are all strongly interested in safe as many as possible lives and as quickly as possible.

2. **Earthquake victims - related people.** In additions, related persons of victims could claim, on rescue time, to use the best available resources to rescue their people.

3. **Rescuers.** They have the experience and acknowledge of what is required and what is better to improve their functions.

4. **Earthquake victims related associations.** Associations related to victims of earthquakes or rescuers will be interested in any mean that actually aid the rescue process.
5. **Inhabitants of earthquake risk areas.** People from risk areas are in different way interested to improve rescue means in case of disaster.
6. **Governments.** Government is responsible to be prepared in case of disasters. They will be interested in improving their response capability in case of disasters.
7. **Mechatronics fans.** Mechatronics fans and enthusiasts are interested in any development or idea about mechatronics, specially in those with a practical meaning and aimed to help people.

3.3.3 Concepts of the required system

This section is aimed to describe the general concepts for the required system in terms of the users and do not from its developers.

3.3.3.1 Operation policies and constrains

The machine shall be able to work in the specific conditions of an earthquake disaster including extreme irregular ground and polluted environment including extreme dirty and dusty air conditions, volatile gases atmosphere (like butane and other flammable gases, etc.); outdoors environment (e.g. precipitation, sun and its radiation, wind, night, temperature changes, different pressures, etc.); Such development shall contain enough self energy, by means of an associated power source, to work several hours continuously.

The machine shall be able to be operated easily and by low training persons. It shall be secure for potential trapped victims as well as for operators and for surrounding people.

Additionally, the system to be developed should facilitate its transportation by having the lowest possible total weight and volume. As consequence machine deployment, installation, setup time and shutdown times shall be minimized.

Cost is not essentially a limitation, but the machine results will plenty justify its costs (design, fabrication and operation costs).

3.3.3.2 Limits and interfaces

There are a few aspects that limit the required system. The first one is its transportation and deployment time at the scene, thus it shall have a weight and volume able to be transported or even included its own transportation means (ground transportation). Air transportation should be considered as well in the case of the system is not so big.

Required power limits the system reduction together with specific task to be performed.

About interfaces, the system will be as autonomous as possible. The system control shall be as easy and intuitive as possible, the use of teleoperation, virtual control, haptic-based operation or direct guided operation shall be explored. Human-machine interface shall be able to allow functionality even with hard conditions as high noises, dusty atmosphere, at night, under raining or under direct sunlight.

3.3.4 Operational concepts

In this last section, the minimal operational concepts are given for different procedures, including setup, shut down, calibration, diagnostic, maintenance, training and others.

1. **Setup procedures.** As quick and easy as possible. Including transportation and deployment. Minimizing external energy sources in case that this is not available.

2. **Shut down procedures.** As quick and easy as possible. Minimizing energy consumption during no operational stage.

3. **Calibration procedures.** Machine calibration should be considered only if it is actually necessary. According to specific task of the machine, it is preferred that calibration will be made only during out-operations maintenance.

4. **Diagnostic procedures.** Machine will display at any moment the amoung of its critical resources with the special sense to notify operator when it will require new supplies. For example, monitoring of gas or oil reservoir to supply its power source.

5. **Backup procedures.** No backup is envisioned. If required by specific functions it shall be hidden to the operators with the idea to not distract them. In any case backup procedure shall affect machine performance in any sense.

6. **Maintenance procedures.** Preventive maintenance procedures shall be made during out-operations, out-disasters stages. Maintenance during machine operations shall be minimized.

7. **Training procedures.** Machine shall have a training manual for out-disasters training. Nevertheless its operation should be as easy as possible. Intuitive at least for those people with experience with similar machines or performing similar tasks.

8. **Other procedures.** No additional procedures are envisioned. If any is required by specific machine functions it shall be as easy as possible specially under operations. It shall be as well documented.

Really strict conditions shall be met for this system. Do not met them, they will made the machine useless and not valuable at all. So the importance to analyze and further discuss this ConOps and advance to the system requirements.

3.4 Selection of the functions to accomplish by the system to be developed

After combining the tasks with similar objectives, the options left for the system to develop are: debris cutting system, debris removal and transport system, debris removal and shoring system and exploration and illumination system.

An analysis based on relevance, complexity and energy consumption of the mentioned tasks is presented below in Table 3.4.

Table 3.4: Comparative table of the proposed systems.

	Relevance	**Complexity**	**Energy consumption**
Debris cutting	++	++	++
Debris removal and transport	++	+	++
Debris removal and shoring	++	++	++
Exploration and illumination	++	++	+

Based on this comparative table, the available resources and the limitations established in the thesis protocol document [31], as well as some testimonials from people who participate on the search and rescue labor during the earthquake occurred in Mexico on September 19^{th}, 2017; the exploration and illumination system was selected for its deployment.

3.5 High level requirements for the system to develop

This chapter presents the High Level Requirements (HLR) for a mechatronic system to relief search and rescue after an earthquake disaster based on the ConOps [30] and the Statement of requirements for Urban Search and Rescue Robot Performance Standards from the department of homeland security science and technology directorate and the National Institute of Standards and Technology (NIST) of the United States of America [32].

The HLR are formal statements that establish the main characteristics of a system that must be accomplished and are divided in functional requirements; behavior, or actions that the system must be able to perform; and non-functional requirements; characteristics, properties, or attributes that the system must posses. These HLR must be clear, ascertainable, verifiable and unambiguous, and must accomplish a series of characteristics, in other way they can induce to problems during the development of the project or afterwards.

In the following sections a description of the required system (Section 3.5.1), the Functional Requirements (FR) (Section 3.5.2), Non-Functional Requirements (NFR) (Section 3.5.3) and requirements priority classification (Section 3.5.4) are presented.

3.5.1 Description of the required system

A mechatronic system able to support the search and rescue of injured and trapped people after an earthquake disaster should be developed.

The system to be developed shall practically aid rescuers working at the disaster scene. This will be done by performing exploration and illumination tasks. For this, a system able to move through the debris and access to dangerous affected zones to collect information about the areas, search for victims and able to illuminate the affected zones adjusting the light direction and the intensity to illuminate at any hour of the day, is required.

3.5.2 Functional requirements (FR)

1. **Mobility.**

   FR 1.1 [Motion] The system must be able to move forward, backward and turn 360°.

   FR 1.2 [All-terrain] The system must be able to move on affected zones such as irregular terrain, flat terrain, muddy ground, debris, soft ground, stairs, or steep ramps.

2. **Obstacles avoidance.**

FR 2.1 [Obstacles] The system must be able to avoid obstacles on its way produced by the effects of an earthquake such as rubble.

3. **Sensing.**

FR 3.1 [Sense] The system must be able to process different stimulus:

FR 3.1.a Gases:

FR 3.1.a.1 [CO2-gas] The system must sense the Carbone dioxide level on the air of the inspected area.
Rationale: To identify victims alive.

FR 3.1.a.2 [Toxic-gas] The system must identify the presence of toxic or flammable gases in the air.
Rationale: For the identification of danger zones for the rescuers.

FR 3.1.b Acoustic:

FR 3.1.b.1 [Sound] The system must be able to process sound.
Rationale: To identify the voices or sounds emitted by the trapped victims.

FR 3.1.c Thermal:

FR 3.1.c.1 [Thermal] The system must sense the thermal energy.
Rationale: The victims will emit a thermal signature and this will help to identify the places where a victim could be trapped.

FR 3.1.d Visual:

FR 3.1.d.1 [Visual] The system must recognize motion and human characteristics.
Rationale: To find people trapped in the rubble.

FR 3.2 [Position] The system must send a signal with its position on the affected area.

4. **Illumination.**

FR 4.1 [Illumination] The system must be able to illuminate the area.
Rationale: For the use of video in confined spaces, short-range identification and

for helping the rescuers to inspect te areas.

FR 4.2 [Light-intensity] The system must be able to adjust the light intensity.
Rationale: To illuminate at any hour of the day and night.

FR 4.3 [Light-direction] The system must be able to adjust the direction of the light.

5. **Range-Beyond line of sight.**

FR 5.1 [Range] The system must be able to operate around corners of buildings and other locations beyond line of sight.

FR 5.2 [Op-distance] The system should be able to ingress at least 2km into the affected area beyond line of sight.

3.5.3 Non-functional requirements (NFR)

1. **Weight.**

NFR 1.1 [Weight] The system must weight less than 50 kg.
Rationale: For an easy transportation of the system from one place to another and make it able to move over the debris without destabilizing the area or causing a bigger damage in case of trapped people under it.

2. **Volume.**

NFR 2.1 [Volume] The system should no exceed a volume of 50X35X35cm.
Rationale: To be stored using existing methods and tools and make it able to move into small spaces (35X35cm of area) between the debris or take advantage of pipes, tubes, and other unconventional routes with the same transversal area.

3. **Resistance and durability.**

NFR 3.1 [Durability] The system must be able to be used for the entire duration of a rescue and search labor (approx. 20 days).
Rationale: The mean of days a person can survive under the rubble.

NFR 3.2 [Maintenance] The system is expected to minimize the amount of time required to perform routine maintenance operations in the field.

NFR 3.3 [Temperature] The system must be able to work on temperatures from -10°C to 40°C.
Rationale: The range of temperatures that can be found on the affected area.

NFR 3.4 [Resistance] The system should operate outdoors.

NFR 3.5 [Waterproof] The system must be water resistance.
Rationale: To work under rainy conditions or in case of wet environments caused by external reasons such as a broken pipe.

4. **Installation.**

NFR 4.1 [Installation] The system must be easy to move, unpack and assemble all equipment to a ready state using existing methods and tools.

NFR 4.2 [Setting-up] The system must be able to go from off to fully functional in under 1 minute.
Rationale: To be ready for its use as fast as possible considering that time is a critical factor in search and rescue operations.

5. **Control**

NFR 5.1 [Teleop] The system could be controlled and monitored by an external user.

NFR 5.2 [Communication] The system should be able to communicate with the operator in a wireless way.

NFR 5.3 [Semi-automatic] The system must work in a semi-automatic way.

6. **Self power supply.**

NFR 6.1 [Power] The power supply must provide the sufficient electrical power needed for the operation of the system.

NFR 6.2 [Duration] The system must have sufficient power to operate continuously for at least 1 hour, assuming one power for one out and back mission.
Rationale: The estimated time for the inspection of an specific area.

NFR 6.3 [Power-level] The operator display must inform the remaining power level as a percentage of total runtime.

3.5.4 Requirements priority

The requirements listed above are classified in mandatory and desirable requirements (Fig. 3.1) in order to give a priority level for each functional and non-functional requirement.

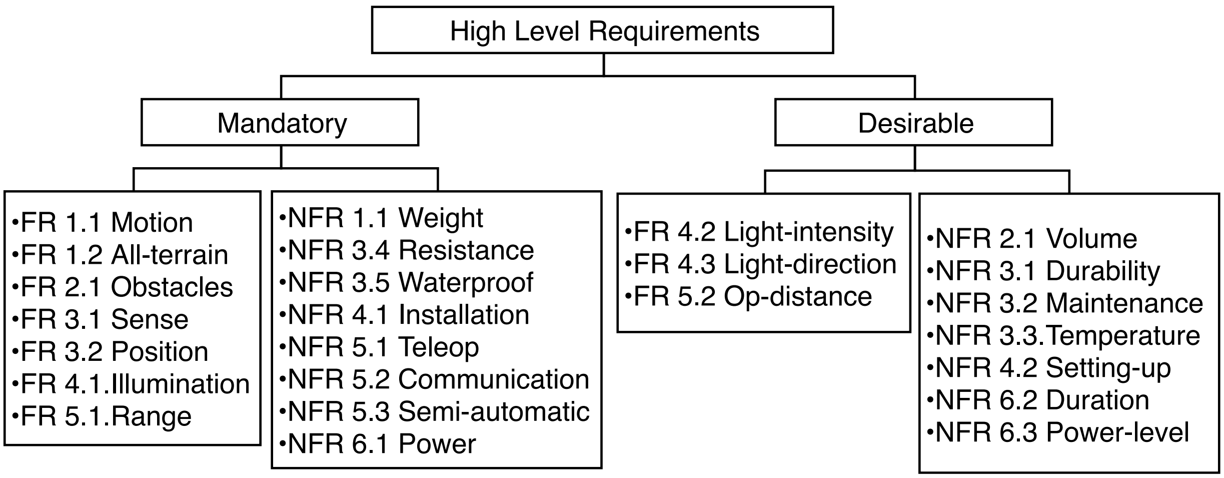


Figure 3.1: Mandatory and desirable requirements classification.

Due to this project is limited to the concept design and tentatively to the preliminary design, this classification will be used to focus the project in the complete or partial fulfillment of the mandatory requirements and trying to cover mostly of the desired ones.

Once the system to be developed was defined, the generation of ideas can be performed in order to obtain a conceptual design of the required system. The following chapters present the alternatives generation and the resulting concept design for the exploration and illumination system.

Chapter 4

Analysis of the system functions

Solutions generation is an essential aspect in design. It is possible to combine a relative small number of elements or basic components in a big number of different shapes.

In order to propose solutions, it was necessary to make an analysis of the system functions and identify the essential ones for the system and after this, make a list of the solutions principles that could be used to perform each function.

4.1 Establishment of the fundamental functions

The establishment of the functions offers a media to consider the essential functions and the problem level that should be approach.

The starting point consists on focus in what the new design should accomplish. This can be done by expressing the design global function in terms of conversion of inputs to outputs. The global function needs to be decomposed in a set of essential secondary functions. Finally, a block diagram can be used to show the interactions between secondary functions, connected by inputs and outputs and establishing the system limits to satisfy the general function of the design.

For the exploration and illumination system the general function consists on the recollection of data and the illumination in case of being necessary of the affected area.

For the exploration task, the following sub-functions were established.

1. Able to move in the affected area.

2. Able to avoid obstacles.

3. Recollect data from the environment.

4. Send the obtained data via wireless to the user.

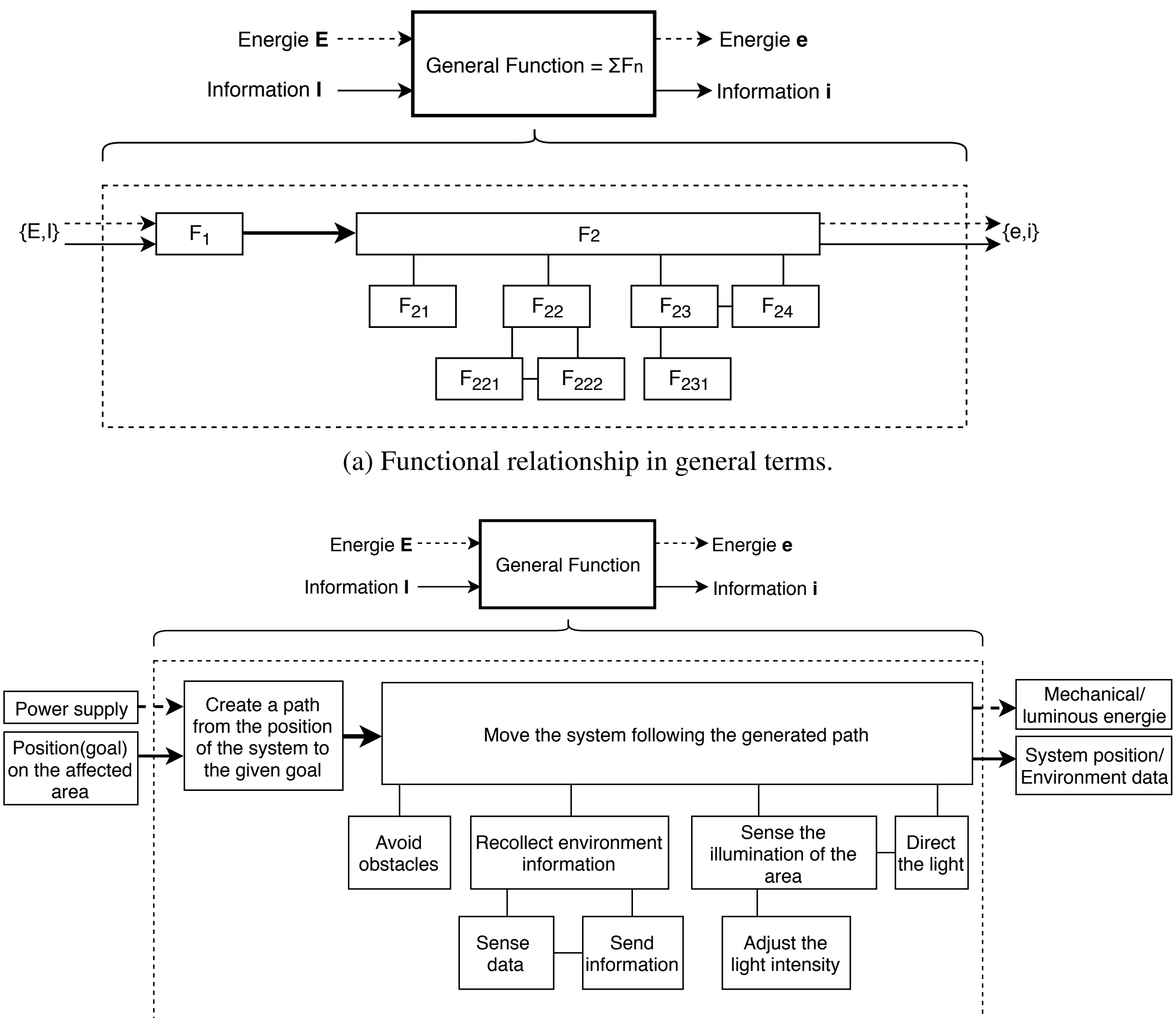
The secondary functions derived for the illumination tasks are listed below.

1. Sense the illumination of the area.

2. Adjust the light intensity.

3. Direct the light to the area to illuminate.

The combination of exploration and illumination functions results in the system represented in Figure 4.1.



(a) Functional relationship in general terms.

(b) Functional diagram of the general function of the system to develop.

Figure 4.1: Functional relationship diagram for the required systems.

A functional relationship diagram in general terms is presented in Figure 4.1a where the general function identifies the overall system task to be performed. The partial functions (F_1, F_2) and their subfunctions (F_{21}, F_{22}, F_{23}, ...) are subdivisions of subtasks that are easier to solve.

A more detailed functional diagram is presented in Figure 4.1b. For the system to be developed, a power supply will act as an energie input and a position signal or goal given by the user will act as an information input. The system will use the given goal to create a path from its actual position to the goal position and then the system should move following the generated path. While the system is moving to the goal, it must be able to identify any existent obstacle on the area and avoid them. At the same time the system should be sensing the environment to recollect data about possible hazards and trapped victims and send that data via wireless to the user. Finally the system should be able to illuminate the area in case of being required to support the visual sensors or the rescuers, the illumination will adjust the light intensity depending on the grade of darkness on the area and should be able to direct the light to where it is required. The outputs for the system will result in mechanical energie due to the movement of the system and luminous energie for the emitted light of the illumination system as well as the environment data recollected by the system and the actual system position for monitoring.

4.2 Solution principles for the fundamental functions

From the establishment of the functions, the essential functions for the system are obtained. The proposed media to perform these functions are listed in Table 4.1.

Table 4.1: Media options for the essential functions of the system.

