



**Zagazig University, Faculty of Engineering,
Computer and Systems Engineering Dept.**

**ZagHexa
Design, Construction and Control
of a Hexapod Walking Robot**

B.Sc. Graduation Project
Submitted by

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to

All, Whom, we, and love.

The best in my life and after ...

Abstract

This report is a documentation of the final year graduation project in electrical engineering at zagazig university. The purpose of this project is to Design, Construction and Control of a six-legged walking robot that is capable of basic mobility tasks such as walking forward, backward, rotating in place and raising or lowering the body height.

The legs are of a modular design that have three degrees of freedom each. This robot will serve as a platform onto which additional sensory components could be added, or which could be programmed to perform increasingly complex tasks.

The components that make up our final design are discussed. Also, we describe the basic robot gaits of locomotion for efficient navigation. This locomotion is tuned to make the robot faster and at same time energy efficient to navigate and negotiate difficult terrain.

The robot is an integrated multi-legged walking robot based on de-facto standard Robotic Operating System (ROS) that employs novel and different walking patterns.

Our robot is teleoperated using hand-held devices such as a smart phone or tablet or a wireless joystick. Furthermore, it has its own navigation system and a camera for instant video recording and streaming.

The power to the entire system is supplied through two 5 volts NiMH batteries. There is an additional power bank to power up the Raspberry Pi and other electronic components. We have an interactive website for robot inspection and online control in addition to leaning materials such as robot building and implementation walkthroughs and as well as step-by-setup tutorials.

Keywords – biologically inspired, legged robot, gait generation, design procedure, simulation

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DOF	Degree of freedom
PWM	Pulse Width Modulation
I^2C	Inter-Integrated Circuit
Hexapod	six-leg walking robot
LTS	Long Term Support
LiPo	Lithium Polymer
RPM	Revolution Per Minute
RP	Raspberry Pi
GPIO	General-purpose input/output
ADC	Analog-Digital Converter
LPF	Low Path Filter
HPF	High Path Filter
FPS	Frame Per Seconds
GND	Ground

“There is nothing more difficult to take in hand, more perilous to conduct or more uncertain in its success than to take the lead in the introduction of a new order of things.”

— Niccolo Machiavelli, (Italian writer and statesman, Florentine patriot, author of 'The Prince', 1469-1527)

Chapter 1

Introduction

In today's technological society, people have grown accustomed to daily use of several kinds of technology from personal computers to supercomputers, from personal vehicles to commercial airplanes, from mobile phones to communicating through the Internet and everything in between. Robotics technology has been a hot topic recent years. As such, the use of robots has become increasingly common. As robots can be used to complete repeated tasks, increase manufacturing production, carry extra weight and many other common tasks that humans do. Therefore, robots can be found everywhere. So far, all mobile robots used in extraterrestrial surface exploration missions were wheel-driven systems. However, even if such a system is equipped with a suspension system, the capability to surmount obstacles and to conquer steep inclinations is limited. Also driving on fine-grained soil can become a problem for these kind of systems. Multi-legged walking systems, in contrast, are equipped with a highly flexible locomotor system. Along with appropriate control strategies it should offer them the capability to securely maneuver in rough and steep environments. Major counter arguments for legged systems are the higher complexity regarding the mechanical design and control as well as the comparatively high power consumption. Thus, the challenge lies in minimizing these drawbacks and in exploiting the potentialities of such systems. One of the most important part of a robot is its chassis. There are several basic chassis types: wheeled, tracked and legged chassis. Wheeled chassis are fast, but not suitable for rough terrain. Tracked chassis are slower, but more suitable to rugged terrain. Legged chassis are quite slow and more difficult to control, but extremely robust in rough terrain. Legged chassis are capable to cross-large holes and can operate even after losing a leg [Saranli, 2002]. Extensive research is conducted in this field because of its large potential. Legged chassis are especially ideal for space missions [terrain hex-limbed extra-terrestrial explorer, , Tedeschi and Carbone, 2014] . There are also several projects in military research [Dynamics, 2015b, Dynamics, 2015a].

One of the interesting features of hexapod robots such as our ZagHexa (shown in Fig.Figure 1.1) is that they can climb over obstacles larger than the equivalent sized

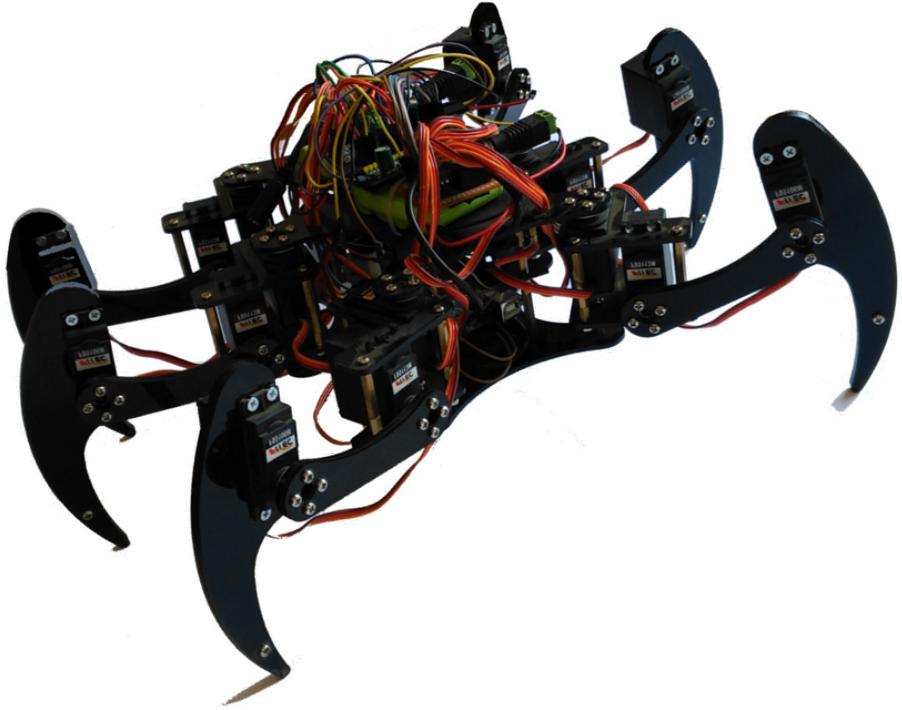


Figure 1.1.: A sex-legged walking robot.

wheeled or trucked vehicle. In fact, the use of wheels or crawlers limits the size of the obstacle that can be climbed to half the diameter of the wheels. On the contrary, legged robots can overcome obstacles that are comparable with the size of the machine leg[terrain hex-limbed extra-terrestrial explorer,]. Hexapod walking robots also benefit from a lower impact on the terrain and have greater mobility in natural surroundings. This is especially important in dangerous environments like mine fields, or where it is essential to keep the terrain largely undisturbed for scientific reasons [Tedeschi and Carbone, 2014].