Function	**Media**			
Movement	Wheels	Continuous track	Animal/Human physiology	
Recollection of data	Sensors			
Obstacles avoidance	Manually	2D range finders Sensors	3D sensors	2D range finders and 3D sensors
Wireless communication	WiFi	3G/4G/LTE	LPWAN	
Illumination	LED	Fluorescent lamp	Incandescence lamp	
Self energy supply	Gas/Fuel	Rechargeable battery		

A brief explanation of each function and the proposed media is presented below in order to analyze each option and select the best media for each function based on the system requirements.

4.2.1 Movement

The movement is an essential function in exploration due to that the system should be able to move through the debris, small spaces and all over the affected zone. The motion system is composed by the motion media and the actuators.

The locomotion of the system can be achieved by using all-terrain wheels, continuous tracks or animal/human characteristics as legs.

For the selection of motion media, a comparative table with advantages and disadvantages of each media proposed for the movement of the system is presented in table 4.2.

Table 4.2: Comparative table of motion media [34] [35] [36].

Media	Advantages	Disadvantages
Wheels	• Speed • Accuracy • Stability • Light weight • Simplicity	• To get over a vertical obstacle, it has to be twice as tall as the vertical obstacle
Continuous track	• High traction • Can operate on rough terrain • Surmount obstacles • High performance • Less impact on the ground	• Low speed • Less precise in maneuverability • More power when turning • Difficult to repair
Animal/human physiology	• Creep into small spaces • Legged systems can navigate on any kind of surfaces • Able to jump or step over obstacles	• Complexity • Price • Maintenance

In addition, the selection of a motor as an actuator for the required application should be done by evaluating all the important parameters to cover the necessities of the system. The following types of DC motors are considered for the system:

1. **Servomotors.** A servomotor can rotate to any position of its operation range and maintain that position. They can be small in size and they are very energy-efficient [37].
2. **Stepper motors.** A stepper motor is a type of motor whose shaft is indexed through part of a revolution or step angle for each DC pulse sent to it. Trains of pulses provide input current to the motor to increments that can ”step” the motor through 360°, and the actual angular rotation of the shaft is directly related to the number of pulses introduced [37].
3. **Brushless motors.** Brushless DC motors exhibit the same linear speed-torque characteristics as the brush-type PM DC motors, but are electronically commutated. The mechanical brush and bar commutator of the brushless DC motor is replaced by electronic sensors, typically Hall-effect devices [37].
4. **Universal motors.** Universal motors can run from either a D.C. or an A.C. supply. Speed control of small universal motors is straightforward using a triac in series with the A.C. supply. By varying the firing angle, and hence the proportion of each cycle for which the triac conducts, the voltage applied to the motor can be varied to provide speed control. If torque control is required, the current is controlled rather than the voltage, and the speed is determined by the load [38].

The advantages and disadvantages of the mentioned types of motors are presented in the following comparative table (Table 4.3).

Table 4.3: Advantages and disadvantages of different types of motors [39] [37].

	Advantages	Disadvantages
Servomotors	• High efficiency • High speed • High torque application • High dynamic response • Precision	• Closed-loop operation (Need feedback to provide position data) • More expensive than steppers
Steppers	• Precision • Does not need enconder to determine position • High holding torque • Pulses determine the amplitude and direction of current flow • Flexibility between open and closed control loop	• Operatig in a constant current mode creates a significant amount of heat • Low to medium acceleration applications
Brushless motors	• Does no need replacement of brushes or cleaning residue caused by brush wear • With no electrical arching, do not present fire or explosion hazards in environments with flammable gases, dust or liquids • Electromagnetic interference is minimized with electronic commutation • Faster and more efficient than brushed motors	• Cannot be reversed by reversing the polarity of power source • High cost • Additionally system wiring is required to power the electronic commutation circuitry • Motion controller and driver electronics needed are more complex and expensive than conventional motors
Universal motors	• High power density • Low cost • Portability • Able to run without a control	• Noisy • Inefficient at low voltages • Burnout quickly in stall conditions • Require high maintenance • Poor speed regulation • High speeds prevent gearbox usage

4.2.2 Obstacles avoidance

The system should be able to avoid any obstacle on its way while moving on the affected area. This can be done manually or by the use of 2D sensors or 3D sensors.

A brief description of each media for obstacles avoidance is given in Table 4.4.

Table 4.4: Comparative table of obstacles avoidance media [40] [41].

Media	Description
Manually	• Avoidance of obstacles can be made manually by teleoperation. In a telerobotic system, a human operator controls the movements of a system from some distance away. • Can be less precise due to human error and signal delay.
2D range finders sensors	• Provide accurate high resolution data necessary to achieve good results from SLAM algorithms. • Most 2D range finders feature a wide field of view and a wide sensing range useful for mapping and obstacle avoidance.
3D sensors	• These sensors open up a whole new dimension for robotics. • Can measure depth of an object. • Acquire data about the geometrical shape of an object in a 3D space.

4.2.3 Wireless communication

The system should be in constant communication with the user in a wireless way and the information recollected by the system should be transferred to the user in order to analyze it and make use of it.

From the existent communication protocols used in robotic systems, WiFi, cellular technologies (3G/4G/LTE) and Low Power Wide Area Networks (LPWAN) were considered as options for the system to develop.

A table with characteristics of each of the communication protocols selected as options for the system is presented below (Table 4.5).

Table 4.5: Comparative table of wireless communication media [42].

	WiFi	3G/4G/LTE	LPWAN
Range	Up to 1 Km	Up to 100 Km	Up to 100 Km
Area	Local area	Wide area	Wide area
Power consumption	Low	High	Low
Other	• Sends/receives large amount of data	• High quality mobile voice and data services • High cost of service	• Low cost • Sends/receives large amount of data

4.2.4 Illumination of the area

The rescue and exploration operations are required at any time of the day and a good illumination is required. Even in daylight the confined spaces could need an illumination source for an effective exploration. The illumination can be done by using LEDs, fluorescent lamps or incandescent lamps as light source.

Table 4.6 contains some advantages and disadvantages of media options for illumination source of the system.

Table 4.6: Comparative table of illumination media [43] [44] [45].

Media	Advantages	Disadvantages
LED	• Directionality of the emission of light • Size • Resistance • Immediate turning on • High capacity of commutation • Compatible with electronic control systems	• Price • Temperature dependence
Fluorescent lamp	• It can be used outdoors and indoors • Long life • Can be manufactured in small shapes	• Can use significant amount of energy • Needs a converter when using with DC • Not practical for large areas
Incandescence lamp	• Quality of light • Affordability • Aesthetics • Dimmability	• Short life • Options limitations • Produce heat

4.2.5 Self energy supply

It is difficult or impossible to find energy sources on an affected area. For this reason, a self energy supply is necessary for the system. Some options for energy supply are: Fuel and rechargeable batteries.

The advantages and disadvantages for using the mentioned options for energy supply are listed in Table 4.7.

Table 4.7: Comparative table of self energy supply media [46].

Media	Advantages	Disadvantages
Gas/Fuel	• Engine power	• Not a renewable source • Flammable
Rechargeable battery	• Environmentally friendly • Can be used repeatedly • Save money	• Lower voltage rating than single use batteries • They can often become weak and unpredictable with age

After the analysis of the generated alternatives to perform the essential functions of the exploration and illumination system, it is necessary to select the best option that satisfies the established high level requirements for each function.

A morphological diagram (Table 4.8) was used to represent the selected media and the concept generated by this selection.

Table 4.8: Morphological diagram of the exploration and illumination system.

Function	Media			
Movement	Wheels	Continuous track	Animal/Human physiology	
Recollection of data	Sensors			
Obstacles avoidance	Manually	2D range finders Sensors	3D sensors	2D range finders and 3D sensors
Wireless communication	WiFi	3G/4G/LTE	LPWAN	
Illumination	LED	Fluorescent lamp	Incandescence lamp	
Self energy supply	Gas/Fuel	Rechargeable battery		

The fundamental functions of the system to develop and solution principles for those functions were presented in this Chapter. Then, a general concept idea of the system to be developed was generated from the selected solution principles.

The following chapter contains the conceptual design of the required system generated from the resultant morphological diagram as well as an explanation of the components and elements that are part of it.

Chapter 5

System concept design

In the last chapter the most promising alternatives for those defined essential functions were described and compared. Based on the selected alternatives and the reviewed state of the art for “exploration systems” and “exploration and illumination systems” (Section 2.4 and 2.6), a system concept was generated. This chapter presents the conceptual design of the proposed system.

A representation of the resulting concept is presented in Figure 5.1. The system is broken down in its different components and elements that conforms it.

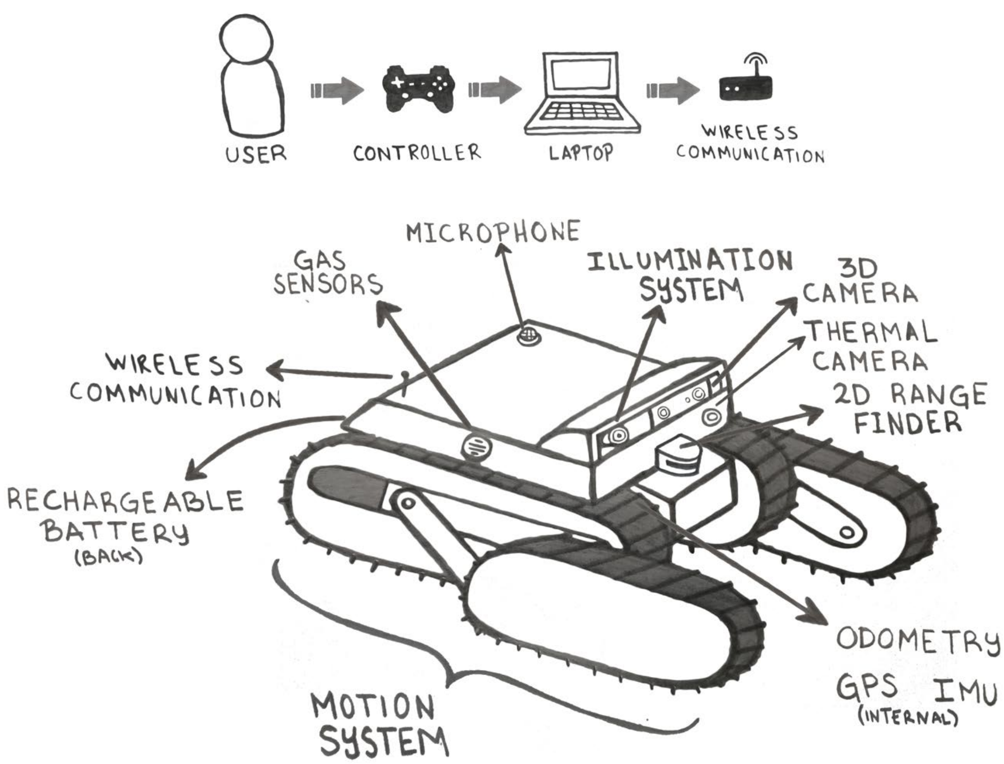
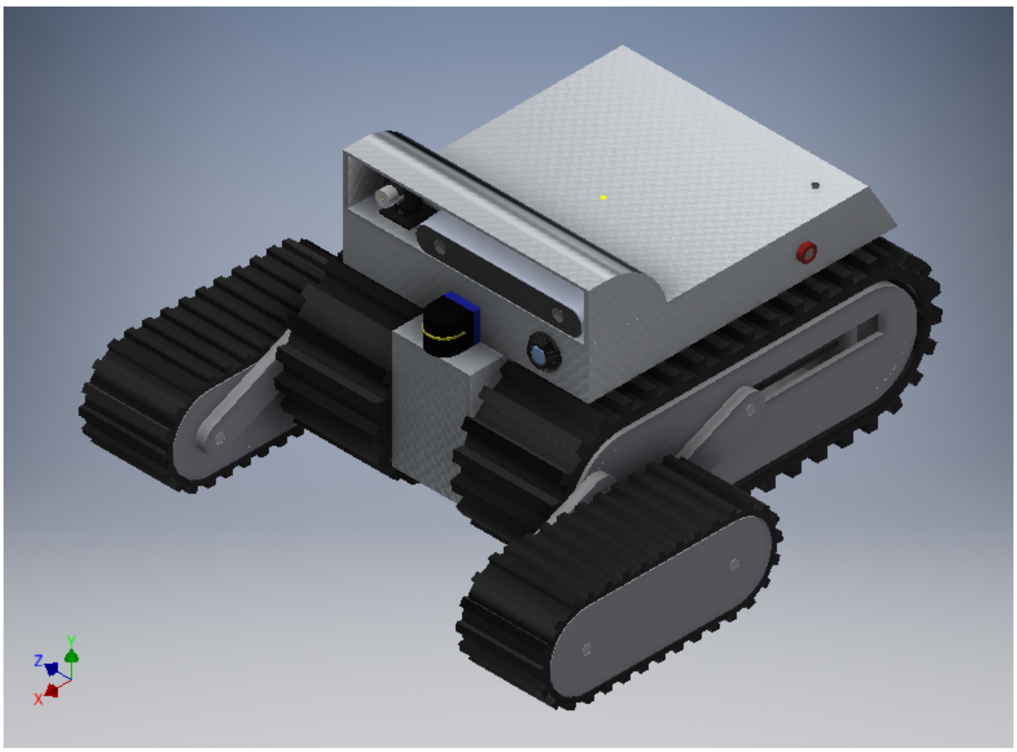


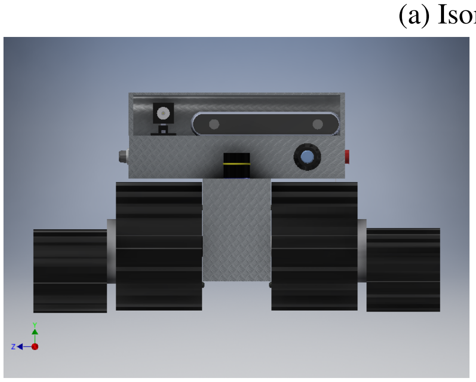
Figure 5.1: Conceptual design of the whole system.

It consists on a mobile robot similar to a tank with its own power source. The system counts with different kinds of sensors for the odometry (GPS, IMU), recollection of data (Gas sensors, microphone, thermal camera) and obstacles avoidance (3D camera, 2D range finder) as well as an illumination system able to change the direction and intensity of the emitted light beam. It will be monitored and controlled via wireless from a user with the help of a controller, a laptop and a wireless communication module.

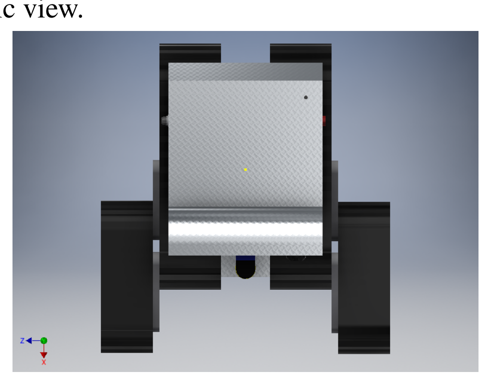
For the motion of the mobile robot on an affected zone, it counts with continuous track at both sides, one of them acting as a mobile arm. This mobile arm differs from other existent designs where a continuous track acting as a flipper with just one DOF is used. The proposed design for the mobile arm will count with two DOF, translational movement and rotational movement.



(a) Isometric view.



(b) Frontal view.



(c) Top view.

Figure 5.2: Preliminary CAD model of the mobile robot.

In Figure 5.2 a preliminary CAD model based on the conceptual design of the mobile robot can be observed. This design is just a preliminary view to have a better idea of how the mobile robot should look like. The used dimensions are just an approximate.

5.1 Motion capabilities

The designed mobile robot will be able to move over different types of terrains and overcome different obstacles that could be presented in the affected area such as debris produced by collapsed buildings, bricks, rocks, dirt, slopes, objects, among others; while recollecting environmental data. Figure 5.3 presents a representation of some of the different surfaces that can be presented in a disaster area that can be handled by the system.

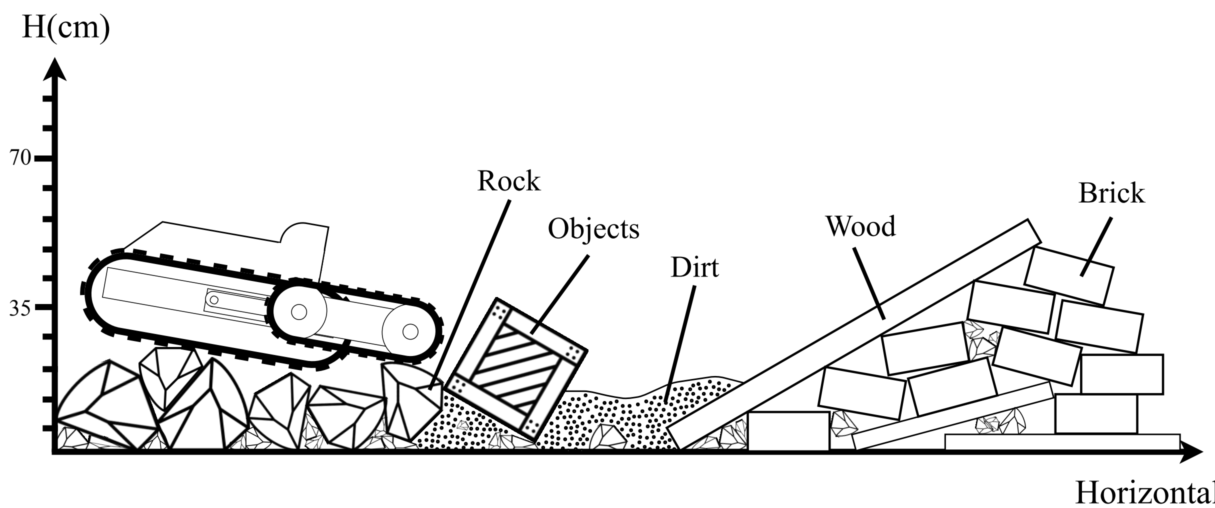


Figure 5.3: Examples of terrains that the system can overcome.

The motion mechanism allows the robot to overcome different situations. For example, a stair way is a common obstacle that can be found in an indoor environment. Whether destructed or not a rescue system should have the ability to overcome it in order to cover the whole area. Normally, a mobile system with continuous track should have a minimum length of twice the pendent between one step to the other to be able to surmount them, nevertheless the designed system is able to climb stairs easily with a shorter total length by using its mobile arms as a support. The necessary steps that should be performed by the system for climbing up stairs can be observed in Figure 5.4.

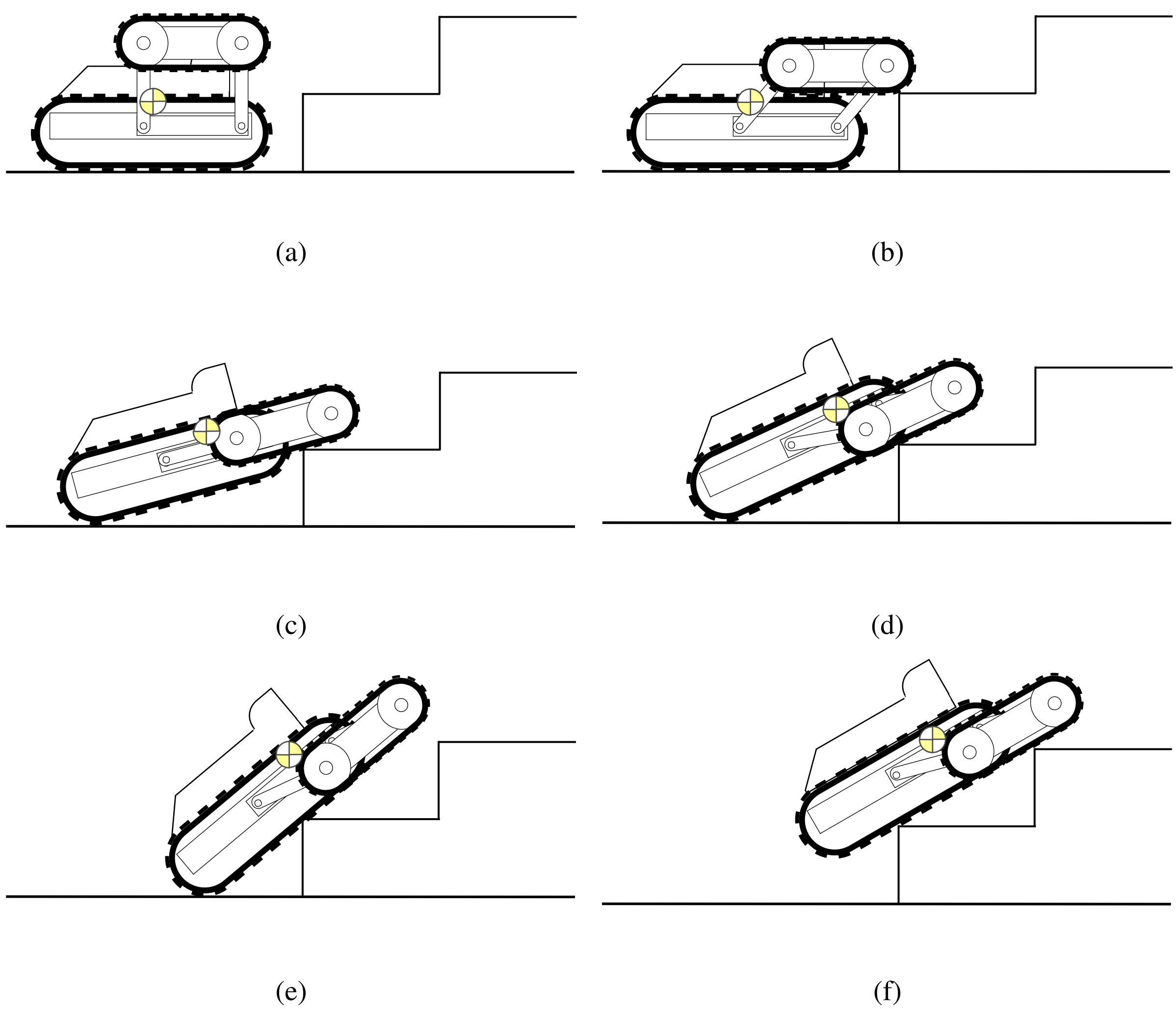


Figure 5.4: Motion of the system for climbing up stairs.

The robot will also be able to pass through any alternative routes where it can ingress such as openings between the rubble or pipes. The Figure 5.5 shows a representation of an opening between the rubble resulting from a collapsed building. The opening should have a minimal height from at least 5 cm larger than the height of the system and a minimal width of at least 5 cm larger than the width of the system to allow the entrance of the system with any difficulties.

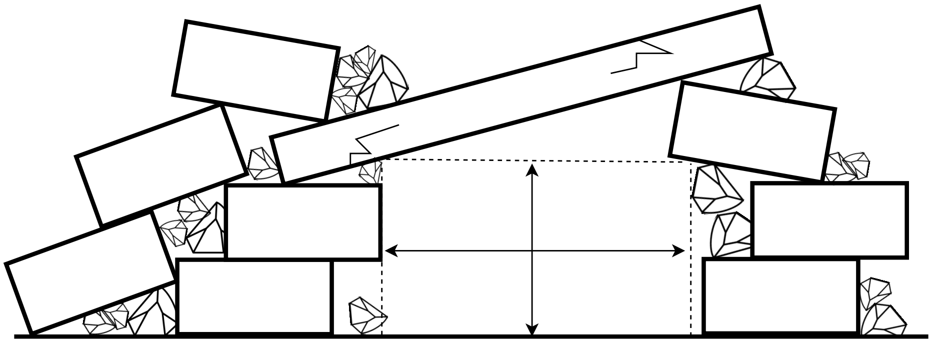
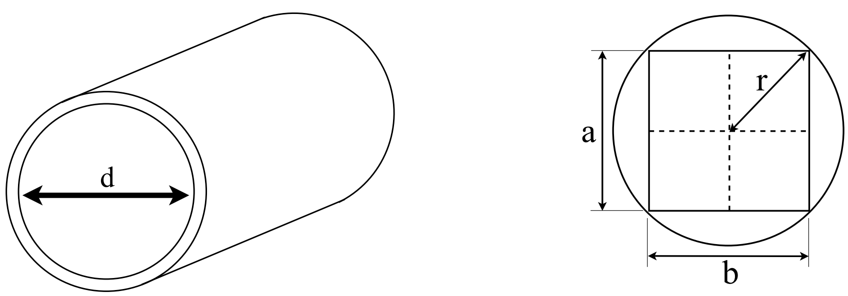


Figure 5.5: Representation of an opening between the rubble.

As it was mentioned before, pipes can be used by the system as alternative route to move in the affected area. For this, the minimal internal diameter that the pipe should have to allow the entrance of the system through it can be obtained by the Equation 5.1

$$d = 2r = 2\sqrt{\frac{a}{2}^{2} + \frac{b}{2}^{2}} \tag{5.1}$$

Where d is the diameter, r is the radius, a is the height of the system and b is the width of the system.



(a) Pipe internal diameter representation.

(b) Dimensions to obtain the minimal internal diameter of the pipe.

Figure 5.6: Main dimensions for a pipe as alternative route.

A description of the motion system and the components in which it can be divided as well as their functionality are presented later in this chapter.

5.2 System architecture

The system general architecture can be divided in two main subsections, the base station and the mobile robot. The parts in which the subsystems are divided can be observed in Figure 5.7.

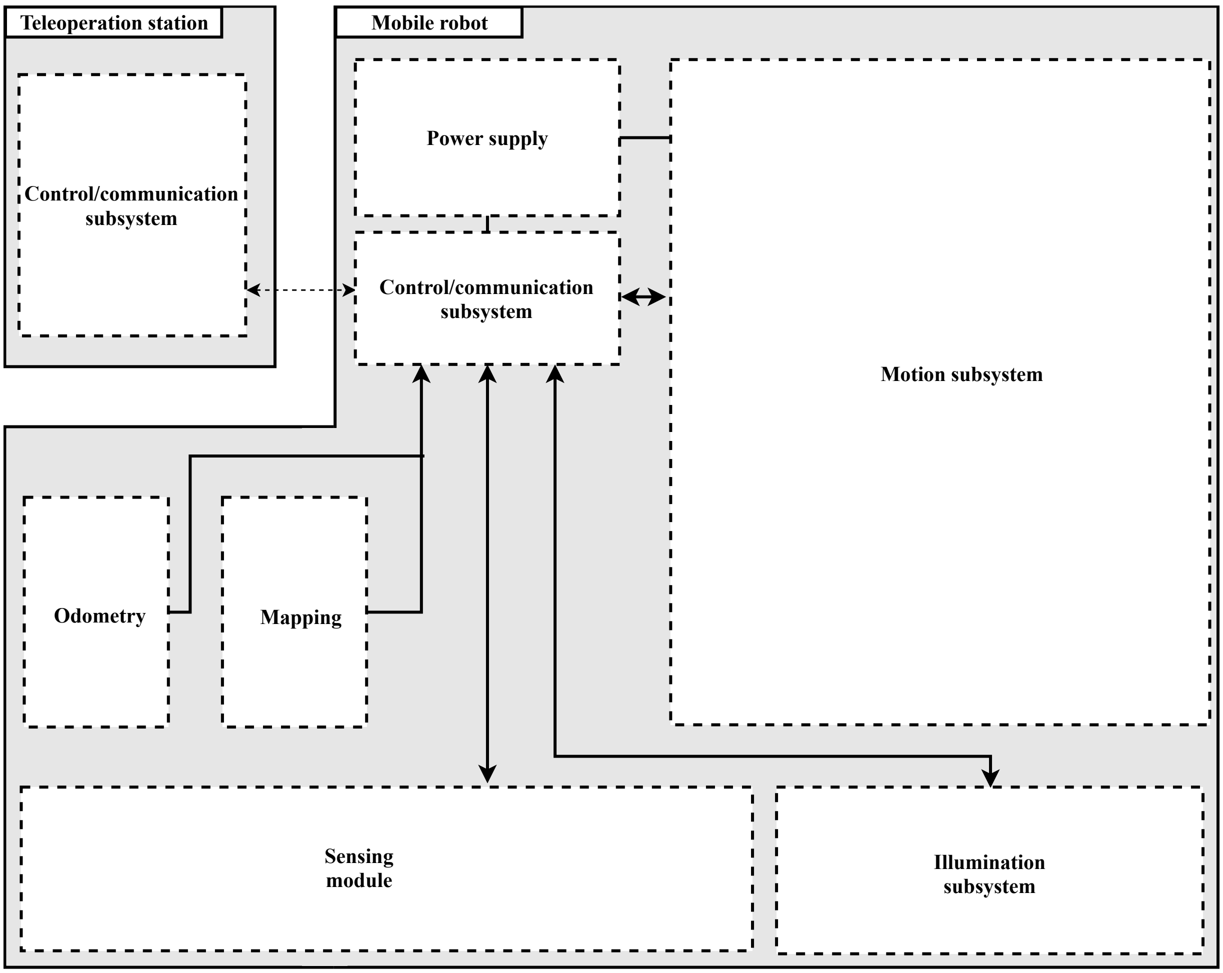


Figure 5.7: General architecture diagram of the system.

The main subsystems or modules in which the system is divided depend on the function that will be performed by them. These subsystems are listed below.

1. Mobile subsystem
2. Mapping
3. Sensing module
4. Odometry

5. Illumination subsystem
6. Power supply
7. Control/communication subsystem

The detailed architecture of the whole system with all its components and elements is presented in Figure 5.8. The blocks with dotted lines represent subystems or modules listed above in which the system could be divided. The conections between each component are represented with arrows with continuous lines, the wireless communication with the arrow with a dotted line and the energie distribution is represented by the red line.

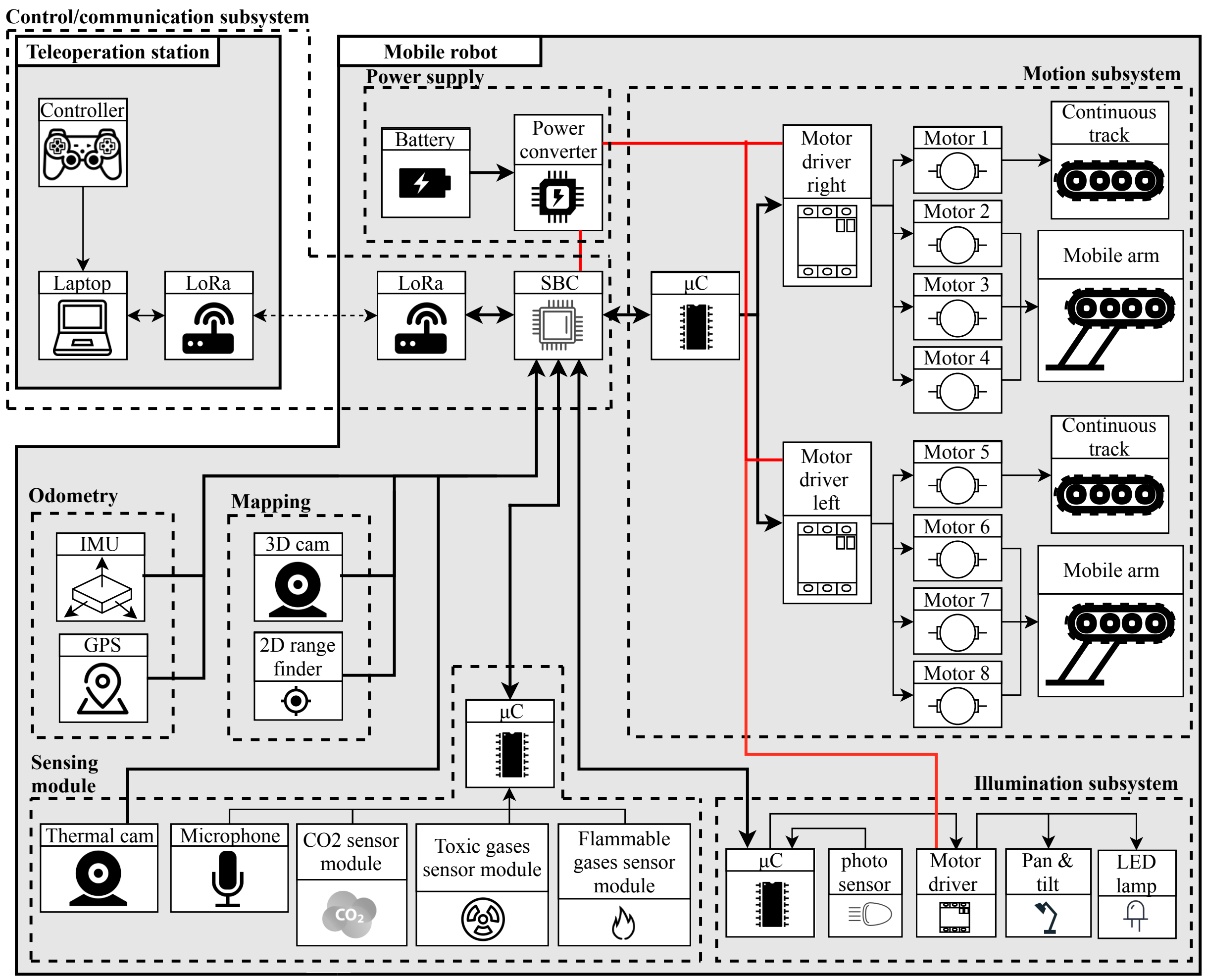


Figure 5.8: System architecture diagram (Red line = energie distribution, dotted arrow = wireless commnication, continuous arrows = conections between components).

The following sections present the concept of the subsystems, components and elements in which the system can be broken down for a better understanding of the generated design.

5.2.1 Motion subsystem

To fulfill the mobility requirements, the motion subsystem consists in two continuous track on each side of the mobile robot, one fixed to the base and the other one acting as a mobile arm. The movement of the mobile robot over the terrain will be in charge of the base fixed continuous tracks. The mobile arm is intended to be used to surmount difficult obstacles and support the mobile robot mobility on different types of terrains. A track with rubber pads is considered to have less impact on the ground and provide damping to the system.

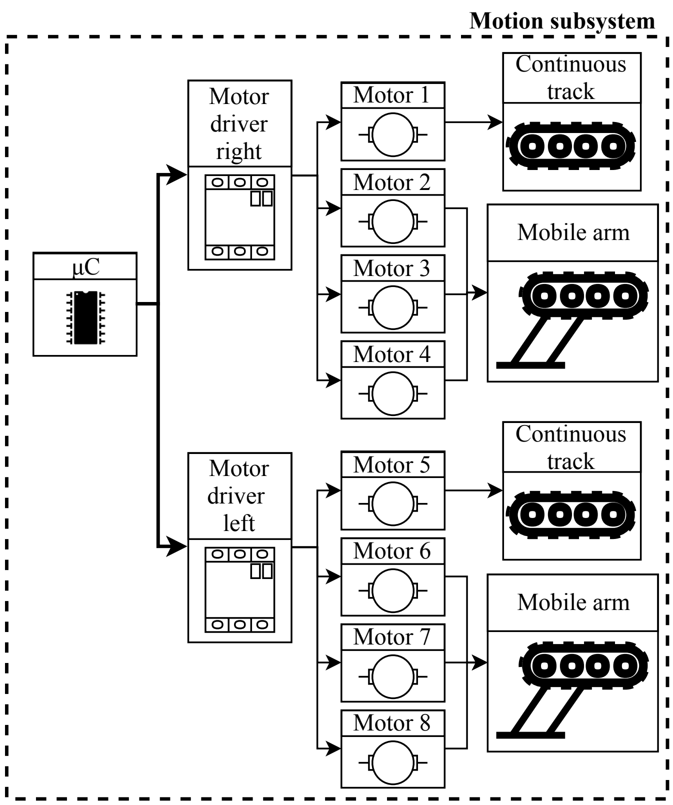


Figure 5.9: Motion subsystem diagram.

The components that forms the motion subsystem are listed below:

1. Continuous track
2. Mobile arm
3. Motors
4. Motor drivers

5.2.1.1 Continuous track

The use of continuous tracks for the movement of the mobile robot on the affected area is selected for their high traction and their facility to surmount different obstacles and operate on different types of terrains, which are important characteristics to fulfill the established requirements.

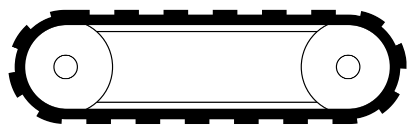
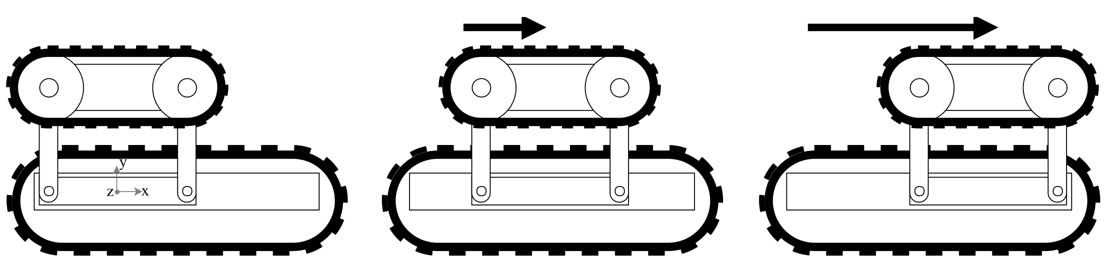


Figure 5.10: Rectangular shape continuous track.

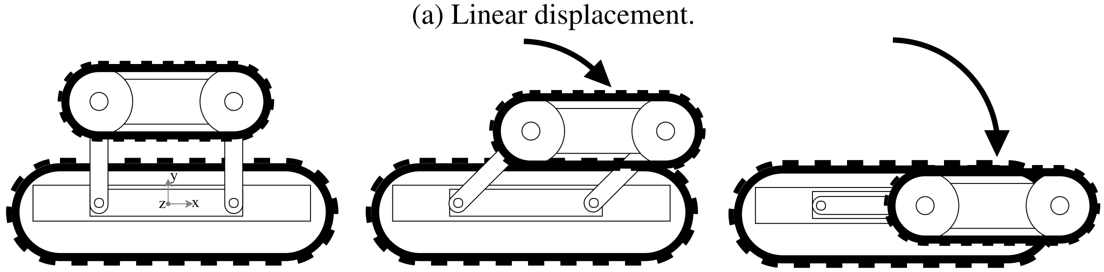
There exists different configurations for the continuous track which can apply for a variety of situations. The most common configuration is the rectangular shape (Fig. 5.10) or simple configuration. This configuration is the easiest to fabricate, nevertheless, the main disadvantage is that in order to surmount obstacles like stairs, its length should be longer than other configurations. To dismiss this drawback, a mobile arm is proposed as a support to surmount difficult obstacles for the rectangular continuous tracks.