Hexapod legged robots have been used in exploration of remote locations and hostile environments such as seabed [Dynamics, 2015b], in space or on planets [Dynamics, 2015a, Moore and Buehler, 2001] in nuclear power stations [Ding et al., 2010], and in search and rescue operations[Manoiu-Olaru et al., 2011]. Beyond this type of application, hexapod walking vehicles can also be used in a wide variety of tasks such as forests harvesting, in aid to humans in the transport of cargo, as service robots and entertainment. Development of hexapods is increasingly robust in the military sector. Armies all over the world are exploring ways of using hexapods to detect land mines, traverse rocky, unstable terrain, and carry out simple delivery missions in danger zones.

2 Introduction

1.1. History

Robots inspired by insects and other animals have previously been designed with physical antennae and tactile sensors to navigate their environment, as in the work by Brooks (1989) [?, ?], Cowan et al. (2005), Hartmann (2001) [?] and Lee et al. (2008) [Digia, 2017]; the last three works employed the use of a single tactile element rather than a pair [MohdDaud and KenzoNonami, 2012]. Because of their extreme mobility and agile adaptability to irregular terrain, insects have long been an inspiration for the designers of mobile and legged robots [Lewinger and Quinn, 2010, Lewinger and MartinReekie, 2011]. Early hexapod robots such as Genghis and later creations such as Tarry implemented insect-like mobility based on observations of insect behaviors. The inter-leg coordination system developed by Holk Cruse [?, ?] has been widely implemented in legged hexapods and its basis is in behavioral experiments that qualitatively analyzed insect walking behaviors [Dürr et al., 2004].

1.1.1. Early Designs

The first hexapods can be identified as robots based on a rigidly predetermined motion so that an adaptation to the ground was not possible. Early researches in the 1950s were focused on assigning the motion control completely by a human operator manually [Schneider and Schmucker, 2006].

One of the first successful hexapod robot was constructed at University of Rome in 1972 (Fig.Figure 1.2a) as a computer-controlled walking machine with electric drives [Paternella and Salinari, 1973]. In the middle 70s, at the Russian Academy of Sciences in Moscow, a six-legged walking machine was developed with a mathematical model of motion control. It was equipped with a laser scanning range finder and was connected with a two-computer control system [Okhotsimski and Platonov, 1973]. In 1976, Masha hexapod walking robot was designed at Moscow State University (Fig.Figure 1.2b). The robot had a tubular axial chassis, articulated legs with three DoFs [Gurfinkel et al.,]. The hexapod was able to negotiate obstacles using contact on the feet and a proximity sensor. Ohio State University in 1977 developed a six-legged insect-like robot system called “OSU Hexapod” [McGhee, 1977]. This hexapod was kept tethered and was made to walk short distances over obstacles (Fig.Figure 1.2c). In 1984, Odetic Inc., California, USA, developed Odex I [Byrd and de Vries, 1990], a six-legged radially symmetric hexapod robot which used an onboard computer to play back pre-programmed motions (Fig.Figure 1.2d).

1.1.2. Recent Developments

The two last decades have been characterized by a rapid development of control systems technology. Hexapod robots were equipped with various sensing systems. Artificial

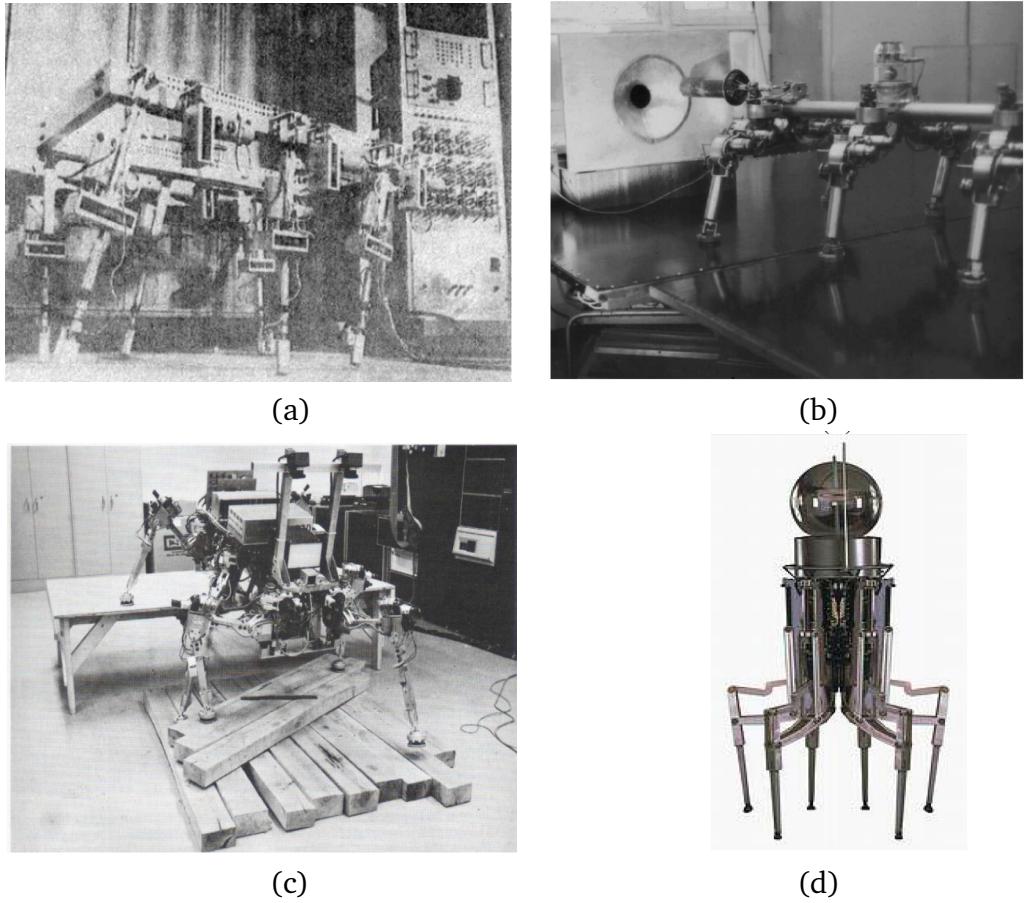


Figure 1.2.: Early hexapod design: (a) University of Rome’s hexapod; (b) MASHA hexapod; (c) OSU hexapod; (d) ODEX I hexapod.