5.2.1.2 Mobile arm

As it was mentioned before, the design of a mobile arm to surmount difficult obstacles is proposed. The mobile arm will consist on a mobile continuous track attached to a fixed continuous track. The mobile continuous track will be able to move along its x axis and to rotate over the z axis as it can be observed in Figure 5.11.



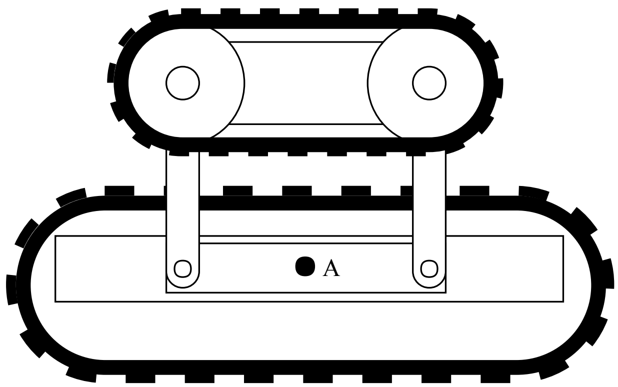
(a) Linear displacement.



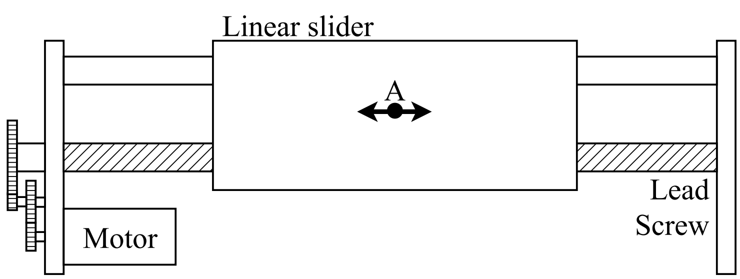
(b) Rotational motion.

Figure 5.11: Movement of the mobile continuous track.

For the linear displacement of the mobile arm, a mechanism consisting on a lead screw and a linear slider is selected (Fig. 5.12). The main advantage of this mechanism is the self-locking feature of the lead screw so after getting the desired position there is no need to use a breaking system or to supply the motor further with electricity to keep it there.



(a) Mobile arm.



(b) Mechanism for linear displacement.

Figure 5.12: Mechanism for linear displacement of the mobile arm.

Attached to the linear slider on the point A (Fig. 5.12) will be the mechanism for the rotational movement of the mobile arm which is given by the mechanism shown in Figure 5.13 and its movement is represented with the dotted lines. The mobile continuous track is connected from the points B and C to two identical bars with a shorter length of BC. The other extreme of the two identical bars are connected to the points A and B of another bar forming a parallelogram. This parallel linkage mechanism is a special case of Grashof's law where the sum of the shortest link (AB) and the longest link (BC) is equal to the sum of the other two links (CD and AD).

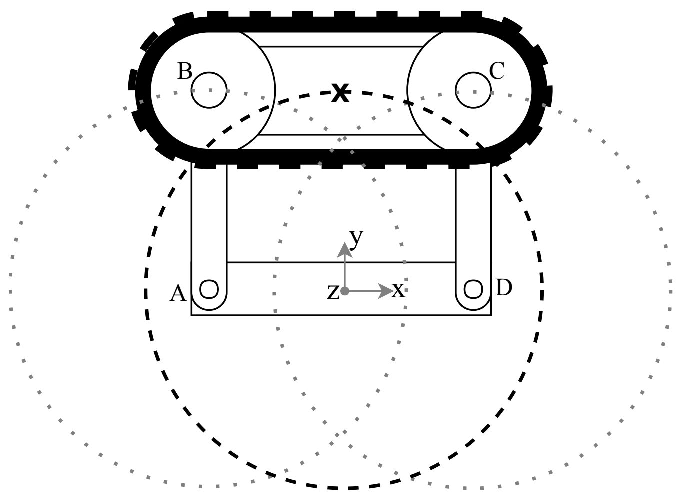
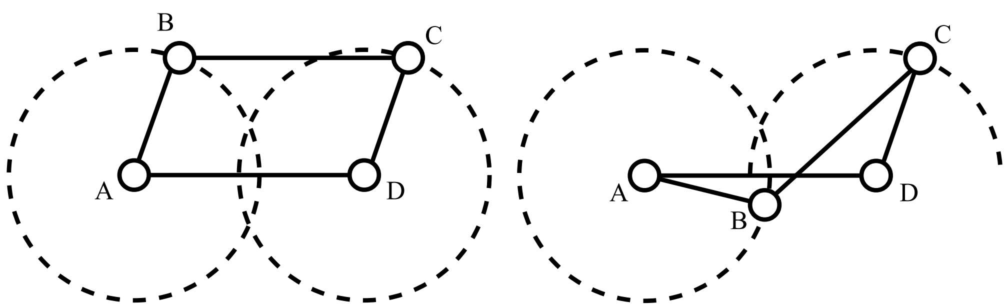


Figure 5.13: Mechanism for the rotatory movement of the mobile arm.

A motor is attached to the axis of point A, considered as the input, in order to give the motion to the mechanism. Nevertheless, the inertia of a part can cause an antiparallel movement (Fig. 5.14b) of the mechanism. To prevent this, it is necessary to transmit the motion from the input (point A) to the output (point D) which can be done by using a gear train or a belt between them.



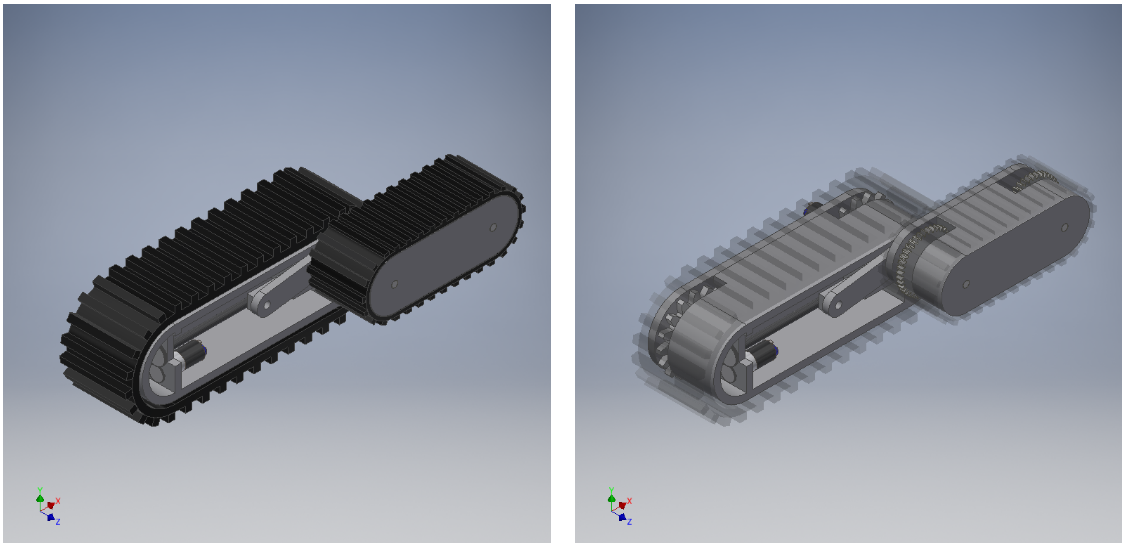
(a) Parallel movement.

(b) Antiparallel movement.

Figure 5.14: Special case of Grashof's law.

This movement allows the robot to recover from a possible upside down position which could be product of a falling of the system in the worst case.

The complete mechanism will be at both sides of the mobile robot and its movement could be independent from the movement of the other providing several possibilities of movement for the robot. A preliminary view of the whole mechanism can be observed in Figure 5.15.



(a) With rubber track. (b) Without rubber track.

Figure 5.15: Arm mechanism preliminary CAD model.

5.2.1.3 Motors

The whole movement of the motion subsystem is produced by the use of motors, one for each continuous track and 2 for each arm mechanism. A description of the types of motors considered for this part can be found in section 4.2.1.

5.2.1.4 Motor drivers

The use of motor drivers arises from the necessity to provide enough current to drive the motors due to the controller could not be powerful enough to provide that current. Motor drivers control the motion of the motors by the received signals from a controller and take the power from the power lines to send it into the motor.

5.2.2 Mapping (Obstacles avoidance)

The obstacles avoidance consists in getting information about the terrain to identify possible obstacles on the way and avoid them by changing the route followed by the robot. For this is necessary the use of sensors to obtain a more precise data of the area.

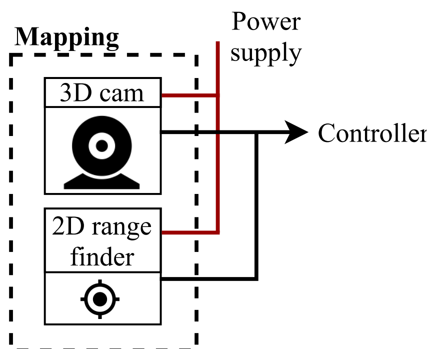


Figure 5.16: Sensors for mapping and obstacles avoidance.

Considering that the affected area will consist on an irregular terrain, a 3D navigation of the mobile robot is required. Based on this, the selected sensors for this function are:

1. 2D range finder
2. 3D camera

5.2.2.1 2D range finder

2D range finders are mainly used for determining distance and direction of objects in their line of scanning and generate 2D maps with that information. Nevertheless, the obtained data from these sensors are not sufficient for 3D navigation because the objects lying below or above the scanning line are not detected. For this reason, the use of a 3D sensor is necessary to overcome this drawback.

HOKUYO PBS-03JN scanning rangefinder (Fig. 5.17) is considered the best option for this application due to its small size, wide scanning angle and configurable detection area. The detection field is scanned by LED, objects coordinates are calculated and then obstacle presence in the setting area is detected.

Figure 5.17: HOKUYO PBS-03JN scanning rangefinder. Taken from [47].

It counts with a protective structure with a protective rating IP64 (IEC standard) which means that it does not allows the ingress of dust, it posses a complete protection against contact and water splashing against the enclosure from any direction shall have no harmful effect.

The main characteristics of PBS-03JN scanning rangefinder are presented in Table 5.1.

Table 5.1: PBS-03JN rangefinder main characteristics [47].

Power source	**Scanning angle**	**Temperature range**	**Protective structure**	**Weight**
24 VDC V	180°	-10°C to 50°C	IP64 (IEC standard)	500 g

5.2.2.2 3D camera

3D cameras are used to obtain the depth of the objects and information about the geometrical shape in a 3D space. There are two types of 3D cameras depending on their principle of operation: stereo vision cameras and Time of Flight (TOF) cameras.

The combination of the 3D camera and 2D range finder will provide the sufficient data for mapping and path planning in order to avoid any obstacle presented on the affected area.

In addition, the 3D camera can also be used to identify motion which could be useful to detect a person in case of a trapped victim.

Some commercial options for 3D cameras used for this application are listed below.

1. **Flexx** (Fig. 5.18a) is a 3D camera based on pmd TOF technology. It is a slim external USB device, about the size of a pack of gum, for flexible 3D sensing use cases using a VCSEL based IR illumination.

2. **Monstar** (Fig. 5.18b) is a high-end 3D camera based on pmd TOF technology. It features a wide Field of View (FOV) of 100° x 85° degrees, a high pixel count of 352 x 287 pixels and covers a massive 6m measurement range.

3. **ZED** (Fig. 5.18c) is a high resolution stereo camera from stereolabs. It has a depth perception indoors and outdoors at up to 20m and captures stunning 2K 3D video with best in-class low-light sensitivity to operate in challenging environments.

4. **The DUO MLX** (Fig. 5.18d) is an ultra-compact imaging sensor with a standard USB interface. Its high speed and small size make it ideal for existing and new use cases for vision based applications. It counts with a programmable illumination board and built-in IR filters that allows for precise control of lighting environment.

(a) PMD Flexx time-of-flight camera. Taken from [48].

(b) PMD Monstar time-of-flight camera. Taken from [48].

(c) ZED stereo vision camera. Taken from [49].

(d) DUO MLX stereo vision camera. Taken from [50].

Figure 5.18: 3D Time-of-flight and stereovision cameras.

The important features of the mentioned 3D cameras are compared in Table 5.2.

Table 5.2: 3D cameras specifications comparative table.

	pmd Flexx	**pmd Monstar**	**ZED**	**DUO MLX**
Type	Time-of-flight	Time-of-flight	Stereo vision	Stereo vision
Measurement range	0.1-4 m	0.5-6 m	0.5-20 m	-
Resolution	224 x 171 px	352 x 287 px	Up to 4416 x 1242	Configurable (Up to 752x480)
Field of view	62° x 45° (H xV)	100° x 85° (H xV)	90° x 60° (H xV)	165° wide angle lens
Framerate	Up to 45 fps	Up to 60 fps	Up to 100 fps	0.1-3000+ fps
Interface (data & power)	USB2.0/ USB3.0	USB3.0	USB3.0	Micro USB2.0
Operating system	-Windows 7/8/10 -Linux/ARM -Ubuntu Linux 16.04 + Qt5.5 -macOS -Android/ARM	-Windows 7/8/10 -Linux/ARM -Ubuntu Linux 16.04 + Qt5.5 -macOS	-Windows 7/8/10 -Linux	-Windows 7/8/10 -Linux -Ubuntu Linux 14 or later
Software	Royale SDK (C/C++ based, Matlab, DotNet, CAPI, OpenCV, OpenNI2, ROS)	Royale SDK (C/C++ based, Matlab, DotNet, CAPI, OpenCV, OpenNI2, ROS)	ROS, unity, unreal engine, OpenCV, Matlab	OpenCV, Qt5, ROS
Dimensions	68x17x7.35 mm	62x66x29 mm	175x30x33 mm	52.02x25.4x13.3 mm
Weight	8g	142g	159g	12.5g

5.2.3 Sensing module

There exist many kinds of sensors able to measure different parameters that can be used to obtain important information to identify hazards and trapped victims in the inspected area.

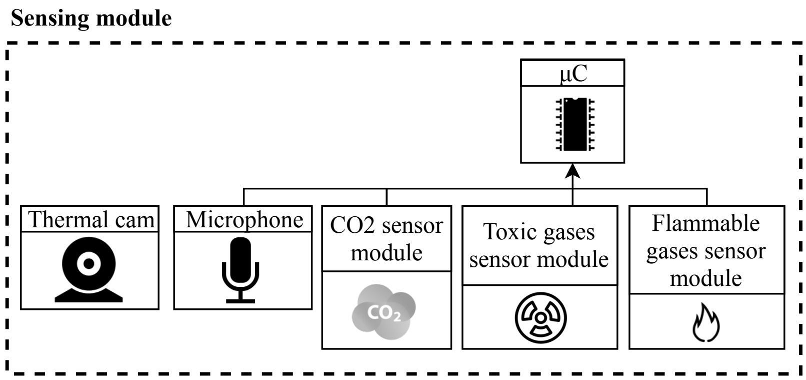


Figure 5.19: Sensing module for recollection of data.

The types of sensors selected based on the requirements are:

1. Gas sensors.
2. Sound sensors.
3. Temperature sensors.

5.2.3.1 Gas sensors

Gas sensors measure and indicate the concentration of certain gases presented in the air via different technologies.

From the variety of gases that can be presented in an affected zone by an earthquake and based on the requirements, the gases to be monitored by the system are:

1. **CO_2:** To identify areas where can be trapped victims alive.
2. **Toxic and flammable gases:** To identify hazardous environments in the affected zones.

Some available options of commercial CO_2 sensors considered for the system are listed below.

1. **CDM7160** (Fig. 5.20a) is a small size, low power and high accuracy CO_2 sensor module fron FIGARO USA, INC. It measures infra-red light intensity at the reference wavelength simultaneously, and calculates CO_2 concentrations from the difference between light intensities at the CO_2 absorption wavelength and the reference wavelength, resulting in accurate and stable measurement of CO_2 gas concentrations.

2. **The CO_2 Gas sensor module #27929** (Fig. 5.20b) is designed to allow a microcontroller to determine when a pre-set Carbone Dioxide gas level has been reached or exceed. It is compatible with most microcontrollers and posses Low-power standby mode. This module uses a gas sensor MG811 from Hanwei Electronics.

3. **TGS4161 module** (Fig. 5.20c) from Logoele Electronic uses a FIGARO CO_2 sensor. It counts with an analogical signal that can be connected directly to the data acquisition and a digital output that can be connected to a microcontroller.

(a) CDM7160 C0$_2$ sensor module. Taken from [51].

(b) Module #27929 for CO_2 sensor. Taken from [52].

(c) Module for TGS4161 CO_2 sensor. Taken from [53].

Figure 5.20: CO_2 sensors with their modules.

A comparative of the main characteristics of the mentioned sensors modules is presented in Table 5.3.

Table 5.3: CO_2 sensors comparative table.

	CDM7160	**Module (#27929)**	**TGS4161 module**
Typical detection range	300-5000 ppm	350-10000 ppm	350-10000 ppm
Driving voltage	4.75∼5.25 VDC	6.5-12 VDC	0∼5 VDC
Power consumption	Current: 60 mA peak, 10 mA avg	-	$\leq$ 500 mW
Operating conditions	0∼50°C 0∼85%RH	0∼50°C	-10∼50°C 5-95%RH
Dimensions	32 x 17 x 7.5 mm	38.1 x 25.4 x 25.4 mm	35 x 21 x 15 mm
Weight	approx. 3g	-	approx. 6g
Operating principle	NDIR	Solid electrolyte	Solid electrolyte

All of these sensors require a special housing in order to isolate them from the environment to which the mobile robot will be exposed. There are no available commercial housings for these type of sensors, nevertheless there are a variety of industries dedicated to the design of housings for sensors. For the CDM7160 CO_2 sensor, FIGARO offers housing design as part of its technical support and other customer-specific technical help.

There are also a great variety of commercial sensors for detecting toxic and flammable gases. The selected options for this sensors are listed below.

1. **MQ2** (Fig. 5.21a) is an analog gas sensor used in gas leakage detecting equipments. This sensor is suitable for detecting Liquefied Petroleum Gas (LPG), i-butane, propane, methane, alcohol, Hydrogen, smoke. It has a high sensitivity and fast response time. And the sensitivity can be adjusted by the potentiometer.

2. **MQ9** (Fig. 5.21b) is a semiconductor gas sensor that detects the presence of Carbon Monoxide at concentrations from 10 to 1,000 ppm and flammable gas from 100 to 10,000

ppm and ouputs its reading as an analog voltage. The sensor can operate at temperatures from -10 to 50°C and consumes less than 150 mA at 5 V.

(a) MQ2 toxic and flammable gases sensor and module.

(b) MQ9 toxic and flammable gases sensor and module.

Figure 5.21: Flammable and toxic gases sensors with their modules. Taken from [54].

The following table presents a comparative of the main features of the flammable gases sensors described above.

Table 5.4: Flammable sensors comparative table.

	MQ2	**MQ9**
Power supply	0∼5 V	0∼5 V
Current	<150 mA	<150 mA
Detection range	300-10000 ppm	100-10000 ppm
Temperature range	-20°C to 50°C	-10°C to 50°C
Power consumption	≤900 mW	<70 mW
Dimensions	32 x 20 x 22 mm	40 x 22 x 17 mm
Weight	20g	6g

These sensors also required special housing to provide isolation from the environmental conditions that the mobile robot will confront. There are available housing designs for the presented types of gases sensors that can be found on the Internet and they also can be designed by industries especially dedicated to this.

5.2.3.2 Sound sensors

For detecting sounds in the affected area, the use of a microphone as a sound sensor is selected. The sounds captured by the microphone can be processed in order to identify voices or sounds coming from trapped victims and support their finding.

5.2.3.3 Temperature sensors

A thermal camera is a must have piece of equipment for rescuers. It can detect a trapped victim by their body temperature. This provide a solution when other visual methods can have problems due to a person wearing the same color clothing as their surrounding making it difficult to detect it.

MicroCAM™ irGO (Fig. 5.22) was selected as the best option for the system. It is a shock resistant, sealed and waterproof miniature thermal imaging camera designed for very low-powered cost-sensitive OEM applications. It has an excellent high shock resistant night vision capability in a cylindrical package that can easily be integrated.

Figure 5.22: Thermoteknix MicroCAM irGo. Taken from [55].

MicroCAM irGO has a supply voltage range that goes fro 2.5 to 15 VCD and a power consumption less than 0.55 W. In the following table (Table 5.5) the main specifications for the MicroCAM irGo thermal camera are presented.

Table 5.5: MicroCAM irGO technical specifications [55].

Resolution	**Spectral range**	**Temperature range**	**Field of view**	**Dimensions**	**Weigth**
384x288 or 640x480	$>7\mu$m	-40°C to +70°C	40°	40Ø x 67mm	107 g

5.2.4 Odometry

The estimation of the position changes of the mobile robot, or odometry, is an important task needed for path planning, obstacles avoidance and monitoring of the system during its navigation on the area to inspect.

In order to cover this requirement, two type of sensor are selected to provide the necessary data for determining the position of the robot: IMU and GPS sensors.

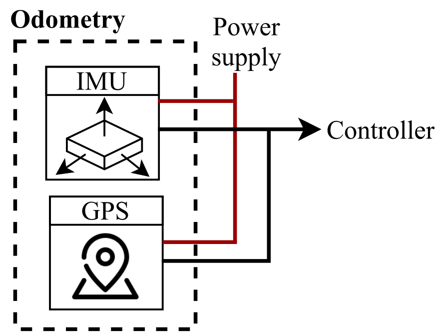


Figure 5.23: Odometry components.

5.2.4.1 Inertial measurement unit (IMU)

An IMU sensor is formed by a combination of accelerometers and gyroscopes in order to provide speed, acceleration, orientation and attitude data of a system. The data obtained by the IMU sensor can be used to obtain a position relative to a global reference frame by using a navigation method called dead reckoning which consists in calculating the current position of an object by using a previously determined position and advancing that position based upon known or estimated speeds over elapsed time and course.

5.2.4.2 Global positioning system (GPS)

A GPS provides the global position of an object by the use of satellites. This position can have a precision of meters depending on the selected device. The GPS will be used to complement the estimated position by the IMU sensor and obtain a more accurate data of the position of the system on the area. GPS are generally not suitable to establish indoor locations, since microwaves will be attenuated and scattered by roofs, walls and other objects. However, in order to make positioning signals ubiquitous, integration between GPS and indoor positioning can be made. In other way GPS can be perfectly used when the system is operated in an outdoor environment and when it ingress to an indoor area the IMU sensor could be sufficient to determine the position of the mobile robot.

5.2.5 Illumination subsystem

The purpose of the illumination subsystem is to provide a dirigible light source which should be able to adjust the intensity depending on the darkness of the area, for the use of video in confined spaces and for helping the rescuers to inspect te areas with a poor illumination.

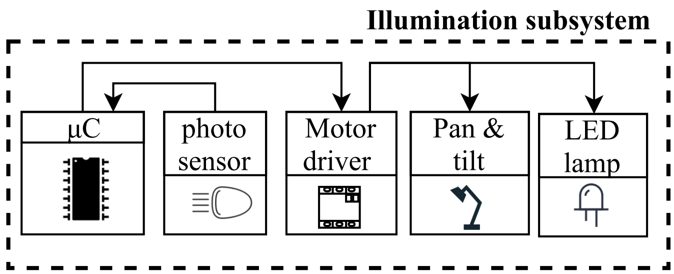


Figure 5.24: Illumination subsystem diagram.

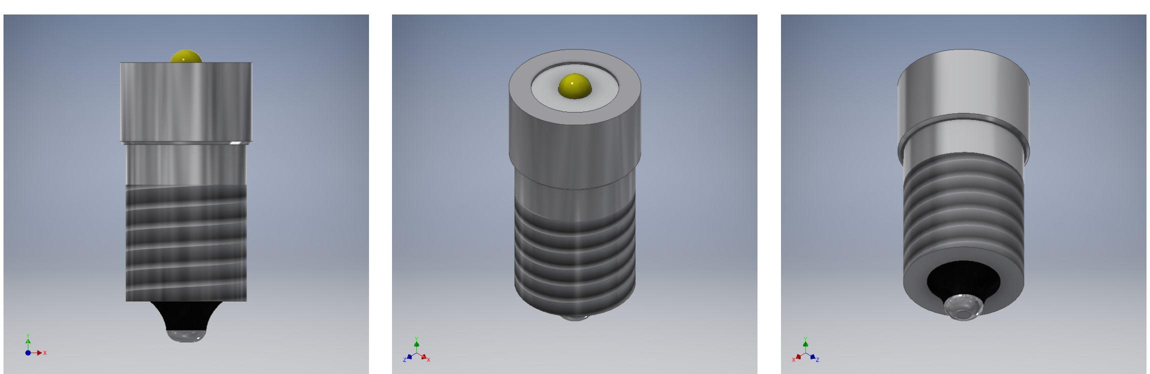
The illumination subsystem (Fig 5.24) is formed by the following components:

1. A LED lamp acting as the light source.
2. A mobile base to adjust the direction of the emitted light.
3. A photosensor to measure the illumination of the environment.

5.2.5.1 LED lamp

A LED lamp was chosen as a light source due to its compatibility with electronic systems, its small size and its low power consumption.

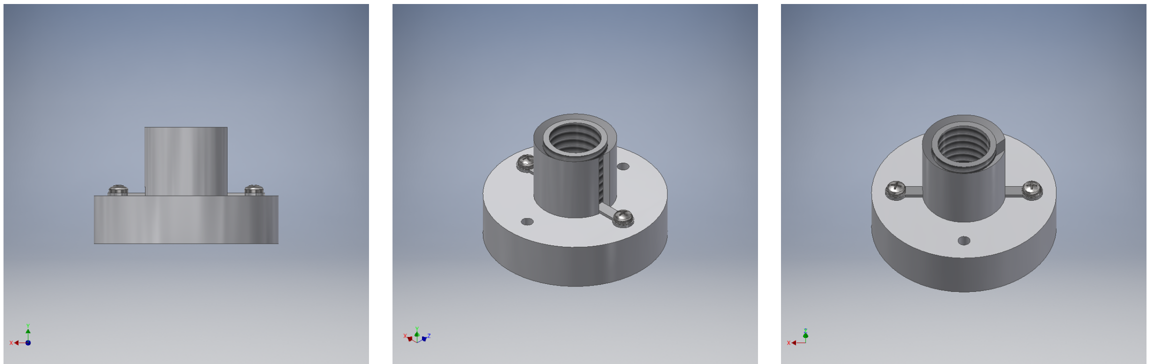
In Figure 5.25 a Computer-aided design (CAD) model of a 1 W LED flashlight bulb with screw base can be observed. It has an E10 base type, white light and RoHS compilant certification. Its dimensions are of 9.84mm diameter and 21.84mm length.



(a) Front view. (b) Isometric view. (c) Front-bottom view.

Figure 5.25: LED Flashlight bulb CAD model.

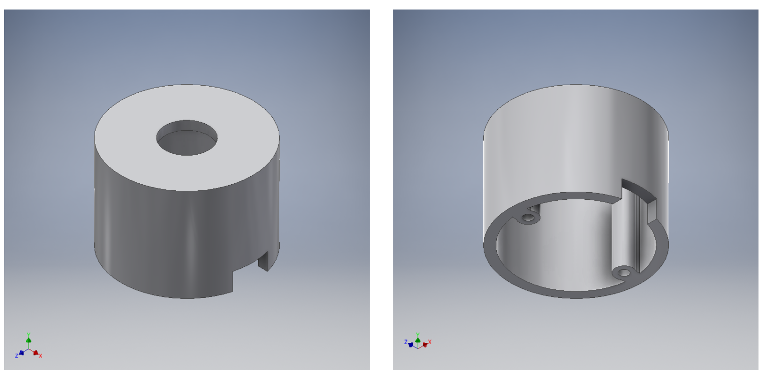
An E10 type light bulb holder for the LED flashlight bulb is shown in Figure 5.26 as a CAD model. It has dimensions of 30mm diameter and 19mm height and an electrical rating of <9 V and <2 A.



(a) Front view. (b) isometric view. (c) Front-top view.

Figure 5.26: E10 miniature light bulb holder CAD model.

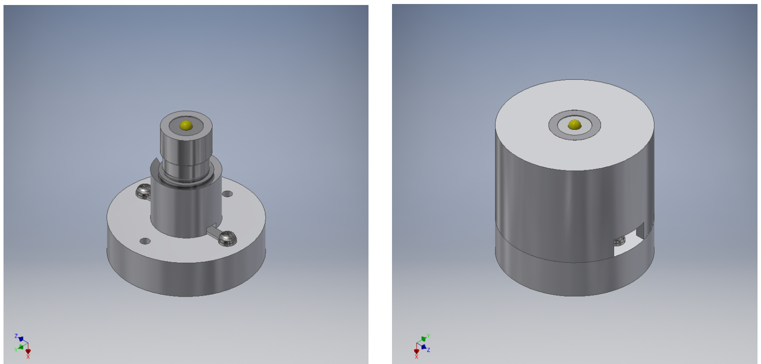
A housing is necessary to provide protection from the environment to the LED flashlight bulb. In Figure 5.27 a CAD model of a housing for the LED flash bulb with 30mm of diameter is presented.



(a) Isometric view. (b) Isometric down view.

Figure 5.27: LED Flashlight bulb CAD model.

An isometric view of the LED flashlight bulb mounted in the miniature bulb holder with and without housing can be observed in Figure 5.28.



(a) Without housing. (b) With housing.

Figure 5.28: LED flashlight bulb mounted in bulb holder CAD model.

5.2.5.2 Mobile base

The base for the lamp will be able to rotate in Y and Z axis as can be seen in Figure 5.29. It consists in a mini pan tilt mechanism with two DOF to allow the change in the direction of the light emission depending on the situation.

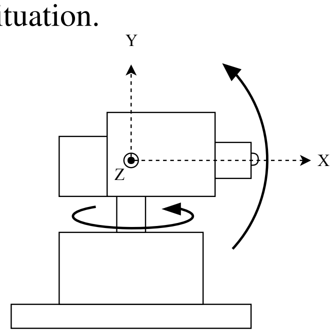
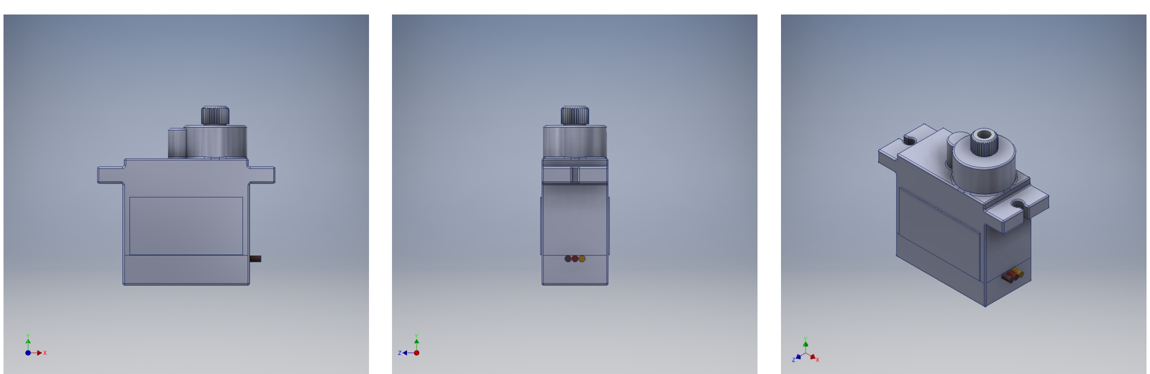


Figure 5.29: Rotational movement in Y and Z axis.

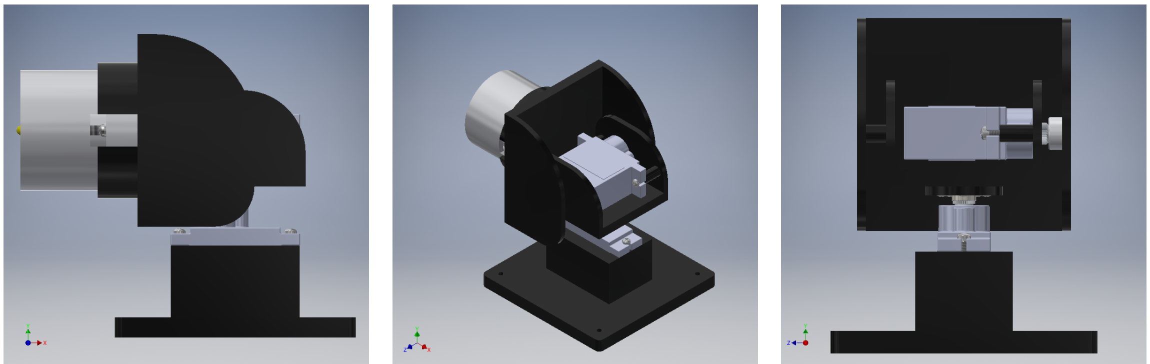
For the rotational movement in the two axis, two micro servomotors MG90S with dimensions of 22.5X12X33.5mm are proposed. Each servomotor weights 13.4g, can rotate approximately 180° and their operating voltage goes from 4.8 to 6 volts.



(a) Front view. (b) Lateral view. (c) Isometric view.

Figure 5.30: Micro servomotor CAD model.

A CAD model of a preliminary design of the mobile base with all its elements is presented in Figure 5.31.



(a) Lateral view. (b) Isometric view. (c) Back view.

Figure 5.31: CAD model of the micro pan tilt mechanism with LED lamp.

5.2.5.3 Photosensor

A photosensor will be used to detect the presence of light in the surroundings in order to turn on and off the lamp or adjust the light source intensity depending the grade of darkness of the area.

5.2.6 Power supply

The power supply of the mobile robot is conformed by two elements: the power source and a DC to DC power converter.

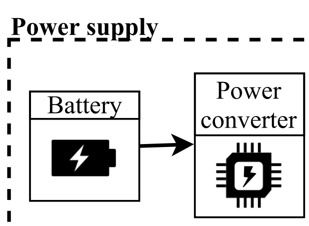


Figure 5.32: Power supply of the system.

A rechargeable battery was selected as power source for the mobile robot and from the different types of rechargeable batteries, $LiFePO_4$ batteries are selected due to their stability, security and durability. These type of batteries are reliable and does not present combustion risk. For this, they are used for critical applications such as aeronautic, automotive, robotic and medicine, where a failure can mean something bigger than a lost.

$LiFePO_4$ batteries are ecological, maintain all their power until the moment of discharge, fast charge time, do not require maintenance and have a long life cycle. Some main characteristics of $LiFePO_4$ batteries are presented in Table 5.6.

Table 5.6: Characteristics of $LiFePO_4$ batteries [56].

Nominal voltage	**Energy density**	**Specific capacity**	**Charge-Discharge cycles**	**Temperature range**
3.2-3.3 V	130 Wh/kg	145 Ah/kg	2000/3000 cycles	-20°C to 70°C

A power converter is necessary to provide and distribute the appropriate voltage to each element of the robot. DC to DC converters are commonly used in portable systems with several components with their own voltage level requirement which are supplied with a primarily power source. DC to DC converters also are used as a method to increase voltage from a partially lowered battery voltage for saving space instead of using multiple batteries.

5.2.7 Control/Communication subsystem

For the control subsystem (Fig. 5.33), a base station is necessary for monitoring and teleoperation of the exploration and illumination system. For this, a controller connected to a laptop and a Long-Range (LoRa) wireless module are selected as components of the base station. Besides, for the exploration and illumination system control, a LoRa module is also necessary for wireless communication between the mobile robot and the teleoperation station and a Single Board Computer (SBC) acting as the main processor is selected.

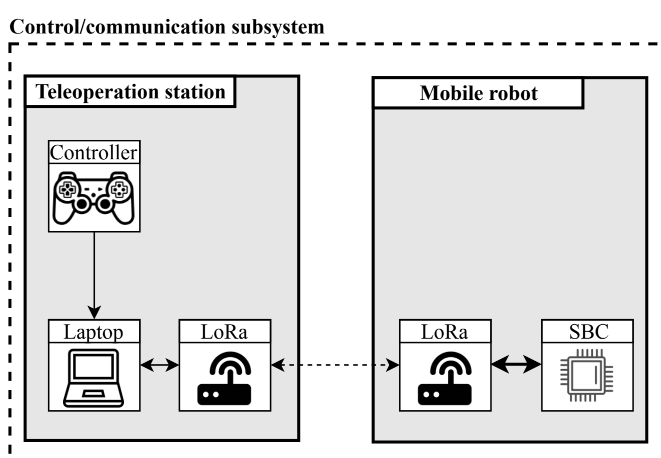


Figure 5.33: Control/communication subsystem diagram.

5.2.7.1 Human-Machine interface

For the user interface, a game controller connected to a Laptop is selected. A great variety of game controllers with different configuration of buttons and joysticks are available in the market which can be easily adapted to the needed commands to control the mobile system. A laptop will be used for the Graphic User Interface (GUI) to show the information recollected by the mobile system and the interaction with it.

5.2.7.2 Communication

For wireless communication a LoRa protocol is selected. LoRa is a long range wireless platform with a prolonged battery lifetime of up to 10 years due to its low power consumption, minimizing battery replacement costs. It enables GPS-free tracking applications and is able to maintain communication with devices in motion and support millions of messages per base station without strain on power consumption.

5.2.7.3 Processor

A SBC is selected to act as the main processor of the mobile system. It consist on a single circuit board with a wide range of microprocessors, internal memory, inputs and outputs (I/O) among other components required on a functional computer. A single-board configuration reduces the cost and size of the overall system by reducing the number of circuit boards required and eliminating unnecessary connectors and bus driver circuits.