Intelligence systems were widely applied to the analysis of environment and motion of robots on a complex surface. A series of bio inspired robots was developed at Case Western Reserve University (USA) at the end the 90s, such as, for example, Robot III that had a total of 24 DoFs. Robot III architecture was based on the structure of cockroach, trying to imitate their behavior [?]. In particular, each rear leg had three DoFs, each middle leg four DoFs and each front leg five DoFs. Similarly, Biobot was a biomimetic robot physically modeled as the American cockroach (*Periplaneta Americana*) and powered by pressurized air [?]. This hexapod had a great speed and agility.

Each leg of the robot had three segments, corresponding to the three main segments of insect legs: coxa, femur, and tibia.

4 Introduction

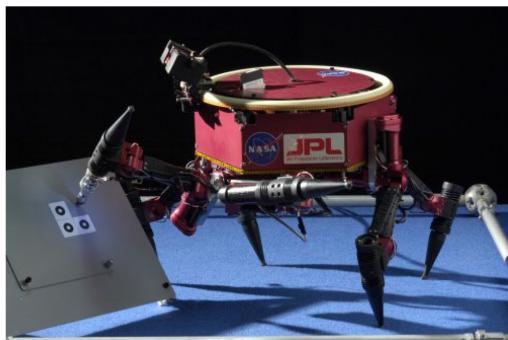
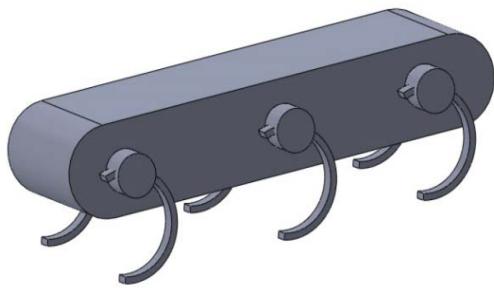


Figure 1.3.: Some Example on recent developments in hexapod design

“It is impossible for us, who live in the latter ages of the world, to make observations in criticism, morality, or in any art or science, which have not been touched upon by others. We have little else left us but to represent the common sense of mankind in more strong, more beautiful, or more uncommon lights.”

— Joseph Addison, (English essayist, poet, and politician, 1672–1719), *Spectator*, No. 253

Chapter 2

Design Considerations

Designing hexapod legged robots is far from trivial. A very numerous and a wide range of possibilities exist to design a hexapod as also described in the previous section. Designers must take several decisions which influence the operation and technical features. Some of the most important design issues and constraints according to [?] can be outlined as:

- The mechanical structure of robot body.
- Leg architecture.
- Max sizes.
- Actuators and drive mechanisms.
- Control architecture.
- Power supply.
- Walking gaits and speed.
- Obstacle avoidance capability.
- Payload.
- Autonomy.
- Operation features.
- Cost.

The above mentioned design issues and constraints can be classified as design input (or key features) and design output (or main design characteristics) as shown in the scheme of Fig. Figure 2.1.

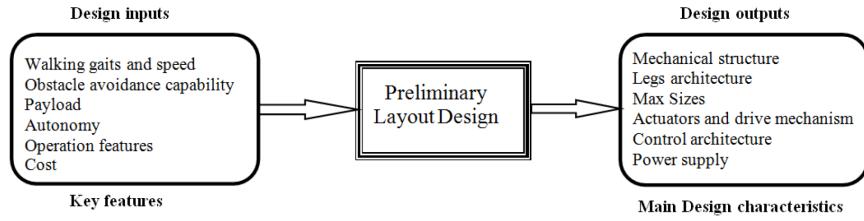


Figure 2.1.: A scheme for preliminary layout design of hexapod walking robots.

2.1. Hardware

ZagHexa is a hexapod robot with 18 DOFs (three degrees of freedom (DOF) for each leg), it can walk in any direction (translation), or turn in place (rotation), or any combination of the two. The leg lift and ride height is adjustable as well. The robot uses a distributed walking control system based on the neurobiology of insects, stepping in the sagittal plane to angled stepping, which then induces turning in the robot. It is an integrated multi-legged walking robot based on de-facto standard Robotic Operating System (ROS) that employs novel and different walking patterns. Our robot is teleoperated using hand-held devices such as a smart phone or tablet or a wireless joystick (see Fig. Figure 2.2). Furthermore, it has its own navigation system and a camera for instant video recording and streaming. The power to the entire system is supplied through two 5 volts NiMH batteries. There is an additional power bank to power up the Raspberry Pi and other electronic components. We have an interactive website for robot inspection and online control in addition to leaning materials such as robot building and implementation walkthroughs and as well as step-by-setup tutorials.

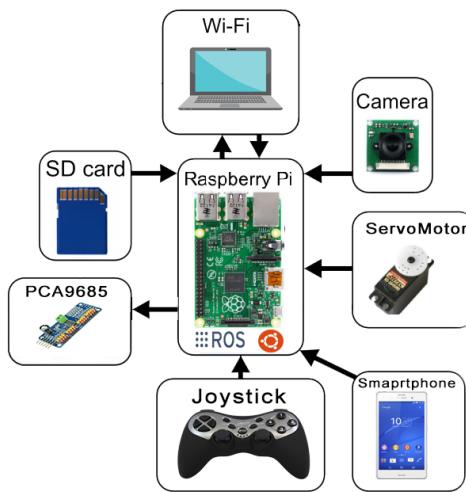


Figure 2.2.: The electronic system of the robot.

8 Design Considerations

2.1.1. Components needed

Metal sheet Aluminum structure
Raspberry Pi 3 Model B
Arduino Mega
Metal Gear Servo motor standard size (13 kg.cm)
Metal Gear Servo motor standard size (7.5 kg.cm)
Metal Servo gear hub
NiMH rechargeable battery (5V -1500 mAh)
Copper Spacers
Plastic Spacers
Screws and nuts
Jumper wires
Power Bank 8000 mAh
android smart phone.

2.2. Hardware and Software Architecture

The final design of the ZagHexa robot constructed mainly with acrylic is shown in Fig.Figure 1.1. ZagHexa body moves independently of its ground contact points. To make its center of gravity shift on a horizontal plane, forward/backward, and sideways moving functions are effective. These functions can also produce a smooth body movement independently of intermittent leg traveling. The robot has been designed with three degrees of freedom in the front, middle and rear legs respectively. The physical specifications are given in Table 2.

Parameter	Description
Length	30cm
Width	27cm
Height	17cm
Weight	3Kg
Construction Material	
Actuators	DC servo motors
Motion Control	Servo Sequential Control
Leg Stroke (Max)	6cm
Leg Lift (Max)	5cm

2.2.1. Hardware Architecture

As illustrated in Fig.Figure 2.2, ZagHexa is equipped with all necessary resources to interact with the environment. The system is supplied with an embedded computing

system, which is Raspberry Pi 3 Model B running Ubuntu Xilinx. Raspberry Pi is a miniature computer the size of a credit card, to which a standard monitor, a keyboard and a mouse can be connected. It has extremely low power consumption (max. 3.5 W) and can run ROS based on Ubuntu operating system. There are several models, which differ in RAM, the number of USB ports or GPIO pins and the connection methods. Raspberry Pi is equipped with a USB Wi-Fi dongle, which is connected to a wireless network, and runs Qt [11] client program, that connects to the server and communicate with it. Sensor data are sent to a computer after successful connection. Client is also capable of automatically reconnect in case of connection disruption. To sense the environment and deal with it, different modalities of sensors are imported from an attached smart hand-held device. As ZagHexa can use all the sensors from any mobile phone thanks to its own android subsystem that communicate these information with the smart phone over Wi-Fi or Bluetooth.

2.2.2. Joint Actuators

The leg joints are actuated by metal gear servos: FS5113M on coxa, femur and FS5106M on tibia joints. These motors were chosen for their high torque. Each of the three joint actuators per leg directly drives its associated leg segment. By attaching the leg segment directly to the servo output horns, the mechanical design of the joints is simplified. This direct connection also allows the joints to take advantage of the nominal $\pm 90\text{deg}$ range-of motion (RoM) of the servos, which is approximately the same RoM as the insect [KanYoneda, 2007].

It is important for the leg control system to know current joint angles (servo position) and joint loads (current consumption). As this information is not available from standard servos, the motors were modified. The servo internal PCB, which is responsible for receiving PWM position commands from a host and converting those commands into servo output positions. All servomotors are connected and driven by the PCA9685 controller. This controller receives the desired walking pattern from the Raspberry through I2C pins controlling the leg lift-swing-shift sequence.

2.3. Software

The high-level functionality and control of the robot are implemented in ROS packages. The Robot Operating System (ROS) is a standard and open-source operating system for robot control [Cousins, 2011]. ROS is not an operating system in the traditional sense of process management and scheduling; rather, it provides a structured communication layer above the host operating systems of a heterogeneous compute cluster. Our software ROS packages interact with each of the subsystems in C++ and Python for

direct system control. The system described uses a Linux based software framework as an operating system (OS) for providing the advantages of using an OS, which supports developing additional modules that can be easily implemented and integrated.

ROS provides operating system like service for the robot. It is a meta-operating system, which loads on top of an operating system to provide a standardized set of software framework and APIs. These facilities cannot only help robots but also other embedded systems with a rich set of tools to successfully manage the complexity. With ROS handling the basic communications and data exchange.

Chapter 3

Simulation

Programming directly on a real robot gives us good feedback and it is more impressive than simulations, but not everybody has possible access to real robots. For this reason, we have programs that simulate the physical world.

The first phase of robot manufacturing is its design and modeling. We can design and model the robot using CAD tools such as Solid Works, Blender, and so on. One of the main purposes of modeling robot is simulation. The robotic simulation tool can check the critical flaws in the robot design and can confirm the working of the robot before it goes to the manufacturing phase.

The virtual robot model must have all the characteristics of real hardware, the shape of robot may or may not look like the actual robot but it must be an abstract, which has all the physical characteristics of the actual robot.

If we are planning to create the 3D model of the robot and simulate using ROS, you need to learn about some ROS packages which helps in robot designing. ROS has a standard meta package for designing, and creating robot models called robot model, which consists of a set of packages called urdf, robot state publisher and so on. These packages help us create the 3D robot model description with the exact characteristics of the real hardware.

In this chapter, we will cover the following topics:

1. ROS packages for robot modeling
2. Understanding robot modeling using URDF
3. Creating our URDF model
4. Watching the 3d model in RVIZ
5. Making our robot movable

3.1. ROS packages for robot modeling

The way ROS uses the 3D model of a robot or its parts, to simulate them. ROS provides some good packages that can be used to build 3D robot models.

In this section, we will discuss some of the important ROS packages that are commonly used to build robot models:

robot model: ROS has a meta package called robot model, which contains important packages that help build the 3D robot models. We can see all the important packages inside this meta- package:

URDF: One of the important packages inside the robot model meta package is urdf. The URDF package contains a C++ parser for the Unified Robot Description Format (URDF), which is an XML file to represent a robot model.

We can define a robot model, sensors, and a working environment using URDF and can parse it using URDF parsers.

We can only describe a robot in URDF that has a tree-like structure in its links, that is, the robot will have rigid links and will be connected using joints. Flexible links can't be represented using URDF.

The URDF is composed using special XML tags and we can parse these XML tags using parser programs for further processing. We can work on URDF modeling in the upcoming sections.

joint state publisher: This tool is very useful while designing robot models using URDF.

This package contains a node called joint state publisher, which reads the robot model description, finds all joints, and publishes joint values to all non fixed joints using GUI sliders.

The user can interact with each robot joint using this tool and can visualize using RViz. While designing URDF, the user can verify the rotation and translation of each joint using this tool.

kdl parser: Kinematic and Dynamics Library (KDL) is an ROS package that contains parser tools to build a KDL tree from the URDF representation. The kinematic tree can be used to publish the joint states and also to forward and inverse kinematics of the robot.

robot state publisher: This package reads the current robot joint states and publishes the 3D poses of each robot link using the kinematics tree build from the URDF. The 3D pose of the robot is published as ROS tf (transform). ROS tf publishes the relationship between coordinates frames of a robot.

xacro: Xacro stands for (XML Macros) and we can define how xacro is equal to URDF plus add-ons. It contains some add-ons to make URDF shorter, readable, and can be used for building complex robot descriptions. We can convert xacro to URDF at any time using some ROS tools. We will see more about xacro and its usage in the upcoming sections.