The concept idea of the system was presented on this section. The presented proposals of commercial components for some of the system functions were selected as the best options. Nevertheless, a further analysis need to be executed for the correct selection of components and materials in order to ensure the correct performance of the system.

Finally, the conclusions of this work are presented in te following section as well as the further work for the continuity of this project.

Chapter 6

Conclusion and further work

The presented work consisted in the definition and conceptualization of an exploration and illumination system for supporting the labor of search and rescue for victims trapped under the rubble after an earthquake disaster. The designed system presents an innovating mechanism for movement for the required application. This mechanism configuration has a big advantage over other configurations used in search and rescue systems and consists in the many ways to surmount different obstacles on its way by the use of its mobile arms without sacrificing the dimensions of the system. Commercial sensors and other commercial components for the system was proposed. However, a deep analysis of the characteristics of these components and their functionality within the whole system is necessary.

The results of this work are being included in an official governmental announcement within the field of “Resilience against natural disasters” that actually counts with the participation of at least 5 national research and academic institutions.

For future work, the next stages from the methodology established in the Chapter 1, going from the preliminary and detailed design of the system to the implementation of a functional alpha prototype that allows to test and prove concrete achievements, are intended. The system is pretended to be used in the future in collaboration with disaster relief organizations such as Topos Rescue Association of Mexico City.

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Appendix A

Chronogram of activities

The activities and documents to be realized in a time of five months in order to accomplish the project are listed and represented in Fig.A.1 as a Gantt graph.

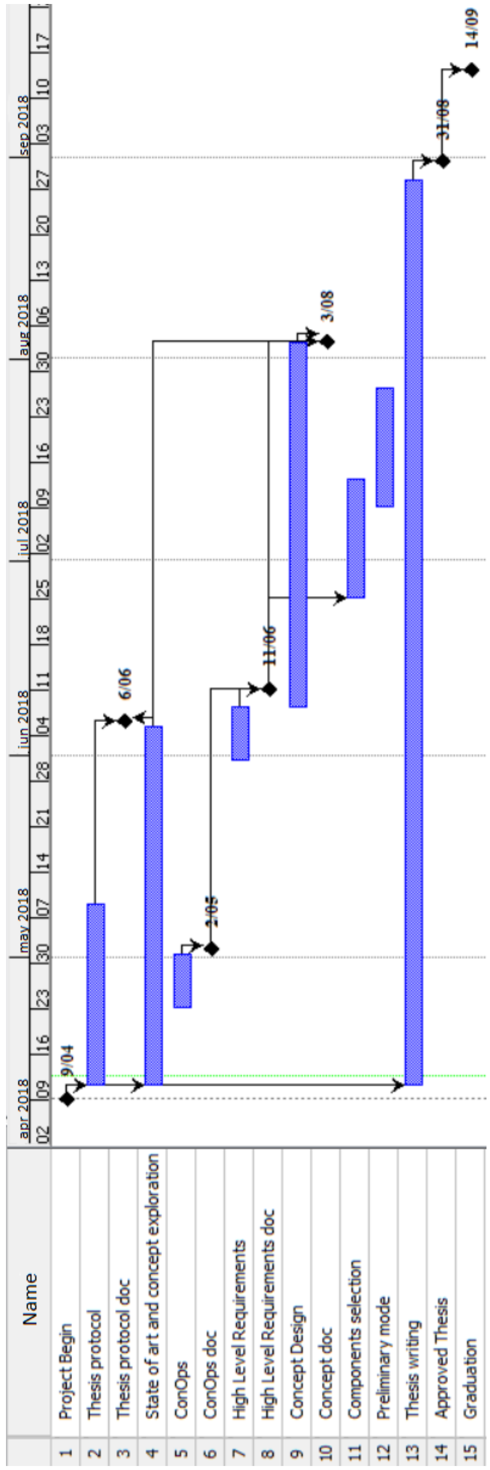


Figure A.1: Gantt graph for the project development created with the free licensed software “Project-Libre” [57].

Appendix B

Objectives tree diagrams

For the approach to the system to develop, the different objectives that could be performed by a disaster relief system were analyzed and organized for the different tasks options. For the easy organization of the relations and interconnections between main objectives and secondary objectives the following tree diagrams were elaborated.

B.1 Debris cutting objectives tree

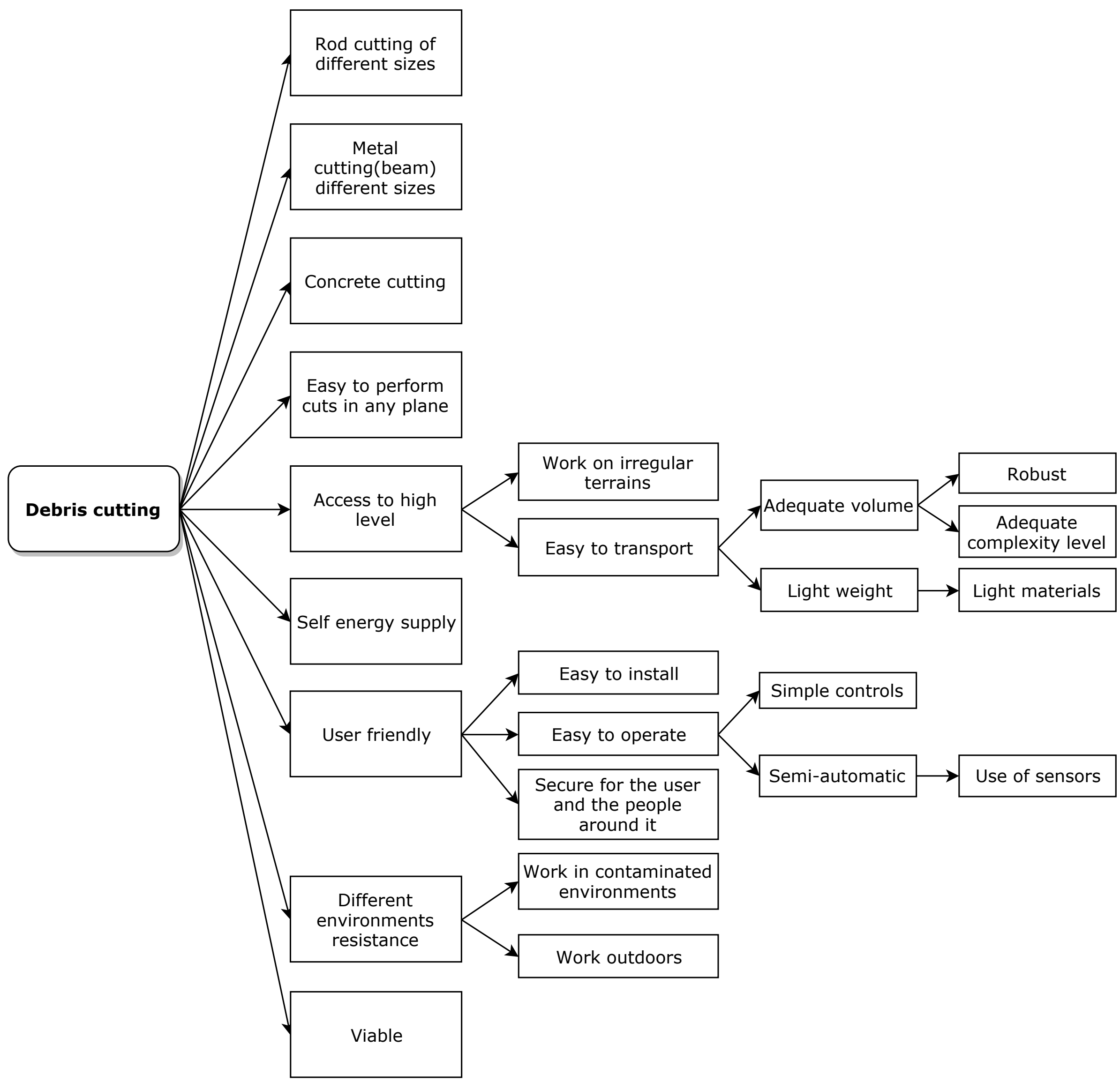


Figure B.1: Debris cutting objectives tree diagram.

B.2 Debris removal objectives tree

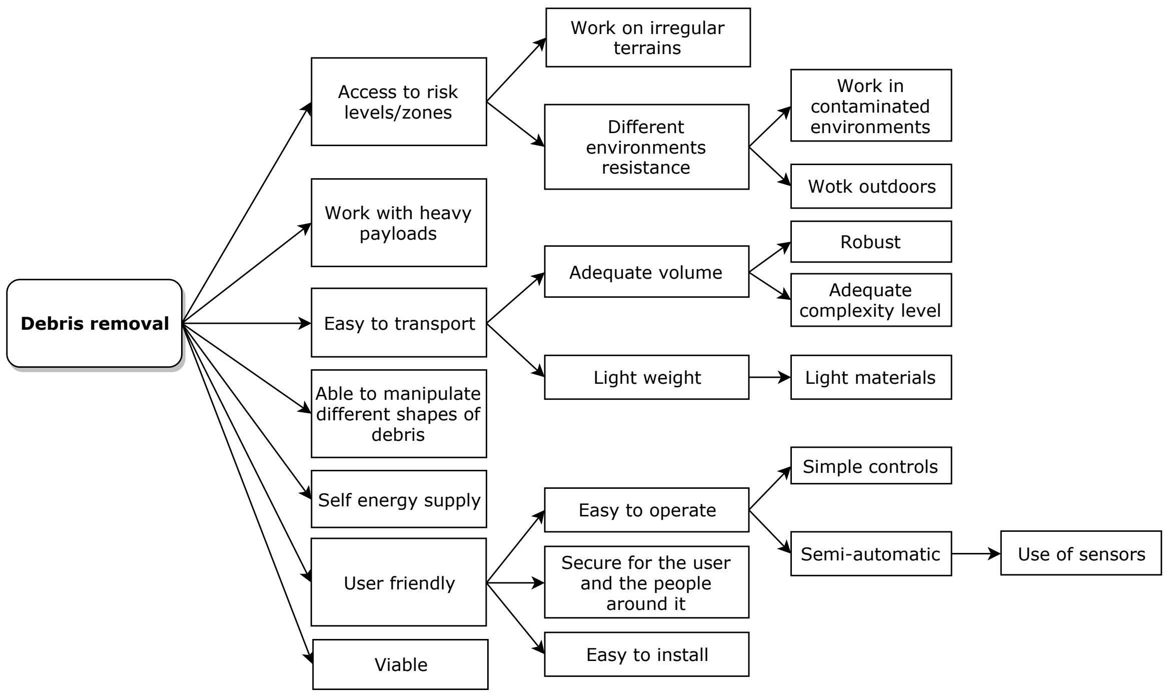


Figure B.2: Debris removal objectives tree diagram.

B.3 Debris transport objectives tree

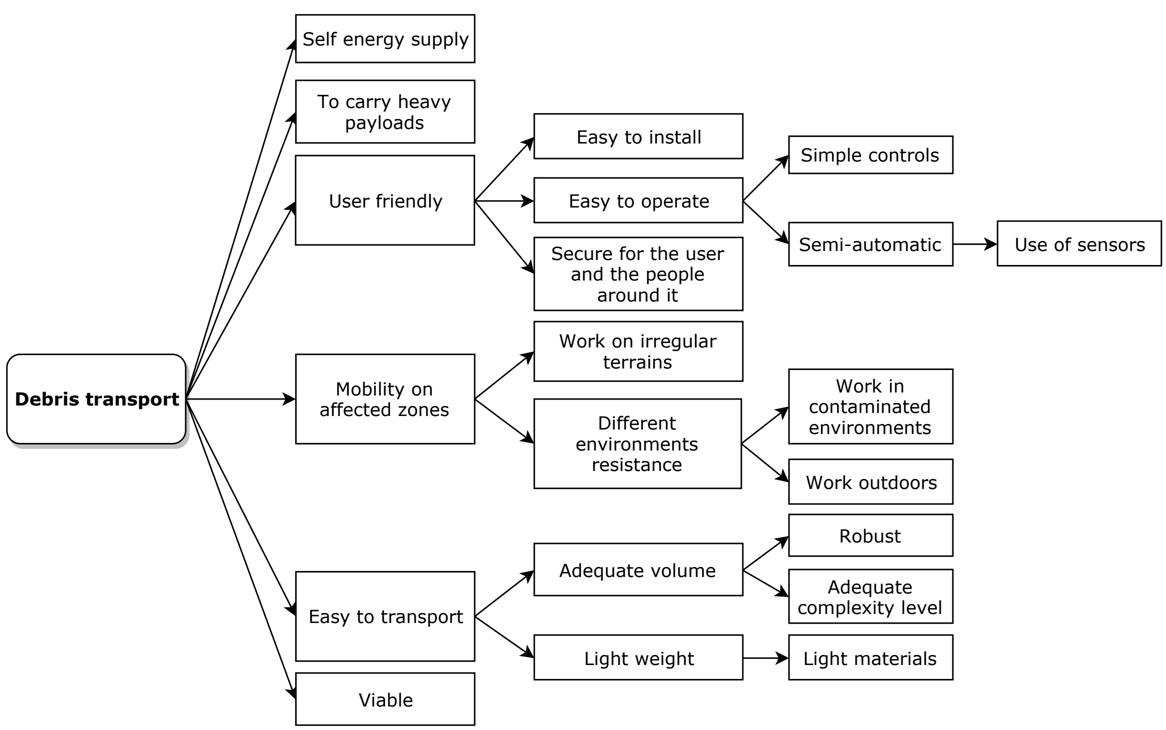


Figure B.3: Debris transport objectives tree diagram.

B.4 Shoring objectives tree

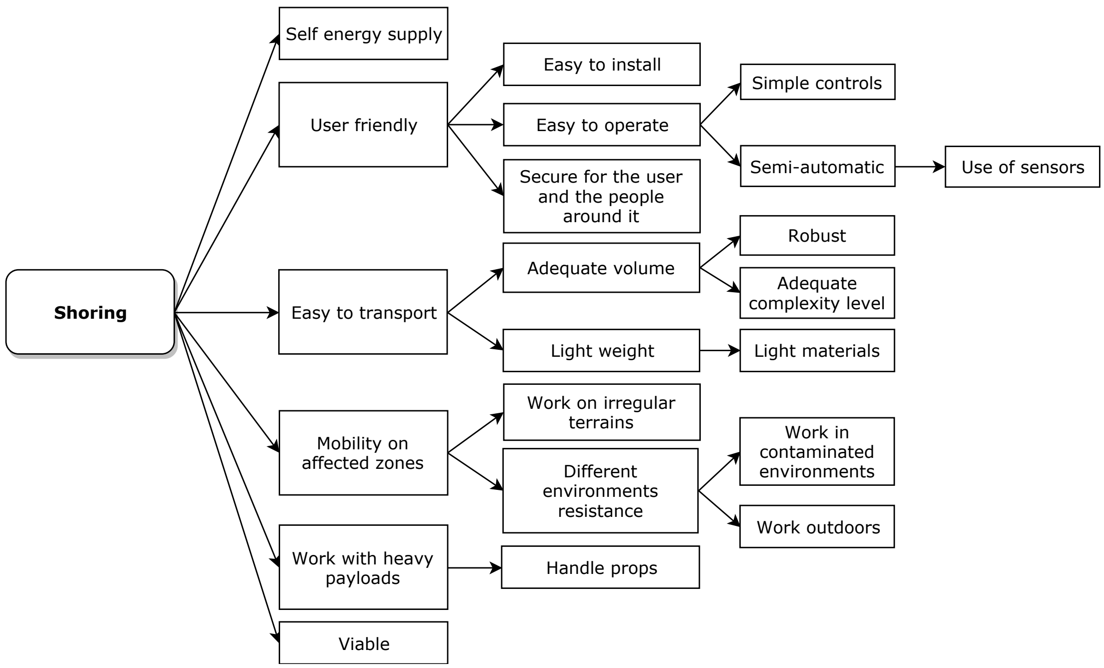


Figure B.4: Shoring objectives tree diagram.

B.5 Exploration objectives tree

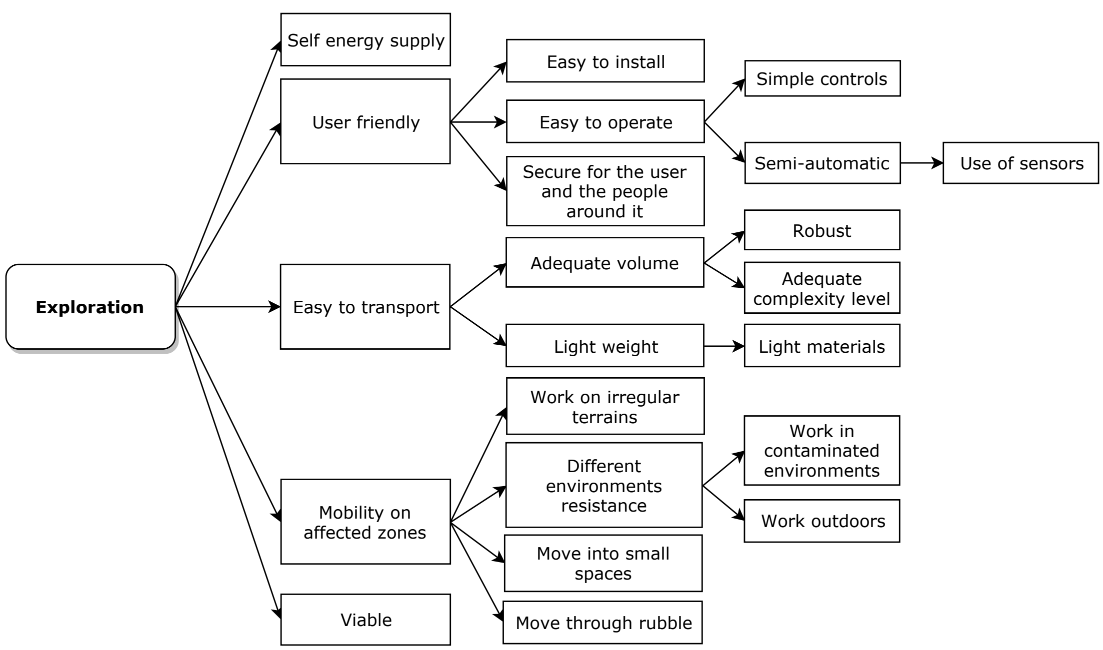


Figure B.5: Exploration objectives tree diagram.