3.2. Understanding robot modeling using URDF

We have discussed the urdf package. In this section, we will look further at the URDF XML tags, which help to model the robot. We have to create a file and write the relationship between each link and joint in the robot and save the file with the .urdf extension.

The URDF can represent the kinematic and dynamic description of the robot, visual representation of the robot, and the collision model of the robot.

The following tags are the commonly used URDF tags to compose a URDF robot model:

link: The link tag represents a single link of a robot. Using this tag, we can model a robot link and its properties. The modeling includes size, shape, color, and can even import a 3D mesh to represent the robot link. We can also provide dynamic properties of the link such as inertial matrix and collision properties.

The syntax is as follows:

```
<link name="<name of the link>">
  <inertial>.....</inertial>
  <visual> .....</visual>
  <collision>.....</collision>
</link>
```

The following is a representation of a single link. The Visual section represents the real link of the robot, and the area surrounding the real link is the Collision section. The Collision section encapsulates the real link to detect collision before hitting the real link.

joint: The joint tag represents a robot joint. We can specify the kinematics and dynamics of the joint and also set the limits of the joint movement and its velocity. The joint tag supports the different types of joints such as revolute, continuous, prismatic,fixed, floating, and planar.

The syntax is as follows:

```
<joint name="<name of the joint>">
  <parent link="link1"/>
  <child link="link2"/>
  <calibration .... />
  <dynamics damping .... />
```

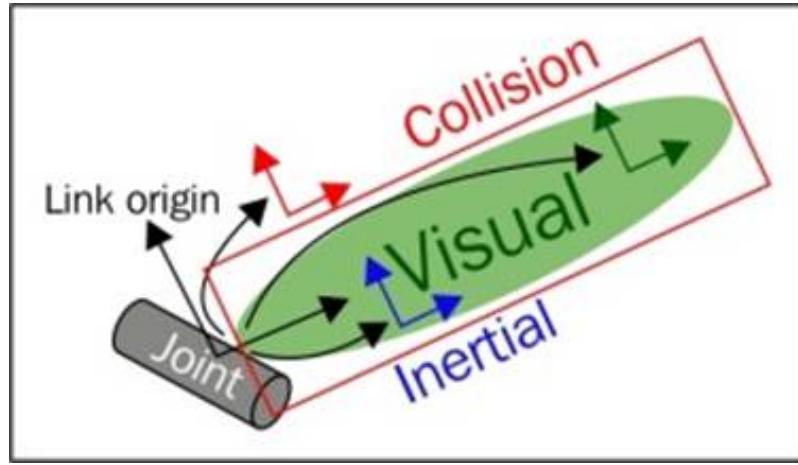


Figure 3.1.: Visualization of a URDF link

```
<limit effort .... />
</joint>
```

A URDF joint is formed between two links; the first is called the Parent link and the second is the Child link. The following is an illustration of a joint and its link:
robot: This tag encapsulates the entire robot model that can be represented using

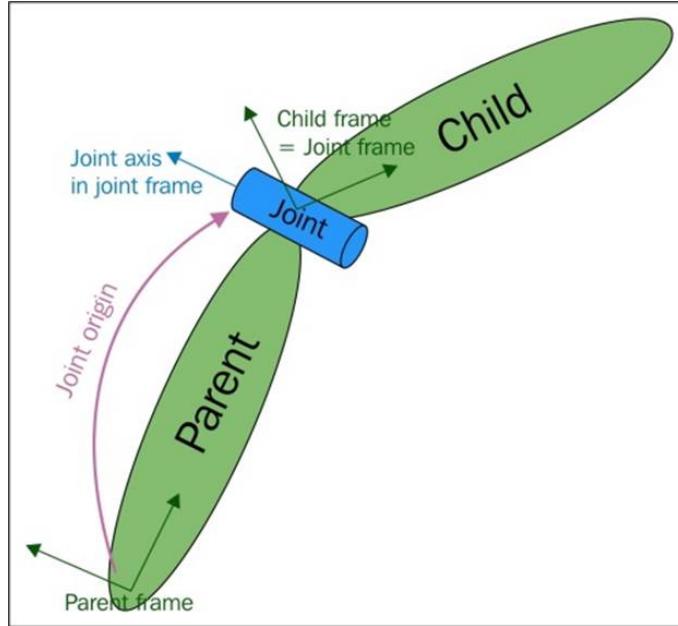


Figure 3.2.: Visualization of a URDF joint

URDF. Inside the robot tag, we can define the name of the robot, the links, and the joints of the robot. The syntax is as follows:

```

<robot name="<name of the robot>">
  <link> ..... </link>
  <link> ..... </link>
  <joint> ..... </joint>
  <joint> ..... </joint>
</robot>

```

A robot model consists of connected links and joints. Here is a visualization of the robot model:

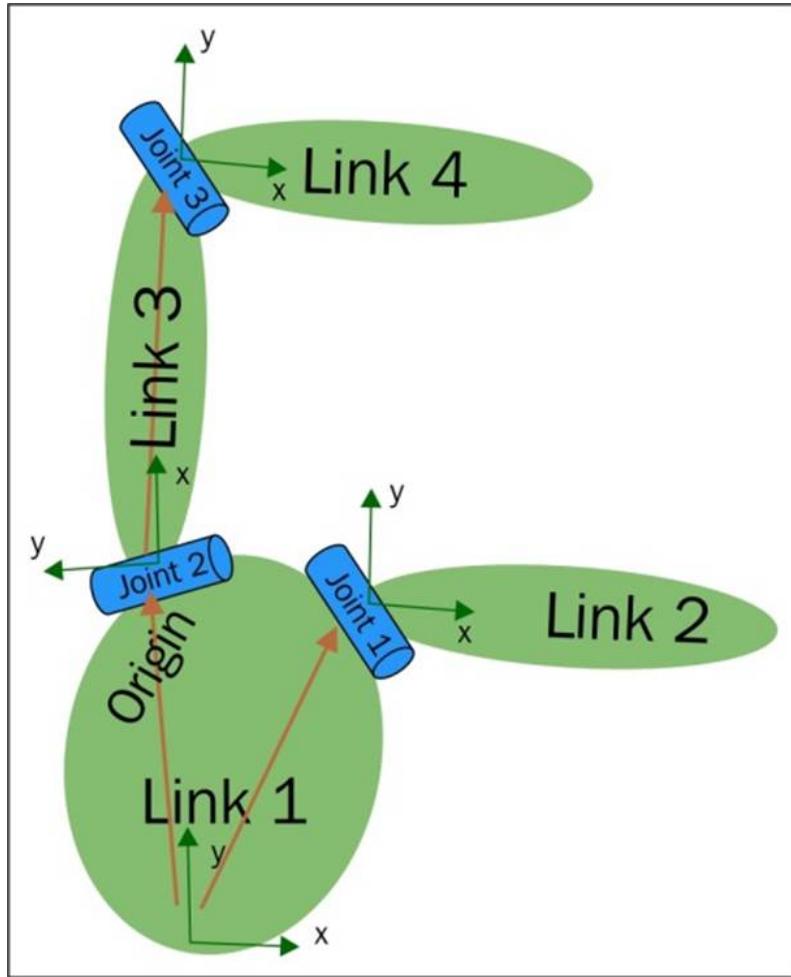


Figure 3.3.: Visualization of a robot model having joints and links

3.3. Creating our URDF model

To start first we create the urdf file, let's call it *zaghexasim.urdf* and put in the following code; this URDF code is based on XML. As you will see in the code, there are two

principal fields that describe the geometry of a robot: links and joints.
the first link has the name base link; this name must be unique to the file

```
<?xml version="1.0" ?>
<robot name="zaghexa" xmlns:xacro="http://ros.org/wiki/xacro">
  <!-- Build the body frame -->
  <link name="base_link"/>
  <joint name="base_joint" type="fixed">
    <parent link="base_link"/>
    <child link="box"/>
    <origin rpy="0 0 0" xyz="0 0 0"/>
  </joint>
  <link name="box">
    <visual>
      <origin rpy="0 0 0" xyz="0 0 0"/>
      <geometry>
        <mesh filename="package://zaghexa_sim/meshes/box.STL"/>
      </geometry>
      <material name="grey">
        <color rgba="0.5 0.5 0.5 1"/>
      </material>
    </visual>
  </link>
```

In the joint field we define the name which must be unique as well also we define the type of joint(fixed,revolute,continous,floating or planar) the parent, and the child. in our case tibia,femur and leg centre joint are the children of base link which is fixed but all of other joints are revolute.

this is a sample of one leg and how does it build

```
<!-- Joint properties -->
<!-- Leg macros -->
<!-- Build robot model -->
<joint name="leg_center_joint_r1" type="fixed">
  <origin rpy="0 0 0" xyz="0.087598 -0.050575 0"/>
  <parent link="box"/>
  <child link="leg_center_r1"/>
</joint>
<link name="leg_center_r1"/>
<joint name="coxa_joint_r1" type="revolute">
  <origin rpy="0 0 -1.0471975512" xyz="0 0 0"/>
  <parent link="leg_center_r1"/>
  <child link="coxa_r1"/>
```

```

<axis xyz="0 0 -1"/>
<limit effort="10000" lower="-1.5" upper="1.5" velocity="100"/>
</joint>
<link name="coxa_r1">
<visual>
<origin rpy="0 0 0" xyz="0 0 0"/>
<geometry>
<mesh filename="package://zaghexa_sim/meshes/coxa_r.STL"/>
</geometry>
<material name="">
<color rgba="0.7 0.7 0 1"/>
</material>
</visual>
</link>
<joint name="femur_joint_r1" type="revolute">
<origin rpy="-1.57079632679 0 0" xyz="0.0294 0 0"/>
<parent link="coxa_r1"/>
<child link="zaghexa"/>
<axis xyz="0 0 -1"/>
<limit effort="10000" lower="-1.5" upper="1.5" velocity="100"/>
</joint>
<link name="zaghexa">
<visual>
<origin rpy="0 0 0" xyz="0 0 0"/>
<geometry>
<mesh filename="package://zaghexa_sim/meshes/femur_r.STL"/>
</geometry>
<material name="">
<color rgba="0 0.7 0.7 1"/>
</material>
</visual>
</link>
<joint name="tibia_joint_r1" type="revolute">
<origin rpy="3.14159265359 0 1.57079632679" xyz="0.08 0 0"/>
<parent link="zaghexa"/>
<child link="tibia_r1"/>
<axis xyz="0 0 1"/>
<limit effort="10000" lower="-1.5" upper="1.5" velocity="100"/>
</joint>
<link name="tibia_r1">

```

You can check the syntax of the urdf whether we have errors, we can use: **check urdf command tool**:

```
$ rosrun urdf_parser check_urdf zaghexa_sim.urdf
```

If you want to see it graphically, you can use the urdf to graphiz command tool

```
$ rosrun urdf_parser urdf_to_graphviz "rospack find zagheda_sim"/urdf/zagheda_sim.urdf"
```

The following is what you will receive as output:

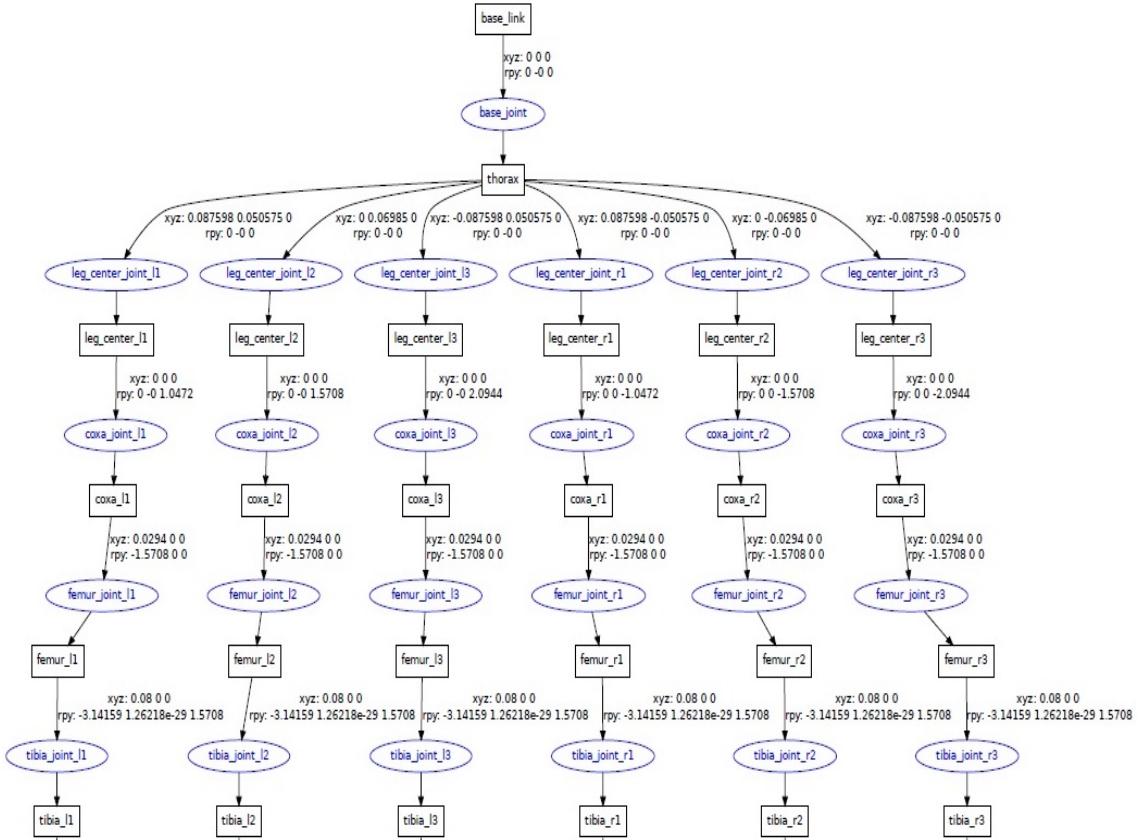


Figure 3.4.: output of urdf to graphics

3.4. Watching the 3D model in RVIZ

Now that we have the model of our robot, we can use it on rviz to watch it in 3D and see the movements of the joints.

We will create the display.launch file in zagheda-sim/launch folder, and put the following code in it:

```
<launch>
```

```

<arg
  name="model" />
<arg
  name="gui"
  default="True" />
<param
  name="robot_description"
  command="$(find xacro)/xacro.py '$(find zagheda_sim)/models/
    zagheda_model.xacro'" />
<param
  name="use_gui"
  value="$(arg gui)" />
<param
  name="rate"
  value="25" />
<rosparam param="source_list">
[leg_joints_states]
</rosparam>
<node
  name="joint_state_publisher"
  pkg="joint_state_publisher"
  type="joint_state_publisher" />
<node
  name="robot_state_publisher"
  pkg="robot_state_publisher"
  type="state_publisher" />
<node
  name="rviz"
  pkg="rviz"
  type="rviz"
  args="-d $(find zagheda_sim)/urdf.rviz" />
</launch>

```

We will launch it with the following command:

```
$ roslaunch zagheda_sim display_model.launch model:='`rospack find
zagheda_sim`/urdf/zagheda_sim.urdf'
```

if every thing is fine and you have no errors, it will load RVIZ and you will see:

3.5. Making our robot movable

A good way of testing whether or not the axis and limits of the joints are fine by running rviz with joint state publisher GUI

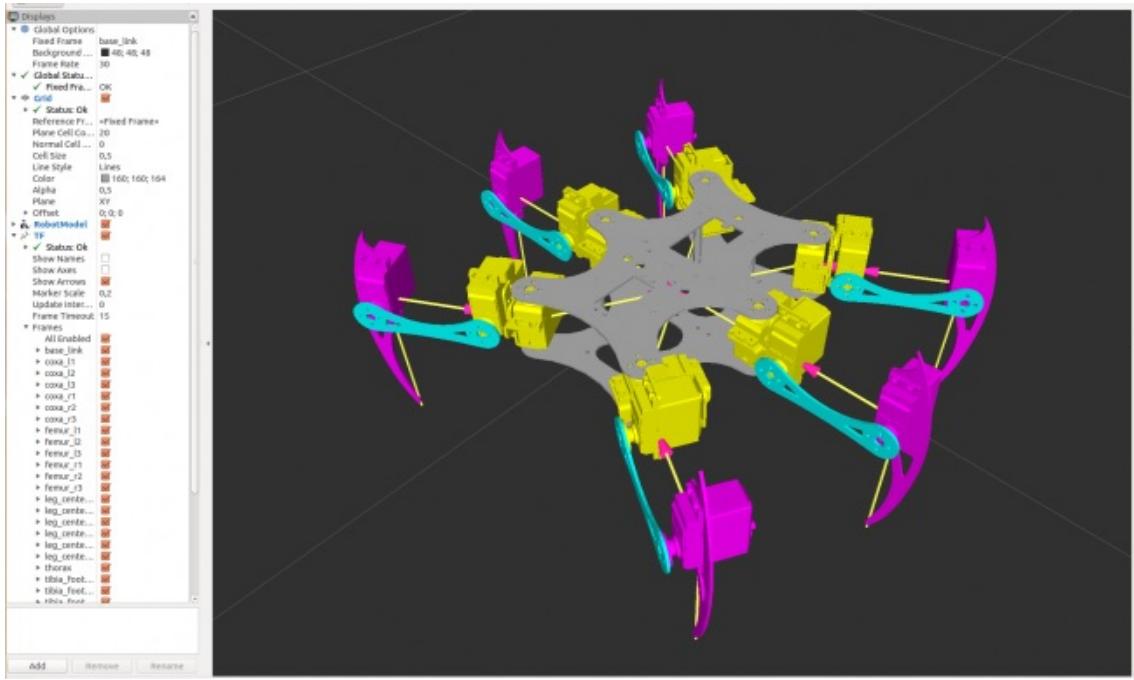


Figure 3.5.: output of urdf to graphics

```
$ roslaunch zagheda_sim display.launch model:='`rospack find
zagheda_sim`/urdf/zagheda_sim.urdf' gui:=true
```

you will see a GUI with some sliders each of them controls one joint of the 18 joints so we have 18 sliders:

In the next figures you will see the effect of changing sliders values to the joints angles and positions