B.6 Illumination objectives tree

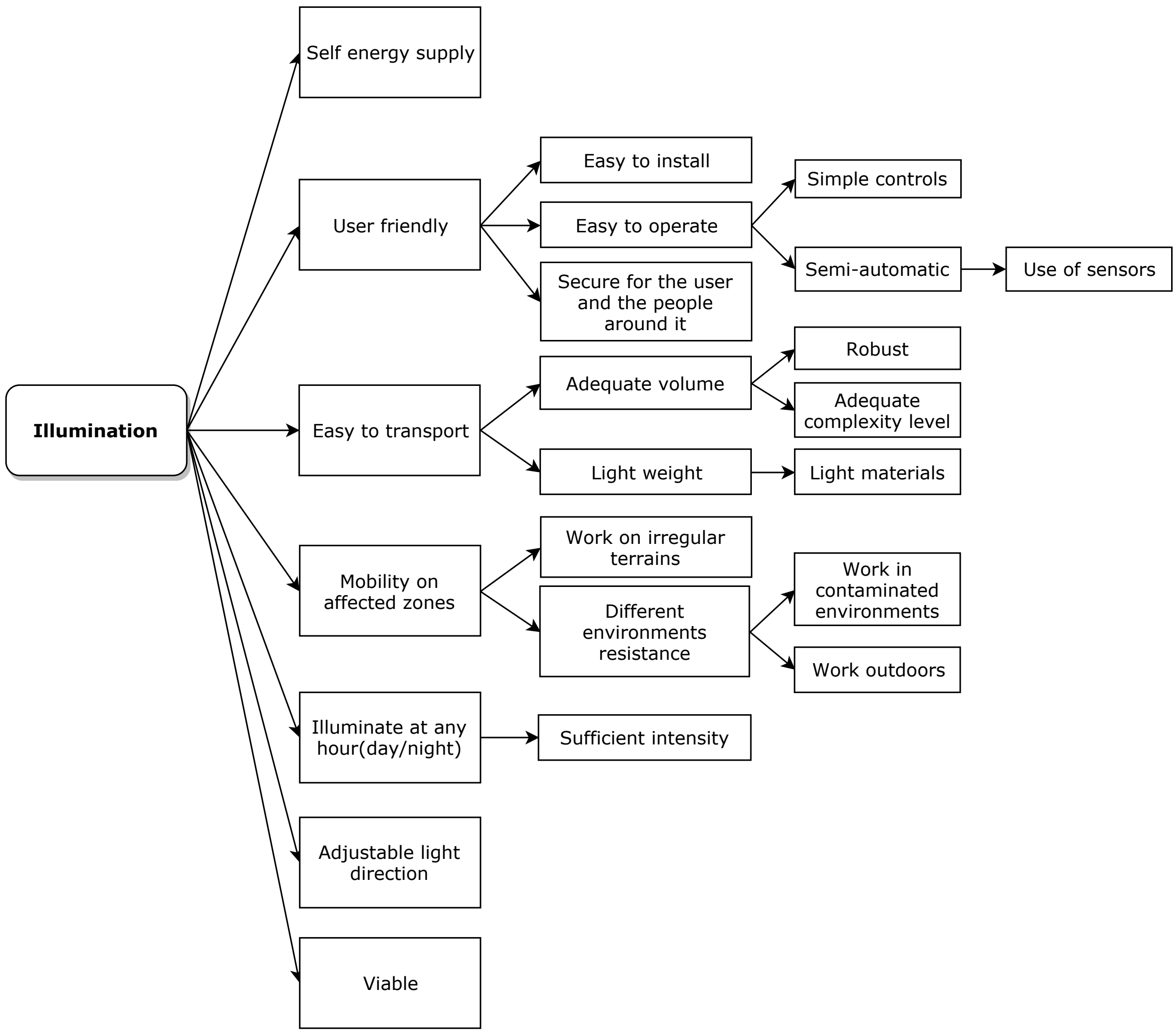


Figure B.6: Illumination objectives tree diagram.

Appendix C

Data sheets

The datasheets of proposed and selected commercial components are presented below.

C.1 CO_2 sensors

C.1.1 CDM7160

TECHNICAL INFORMATION FOR CDM7160

1. Basic Information and Specifications

1-1 *Features*

* Small size
* Low power
* High accuracy
* Absolute measurement via dual sensors

1-2 *Applications:*

* Indoor air quality control
* Fresh air ventilators
* Air conditioners
* Automatic fans and window openers

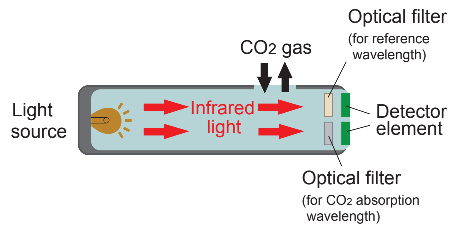


Fig. 1 - Basic structure of CDM7160 optics

1-3 *Basic principle and structure*
Fig. 1 shows the basic structure of the module's optics.

This sensor is a single light source, dual wavelength system. The sensor employs two detectors with different optical filters in front of each detector. One detector measures the intensity of infrared light passing through the optical filter, transmitting only the infrared wavelength region absorbed by CO_2 (CO_2 absorption wavelength). The other detector measures the intensity of infrared light passing through the optical filter, transmitting only an infrared wavelength (3.8μm) not absorbed by CO_2 (i.e. a reference wavelength), and is thus unaffected by the constant presence of CO_2.

Measuring absolute values of CO_2 concentration by CDM7160 is achieved by the module's microprocessor calculating CO_2 concentration from the difference between light intensity transmitted at the CO_2 absorption wavelength and at the reference wavelength.

The single light source, dual wavelength system employed by the CDM7160 measures light intensities at two different wavelengths after separation by two optical filters, thus compensating drift due to accumulated dust and contamination. This ensures long term stability, minimum maintenance, and cost-effectiveness.

Product name	Carbon dioxide (CO2) sensor module
Model No.	CDM7160
Detection range	300~5,000ppm CO2
Operating principle	Non-dispersive infrared (NDIR)
Power supply	4.75~5.25V DC
Current consumption	60mA peak, 10mA avg.
Accuracy (Note 1)	±(50ppm+3% of reading) in the range of 300~5,000ppm CO2
Pressure dependency	approx 1% of reading / kPa
Response time (T90)	2 min. (diffusion)
Operating temperature range	0~50˚C/5~85%RH (no condensation)
Storage temperature range	-30~70˚C/5~85%RH (no condensation)
Communication port	UART/ I2C (gas conc. output 0~10,000ppm)
Measurement interval	2 sec.
PWM output (1kHz)	0~100% duty cycle for 0~5,000ppm, CMOS output
Dimensions	32 x 17 x 7.4 (mm)
Weight	approx. 3g

Table 1 - Specifications of CDM7160

Note 1: Represents accuracy at factory shipment. For long term accuracy, please refer to *Fig. 5 - Long term stability of CDM7160.*

1-4 *Operating conditions & specifications (refer to Table 1)*

1-5 *Absolute maximum ratings (refer to Table 2)*
Products using CDM7160 should be designed so that these maximum ratings are *never* exceeded.

Item	Min.	Max.	u/m
Ambient temperature	-40	85	˚C
Input voltage	-0.3	5.5	V
Maximum input voltage (MSEL in, CAD in, CAL in, Rx/SCL)	-0.3	VDD+0.2 and 5.5	V
Maximum output current (Alarm, PWM, Busy, Tx/SDA)	-	50	mA

Table 2 - Absolute maximum ratings for CDM7160

C.1.2 Gas sensor module #27929

PARALLAX

Web Site: www.parallax.com
Forums: forums.parallax.com
Sales: sales@parallax.com
Technical: support@parallax.com

Office: (916) 624-8333
Fax: (916) 624-8003
Sales: (888) 512-1024
Tech Support: (888) 997-8267

CO2 Gas Sensor Module (#27929)

The CO2 Gas Sensor Module is designed to allow a microcontroller to determine when a preset Carbon Dioxide gas level has been reached or exceeded. Interfacing with this sensor is done through a 4-pin SIP header and requires two I/O pins from the host microcontroller. The sensor module is intended to provide a means of comparing gas sources and being able to set an alarm limit when the source becomes excessive. **Parallax does not provide gas calibration data on this module and such data as well as the alarm settings are the responsibility of the user to define. For information on calibration please see page 3.**

Features

- Easy SIP header interface
- Compatible with most microcontrollers
- Low-power standby mode

Key Specifications

- Power requirements: 6.5 – 12 VDC @ ~165 mA (heater on) / ~1.2 mA (heater off)
- Interface: 1 TTL compatible input (CNTL), 1 TTL compatible output (ALR)
- Operating temperature: 32°F to 158°F (0°C to 70°C)
- Dimensions: 1.50″ x 1.00″ x 1.00″ (38.1 mm x 25.4 mm x 25.4 mm)

Application Ideas

- Gas level over-limit alarm
- Stand-alone/background sensing device
- Environmental monitoring equipment

Packing List

- Gas Sensor
- Gas Sensor PCB Assembly
- Potentiometer adjustment tool

Precautions

Be aware that the gas detected by this gas sensor can be deadly in high concentrations. 1% (10,000 ppm) will make some people feel drowsy. Concentrations of 7% to 10% can cause dizziness, headache, visual and hearing dysfunction and unconsciousness within a few minutes to an hour. Always be careful to perform gas tests in well-ventilated areas.

THIS GAS SENSOR MODULE IS NOT DESIGNED FOR OR APPROVED FOR ANY APPLICATION INVOLVING HEALTH OR HUMAN SAFETY. THIS GAS SENSOR MODULE IS FOR EXPERIMENTAL PURPOSES ONLY. PARALLAX, INC. ABSOLVES ITSELF OF ALL LIABILITY AND RESPONSIBILITY ASSOCIATED WITH THE CUSTOMER'S USE OF THIS GAS SENSOR MODULE AND IS NOT RESPONSIBLE FOR ANY BODILY INJURY, DEATH OR PROPERTY DAMAGE AS A RESULT OF USING THIS GAS SENSOR MODULE.

IMPORTANT: CO2 SENSORS ARE POLARIZED. SENSORS FROM THE FACTORY HAVE A RED DOT ON ONE SIDE. WHEN INSERTING THE SENSOR INTO THE SOCKET ON THE MODULE THE RED DOT MUST BE TO THE LEFT IF YOU’RE LOOKING AT THE FRONT OF THE MODULE WITH THE PINS DOWN. FAILURE TO FOLLOW THIS WILL CAUSE THE SENSOR TO MALFUNCTION AND PREVENT CALIBRATION.

C.1.3 Tgs4162

FIGARO

PRODUCT INFORMATION

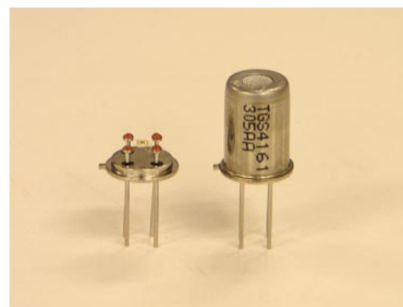
TGS 4161 - for the detection of Carbon Dioxide

Features:

- **High selectivity to CO_2**
- **Compact size**
- **Low dependency on humidity**
- **Long life and low cost**
- **Low power consumption**

Applications:

- **Indoor air quality control**
- **CO_2 monitors**



TGS4161 is a new solid electrolyte CO_2 sensor which offers miniaturization and low power consumption. A range of 350~10,000ppm of carbon dioxide can be detected by TGS4161, making it ideal for indoor air control applications.

The CO_2 sensitive element consists of a solid electrolyte formed between two electrodes, together with a printed heater (RuO_2) substrate. By monitoring the change in electromotive force (EMF) generated between the two electrodes, it is possible to measure CO_2 gas concentration.

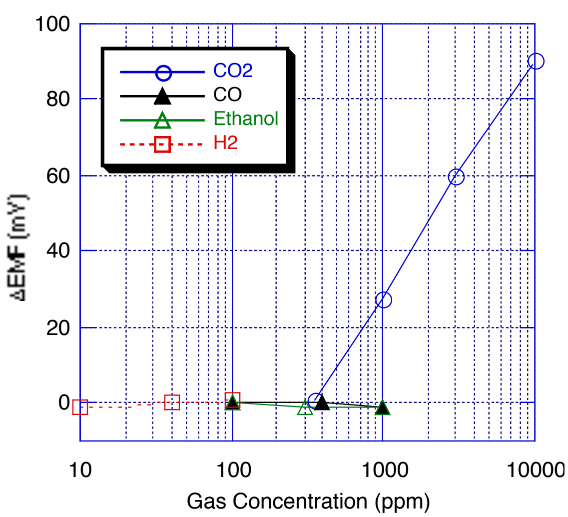
The top of the sensor cap contains adsorbent (zeolite) for the purpose of reducing the influence of interference gases.

TGS4161 exhibits a linear relationship between ΔEMF and CO_2 gas concentration on a logarithmic scale. The sensor displays good long term stability and shows excellent durability against the effects of high humidity.

The figure below represents typical sensitivity characteristics of TGS4161. The Y-axis is indicated as ΔEMF which is defined as follows:

ΔEMF=EMF1 - EMF2
where
EMF1=EMF in 350 ppm CO_2
EMF2=EMF in listed gas concentration

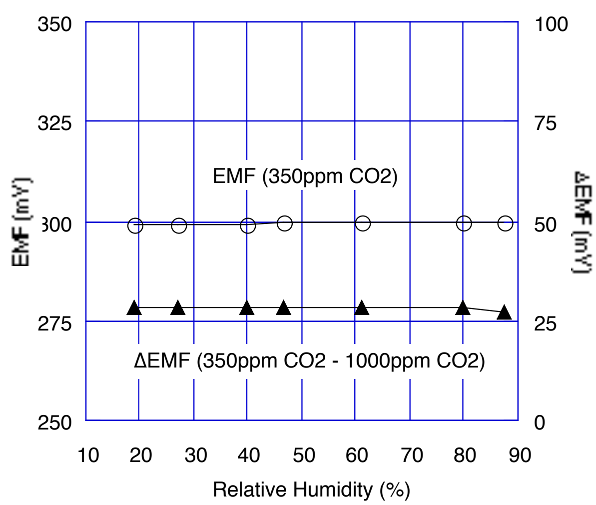
Sensitivity Characteristics:



The figure below shows typical humidity dependency of TGS4161. Again, the Y-axis is indicated as ΔEMF which is defined as follows:

ΔEMF=EMF1 - EMF2
where
EMF1=EMF in 350 ppm CO_2
EMF2=EMF in 1000ppm CO_2

Humidity Dependency:



C.2 Thermal camera

MicroCAM™ irGO

MicroCAM™ irGO

Specification	MicroCAM irGO 384 - 17µm	MicroCAM irGO 640 - 17µm
Sensitivity (*f*/1.0 no lens)	<50mK*	<50mK* (40mK* Option)
Spectral response**	LW Broadband >7µm	
Power consumption	<0.55 Watt	<0.75 Watt
Supply Voltage Range	2.5-15vDC input range	
Detector Material	Amorphous Silicon (ASi)	
Optics	40° Field of View Lens	
Array Size Options	384x288 (Optional 320x240)	640x480
Pixel Count	110,592	307,200
Pixel Pitch	17µm (384 x 288)	17µm (640 x 480)
TEC-Less operation	Yes	
Frame Rate	50/60 Hz (Optional 9Hz)	30Hz (Optional 9Hz)
Video Output	Composite PAL/NTSC (CCIR/RS170)	
Digital Zoom	x2, x4	
Polarity invert	Yes	
Image flip / rotate	Yes	
Text overlay	Yes	
Operating temperature	-40°C to +70°C	
Shock	1000g 0.4ms ½ sine X & Y Axis - 700g 0.3ms ½ sine Z Axis	
Size	40Ø x 67mm / 1.57Ø x 2.64 inches	
Weight	107g / 3.8oz	

*NETD measured with *f*/1.0 aperture and broadband response of detector
**Spectral gauge available on request

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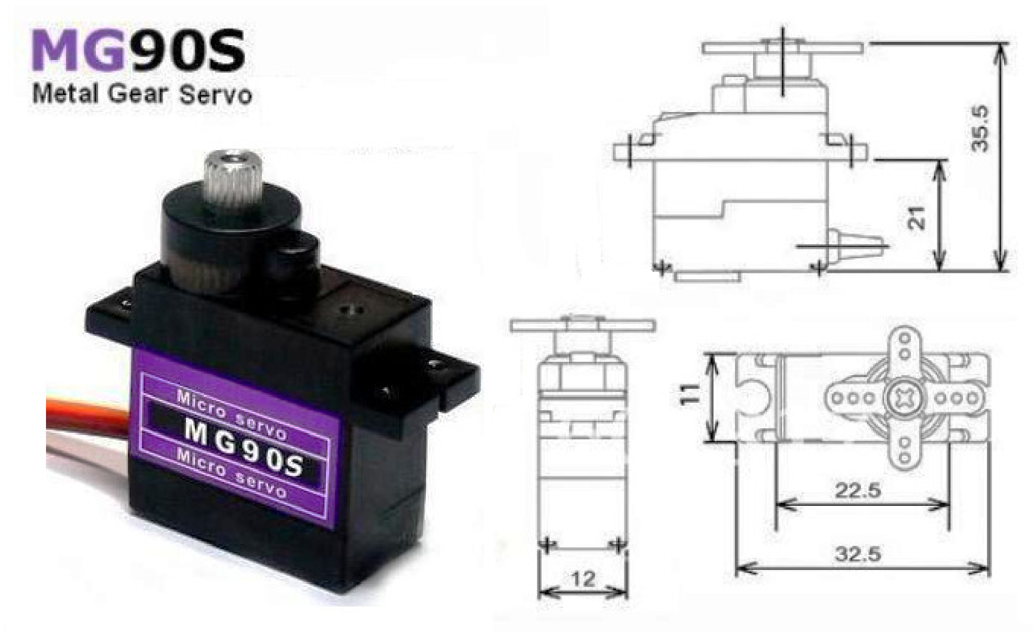
Langham Press May 2016 x500

C.3 Illumination system

C.3.1 MG90S Servomotor



MG90S servo, Metal gear with one bearing

Tiny and lightweight with high output power, this tiny servo is perfect for RC Airplane, Helicopter, Quadcopter or Robot. This servo has *metal gears* for added strength and durability.

Servo can rotate approximately 180 degrees (90 in each direction), and works just like the standard kinds but *smaller*. You can use any servo code, hardware or library to control these servos. Good for beginners who want to make stuff move without building a motor controller with feedback & gear box, especially since it will fit in small places. It comes with a 3 horns (arms) and hardware.

Specifications

- Weight: 13.4 g
- Dimension: 22.5 x 12 x 35.5 mm approx.
- Stall torque: 1.8 kgf·cm (4.8V), 2.2 kgf·cm (6 V)
- Operating speed: 0.1 s/60 degree (4.8 V), 0.08 s/60 degree (6 V)
- Operating voltage: 4.8 V - 6.0 V
- Dead band width: 5 µs

Appendix D

Concept of Operations

The complete version of the documentation for the concept of operations is attached below.

"After earthquake disaster relief machine" Concepts of Operation

Version 1.0

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Centro de Ingeniería y Desarrollo Industrial (CIDESI-CONACYT)

May 22th, 2018

Abstract

This document is aimed to describe the Concepts of Operation (ConOps) of a relief mechatronic machine for after earthquake disasters. It is included system overview, background and objectives, systems stakeholders, operation policies and constrains, and the description of the required system; all from the users point of view.

Table 1: Changes control

Version	Date	Notes/Changes
0.7	2018.05.07	Second draft
1.0	2018.05.22	First formal manuscript

1 Document overview

This document is aimed to describe the Concepts of Operation (ConOps) for a relief machine able to aid rescue (and probably clean) after an Earthquake disaster.

ConOps describe the expected functionality of a future or existence system in terms of it users. It supply important information for the acquisition or development of a system to be developed.

This document is done following was is established in [1]. It includes the current project situation, concepts of the required system and important operational procedures for it.

2 System overview

A mechatronic machine able to help the search and finding of injured and trapped people after an earthquake disaster by a novel proposed machine concept using State of the Art mechatronics and machinery knowledge and those from associated fields.

The machine to be developed shall practically aid rescuers working at the disaster scene. This shall be done by performing at least one function much better than it is now carry out with conventional methods and gear. The following functions are considered: debris cutting, debris removing, debris transportation, scene mapping and exploring, searching for victims, gear transportation and providing, etc. At least one function shall be performed by the machine to be developed, and this function or functions shall justify the development of such machine.

3 Current system status

During earthquake disasters several rescue, first response and associated techniques are used in order to find and rescue injured and trapped persons. Several types of equipment, tools and machinery are used. Most of these gear is general for workshop or industry work, so they are not designed specially for this kind of disasters, either for those specific tasks that are required to perform.

About machinery specifically design to relief earthquake disaster, exist some projects in different entities across the world aimed to design some machinery specially designed to aid search and rescue tasks.

Nevertheless of several efforts, no data about practical and tested systems across the world has been found and if any exist, they are not available for Mexico or other Latin American countries. So the importance to design and develop a system aimed to relief after-earthquake disasters.

At the moment, any system or any related subsystem has been developed yet in our group or institution.

3.1 Background and objectives

In this section it is presented briefly important background data about earthquakes and machinery considering our aim. In the second part the objectives for the machine required to be developed are presented.

3.1.1 Background

In this section, it is included briefly the impact of earthquakes, first responses after earthquake disasters, rescue procedures of victims under the rubble, existing machinery used to relief this kind of disasters and general tasks where machinery is better than humans. This data will be necessary to describe and understand our objectives which are presented in the next section.

Earthquakes and their impact in humankind. Between 1980 and 2009 there were approximately a total of 372,634 deaths, 995,219 injuries and more than 61 million people affected by earthquakes. Inconsistent reporting across data sources suggests that the numbers injured and affected are likely underestimates. Findings from a systematic review of the literature indicate that the primary cause of earthquake-related death was trauma due to building collapse [2].

Of course that the root solution to minimize earthquake impact is to design and build secure structures able to survive earthquakes, nevertheless our aim is to aid the process of find and rescue victims trapped under debris.

First response after an earthquake disaster. In general speaking, immediately after a disaster has been occurred, there are some procedures to be carried out. These procedures have the objective to be relief from the disaster minimizing every negative result and this shall be performed as quickly as possible.

A general procedure after a disaster is: 1) Secure the scene, 2) Help available injured persons, 3) Find and rescue trapped persons, 4) Find and rescue human causalities, 5) Clean and remove debris and 6) Reconstruction.

This is a general and simplified procedure. Additional activities could be considered, for example to search for missing persons could be included in step number 3, and to find and rescue pets as step 3.5 maybe.

Our aim is specially focused in steps number 1, 3, 4 and/or 5, with emphasis in number 3.

Seek and rescue injured and trapped persons (under the rubble). As it is written in [2], most causalities after an earthquake disaster are trauma due to building collapse. So, immediately an earthquake has finished seek and rescue of trapped victims shall be started. Specific general procedures have been develop for this task [3, p.47].

After earthquake disaster search, localization and rescue of victims procedure:

1. Retrieve scene information.
2. Secure scene.
3. Inspect and evaluate structure.
4. Mark structure.
5. Perform structure diagram.
6. Selection of area to search.
7. Decide search pattern.
8. Search pattern execution and mark points.
9. Analyze continuously and adjust.
10. Confirm victim location.
11. Communication, manage and attention to the victim.
12. Perform rescue.

From the steps just given above, a machine could be useful in different levels in all of the points. Nevertheless we are likely to be more assisted by a machine for numbers: 2 and 12. For each of these steps, attributes like duration, required intelligence or experience, force and overall complexity have been proposed (Table 2).

Table 2: General steps to find and rescue victims after an earthquake disaster according to [3, p.47]. For each step it is given approximate mean duration of the activity (time), required intelligence and experience, required force and overall complexity of the task. *Force meaning: 1) light, 2) middle, 3) hard, 4) two or more men, 5) between 100Kg to 1 ton, 6) More than 1 ton.

Step	Time interval (h/m/s)	Intelligence/ Experience [0-100] (%)	Force [1-6]*	Complexity easy, middle, hard
Retrieve scene information	5-30 min	100	1	hard
Secure scene	0-2hr	80	4	hard
Inspect and evaluate structure	30-120 min	100	1	middle
Mark structure	0-15 min	20	1	easy
Perform structure diagram	10-30 min	90	1	middle
Selection of area to search	0-5 min	100	1	hard
Decide search pattern	0-5 min	100	1	hard
Search pattern execution and mark points	10-180 min	100	2	hard
Analyze continuously and adjust	1-5 min	100	1	hard
Confirm victim location	1-30 min	60	2	middle
Communication, manage and attention to the victim	1-72 hrs	30	1	middle
Perform rescue	0-72 hrs	100	3-6	hard

Advantages and disadvantages of machinery vs humans. 3.3 million years ago humans starting to use tools made from stones[4]. Since then, tools have been evolving and they have been more and more complex. Nowadays humankind have a large among of different kinds of machines to improve our live.

In general, tools and their extension, the machines, are successful because they allow to perform task that humans are not able to do (e.g. microscope, telescope, space exploration, X-ray machines, etc.) or, at least, are harder to do for humans (e.g. cranes, pencil, Otto cycle motor, etc.).

So, there are some task that machines are able to do much better than humans or even they are able to do something that humans could not do at all. It is important for our purposes to identify what are the most common general task that a machine is able to perform much better than humans.

1. Force. Machines are able to carry or apply too much force.
2. Accuracy. Machines are able to perform pre-design task with too much accuracy.
3. Repeatability. Machines are able to repeat a task with a minimum or imperceptible error.
4. Senses. Machines are able to extent every kind of human sense, detecting change in a too much accurate way and in an larger interval than humans, for example for vision, listening, temperature sensing, force sensing, smelling (e.g. detecting a given substance), etc.
5. Sensibility. Machines are able to react to tinny changes in given parameters, such like a given sensing physical parameters (e.g. microseconds of arc of a given rotation).
6. Communication. Machines are able to communicate using too much power and several different transmission media as well as to amplified communication signals, all of these make possible the communication across huge distances and using huge speed for information (e.g. communication satellites).
7. Speed. Machines are able to perform most of the task that they are be able to do with faster speed than humans, this include data management, data analysis and computations.
8. Extreme environments. Machines are able, by design, to perform activities even in extremes environments that a human being is not able to live at all (e.g. Outer space, deeply in the see, near the elephant foot at Chernobyl, etc).
9. Continuous working. Machines are able to work with a duty cycle of 100%, this means that they, by a proper design, are able to work without stopping during large periods of time (actually limited only by their proper design or maintenance intervals).

Nevertheless the advantages of machinery compared to human beings, there are, of course a huge among of task and activities that machines are not able to do, at least nowadays. This task are those that make a human-being human, those about work with complex and changing data, creativity, human communications, etc.

In the last decades, considering such tasks where humans are better than machines and vice versa, the combination of both, human and machine qualifications have been proposed and investigated. The idea behind this is to be able to cooperate between humans and machines to apply each one (the human and the machine) his/her and its best characteristics in order to complete a given task in the most efficient way.

The final purpose of this section is to guide the selection of such task that a machine is more suitable to do and considering cooperative machines or collaborative ones.

3.1.2 Objectives

Aid seek and rescue of injured and trapped persons after and earthquake disaster (focused of those under the rubble) through a mechatronic system or mechatronic machine.

A second priority general objective is to aid rubble and debris removal and cleaning disaster areas.

3.2 Current system status

There is no system. Current system is just now an idea and a good purpose. System is formally started through the Thesis protocol [5] and starting to be defined in this document.

3.3 Stakeholders

“Stakeholders” is a concept within Systems Engineering and project management that referees to any person or entity (organization of any kind from social ones to formal associations) that are benefit or affected by a given project or system to be develop, even if they do not know about the existence of such system.

A preliminary stakeholders analysis is important in order to consider them in system development. Within the stakeholders there are those who require the development of the system or at least are direct beneficiaries of the existence of such system. In the opposite sense, there are people which the systems generate some among of damages, and so, they are potential detractors of the proposed system.

A list of the current envisioned stakeholders for the system which is required to be developed is as follow:

1. Earthquake victims. Every victim, related person or friend, rescuers and associations related to victims or rescuers are all strongly interested in safe as much as possible lives and as most as quickly as possible.

2. Earthquake victims - related people. In additions, related persons of victims could claim, on rescue time, to use the best available resources to rescue their people.

3. Rescuers. They have the experience and knowledge of what is required and what is better to improve their functions. Of course they are strongly interested in a system able to reduce effort and time to rescue people.

4. Earthquake victims related associations. Associations related to victims of earthquakes or rescuers will be interested in any mean that actually aid the rescue process.

5. Inhabitants of earthquake risk areas. People from risk areas are in different way interested to improve rescue means in case of disaster. In general this people support the any initiative to be better prepared in case of disasters.

6. Governments. Government is responsible to be prepared in case of disasters. It will be interested improving their response capability in case of disasters and it will be able to support system development. Government could be different entities with different levels, scopes and responsibilities, from town government, state government or the entire country government.

7. Mechatronics fans. Mechatronics fans and enthusiasts are interested in any development or idea about mechatronics, specially in those with a practical meaning and aimed to help people.

8. Humankind? In the general sense, every people of the world since certain age, will be interested in the application of science and technology to solve or aid people, specially in a disaster.

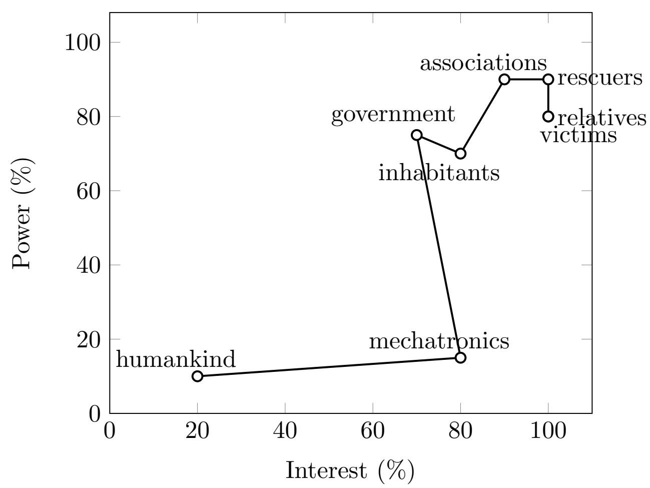
In Table 3, it is reviewed the main characteristics for the envisioned stakeholders.

A second stakeholder analysis is to classify them using a bi-dimensional graph where one axis is the interest on the system and other axis is the power to influence upon the system. In Figure 1 it is shown a graph of this kind according to data of Table 3.

Table 3: "Stakeholders" of the required mechatronic system to relief search and rescue of victims after an earthquake disaster. * Location scope considers than system is firstly developed and tested in Mexico.

Stakeholder	Interest	Power	Age	Location scope*
Victims	100	80	anyone	World-wide
Related	100	80	anyone	Mexico
Rescuers	100	90	18-75	World-wide
Associations	90	90	18-75	World-wide
Inhabitants	80	70	5-80	Mexico
Governments	70	75	25-70	Mexico
Mechatronics	80	15	10-75	World-wide
Humankind?	20	10	10-75	World-wide

Figure 1: Stakeholders analysis for a mechatronic system to relief search and rescue of victims after an earthquake disaster. Horizontal axis represents the interest and the vertical axis represents the power on the required system. These data is given as percentage, where 0% represents any power or interest while 100% represents the maximal interest or power on the sistem.



4 Concepts of the required system

This section is aimed to describe the general concepts for the required system. At the start of this document an idea of the required system was given. After that, information around this system was given as well as a brief background. This section is aimed to describe the required system in term of the users and do not from its developers.

In the next sections, the operation policies and constrains for the required systems, a description of it, its operational concepts, end users, support environment and operational concepts are given.

4.1 Operation policies and constrains

The machine shall be able to work in the specific conditions of an earthquake disaster including extreme irregular ground and polluted environment including extreme dirty and dusty air conditions, volatile gases atmosphere (like butane and other flammable gases, etc.); outdoors environment (e.g. precipitation, sun and its radiation, wind, night, temperature changes, different pressures, etc.);

Such development shall contain enough self energy, by means of an associated power source, to work several hours continuously. It shall be able to replace energy source as quickly as possible. For example, a battery based power source with charging period of several hours, even several minutes, is not acceptable, not useful at all.

The machine shall be able to be operated easily and by low training persons. It shall be secure for potential trapped victims as well as for operators and for surrounding people.

In additional the system to be develop should facilitate its transportation by having the lowest possible total weight and volume. As consequence machine deployment, installation, setup time and shutdown times shall be minimized. System failures (unrecovered errors) are unacceptable.

Machine advantages shall be much more remarkable versus its disadvantages.

Cost is not essentially a limitation, but the machine results will justify plenty its costs (design, fabrication and operation costs).

4.2 Description of the required system

A mechatronic machine able to help the search and finding of injured and trapped people after an earthquake disaster by a novel proposed machine concept using State of the Art mechatronics and machinery knowledge and those from associated fields.

The machine to be developed shall practically aid rescuers working at the disaster scene.This shall be done by performing at least one function much better than it is now carry out with conventional methods and gear.

The following functions are considered: debris cutting, debris removing, debris moving, scene mapping and exploring, underpinning, searching for victims, gear transportation and providing, etc.

At least one function shall be performed by the machine to be developed, and this function or functions shall justify the development of such machine.

4.2.1 Objective

As established in Sec. 3.1.2, the general objective is to aid the search and rescue of injured and trapped persons after and earthquake disaster (focused of those under the rubble) through a mechatronic system or mechatronic machine. A second priority general objective is to aid rubble and debris removal and cleaning disaster areas, this always one the first priority is met.

A more practical general objective is: **"To aid within one or more tasks within the finding and rescue process of victims under the debris; and do it with unquestionable advantages from current methods through a mechatronic system".**

4.2.2 Uses

Several different functions could be imagine for a machine aimed to meet the given objective, following it is described just the current envisioned ones.

1. Debris moving (from small to big ones)
2. Debris cutting
   (a) Iron cutting (including "I" beams)
   (b) Concrete columns and beams cutting (with rod up to number 12?).
3. Debris removing
4. scene mapping and exploring,
   (a) Entry robot
   (b) Recognizing dron
5. underpinning,
6. searching for victims,
7. gear transportation and gear providing

4.2.3 Limits and interfaces

There are few aspects that limit the required system: transportation and deployment, application power,

The first one is its transportation and deployment time at the scene, thus it shall have a weight and volume able to be transported or even included its own transportation means (ground transportation). Air transportation should be considered as well in the case of the system is not so big.

Required power limits the system reduction together with specific task to be performed. For example, if the system will be able to cut debris or move big pieces of it, it will required to apply great amount of power, thus the system could not be too compact.

About interfaces, the system will be as autonomous as possible, maybe with its power sources as an periphery of it, but as part of it. The system control shall be as easy and as intuitive as possible, the use of teleoperation, virtual control, haptic-based operation or direct guided operation shall be explored. Human-machine interface shall be able to allow functionality even with hard conditions as high noises (¿80 dB), dusty atmosphere, at night, under raining or under direct sunlight.

If required, the system shall allow to be easily adapted to other kind of support systems like cranes or firetrucks ladders, to be operated with conventional electrical power 220 V@60 Hz (2 phases from 120V@60 Hz), to be easily moved from one place to an other in the scene or in the damaged city.

As a rescue system it shall have proper signing and devices like siren emergency lighting and sound. The system shall meet proper and specific norms and regulations for its type. Specially to inform surrounding people that the system is being operating and avoid any damage, specially for people.

4.2.4 Relevance

The required system is as relevant as it will be able to help to rescue people and to rescue more people and faster. In order to be possible of such success the system will be feasible to be development including fabrication and test.

System relevance shall have special attention in order to require a useful system able to meet this ConOps.

4.3 Operational concepts

When an strong earthquake is presented and facilities are destroyed, disaster recovery procedures shall be immediately carry out. Especially by governmental rescue and first aid organizations and groups. Nevertheless, every people should know what to do in such events. About collapse buildings immediate attention to find and rescue victims is very important. So the machine to be develop shall be able to be moved to the scene of collapse quickly. Once at the scene, the machine shall be easily deployment, used, moved and reused. During a disaster even, usually tens or even hundreds of building are collapsed, so the machine once started to be used, will be used, moved, used, transported and reused many times, at least for about 120 hrs, maybe more, until it could be maintained and stored to be prepared for the next use.

During operations machine shall be able to be used by low trained people or even general people with fast on-site training.

4.4 End users classes and other involved persons

Users will be operators with perform tasks with the machine. It is envisioned to have trained operators and makeshift operators. It always be important that operators will have experience with related machinery.

4.5 Support environment

As the machine will operate in a disaster zone, support environment is variable, so the necessity than the system will be as autonomous as possible, specially for those external resources, not necessary about autonomous operations. So the system will be able to include self power energy, envisioned spares tools and materials and if designed so, it will require in some cases, supporting equipment to achieve high levels or inaccessible points. In any case, as autonomous will be the machine, the better it could be.

4.6 Operational concepts

In this last section, the minimal operational concepts are given for different procedures, including setup, shut down, calibration, diagnostic, maintenance, training and others.

4.6.1 Setup procedures

As quick and as easy as possible. Including transportation and deployment. Minimizing external energy sources in the case that this is not available.

4.6.2 Shut down procedures

As quick and as easy as possible. Minimizing energy consumption during no operational stage.

4.6.3 Calibration procedures

Machine calibration should be considered only if it is actually necessary. According to specific task of the machine, it is preferred that calibration will be made only during out-operations maintenance.

4.6.4 Diagnostic procedures

Machine will display in any moment the amoung of its critical resources with the special sense to notify operator when it will require new supplies. For example, monitoring of gas or oil reservoir to supply its power source.

4.6.5 Backup procedures

No backup is envisioned. If required by specific functions it shall be hidden to the operators in the idea to not distract them. In any case backup procedure shall affect machine performance in any sense.

4.6.6 Maintenance procedures

Preventive maintenance procedures shall be made during out-operations, out-disasters stages. Maintenance during machine operations shall be minimized.

4.6.7 Training procedures

Machine shall have a training manual for out-disasters training. Nevertheless its operation should be as easily as possible. Intuitive at least for those people with experience with similar machines or performing similar tasks.

4.6.8 Other procedures

No additional procedures are envisioned. If any is required by specific machine functions it shall be as easy as possible specially under operations. It shall be as well documented.

5 Conclusion

On this document, Concepts of Operations for a mechatronic machine able to help the search and finding of injured and trapped people after an earthquake disaster have been given. Really strict conditions shall be met for this machine. Do not met them made the machine unuseful and not valuable at all. So the importance to analyze and further discuss this ConOps and advance to achieve the machine user requirements. So it will be possible to generate an specific machine concept. It is recommended to follow at least one design methodology to generate a preliminary concept or idea of what kind of machine shall be developed. To do this, the collaboration of experienced rescuers on earthquake disasters will be essential.

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