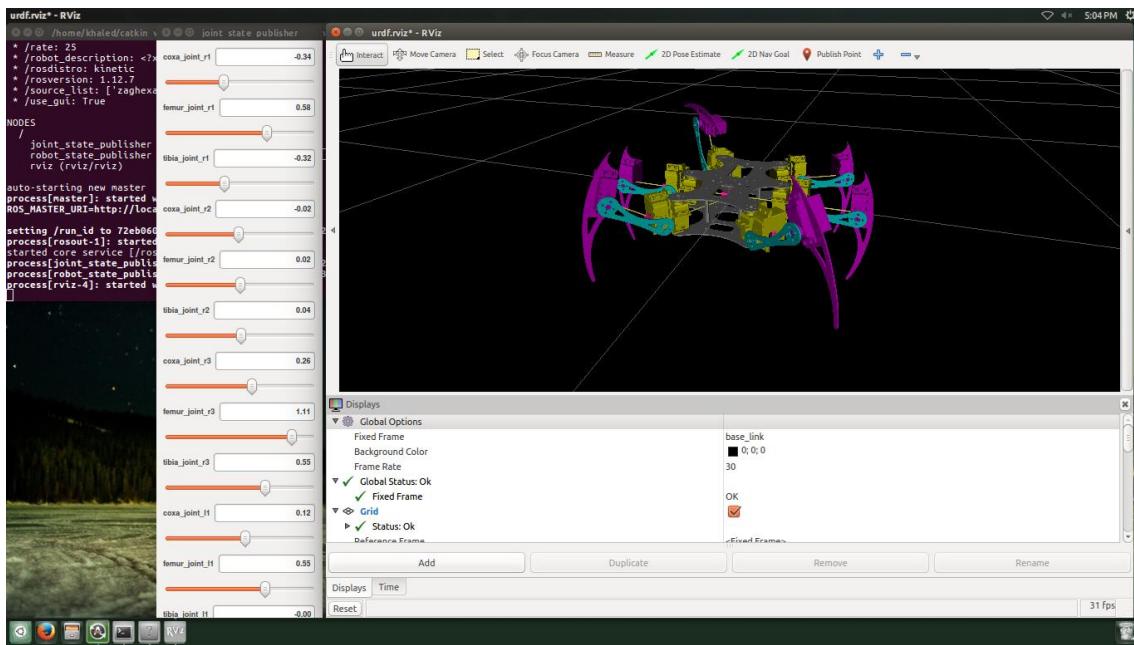


Figure 3.6.: Joint state publisher GUI with its control sliders and their effect on the robot

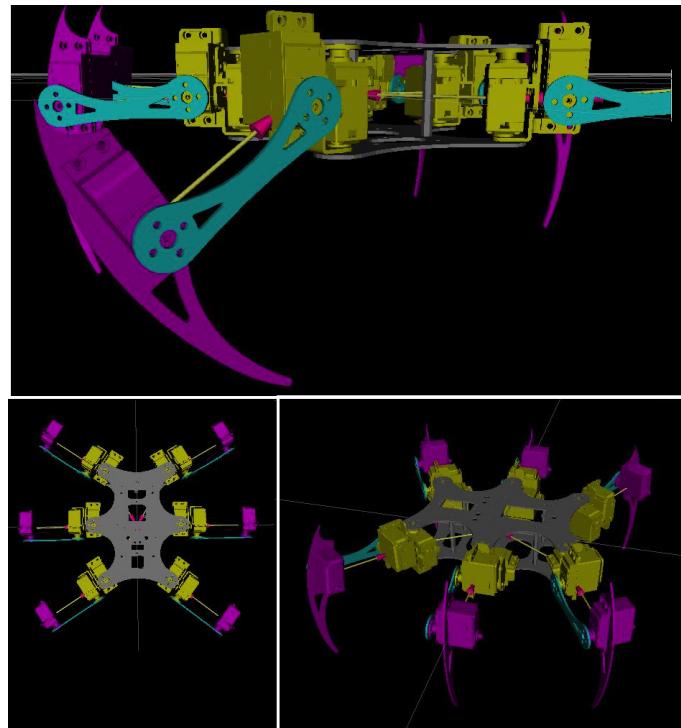


Figure 3.7.: Different views of the robot

Chapter 4

Software Architecture

The high-level functionality and control of the robot are implemented in ROS packages. The Robot Operating System (ROS) is a standard and open-source operating system for robot control [Cousins, 2011]. ROS is not an operating system in the traditional sense of process management and scheduling; rather, it provides a structured communication layer above the host operating systems of a heterogeneous compute cluster. Our software ROS packages interact with each of the subsystems in C++ and Python for direct system control. The system described uses a Linux based software framework as an operating system (OS) for providing the advantages of using an OS, which supports developing additional modules that can be easily implemented and integrated.

4.1. Robot Operating System (ROS)

Robot Operating System (ROS) provides operating system like service for the robot. It is a meta-operating system, which loads on top of an operating system, including hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. It also provides tools and libraries for obtaining, building, writing, and running code across multiple computers. These facilities cannot only help robots but also other embedded systems with a rich set of tools to successfully manage the complexity. With ROS handling the basic communications and data exchange.

ROS currently only runs on Unix-based platforms. Software for ROS is primarily tested on Ubuntu and Mac OS X systems, though the ROS community has been contributing support for Fedora, Gentoo, Arch Linux and other Linux platforms. While a port to Microsoft Windows for ROS is possible, it has not yet been fully explored.

The core ROS system, along with useful tools and libraries are regularly released as a ROS Distribution. This distribution is similar to a Linux distribution and provides a set

of compatible software for others to use and build upon example for this distribution: Hydro, Indigo, Jade, Kinetic, Lunar...etc. [<http://wiki.ros.org>]

Our choice was Kinetic because is the update distribution that have a LTS with high variety of support from ROS community that make it easy to exchange the knowledge and figure out how to solve issues and to come up with new idea to implement it.

4.1.1. Why ROS?

The answer for this question lies in power of ROS the make it preferable for most of the designers:

Inter-platform operability : ROS message-passing means that you can work between very different components and subsystems that are probably running with different languages (maybe something like low-level hardware control with C for speed, and high-level state machines with Java or Python for ease of coding). This also gets around the problem of the mess of APIs you would have had to deal with before.

Modularity : Since things are connected by a distributed message system, if one component crashes, your whole system doesn't crash. Granted, there are plenty of ways to make your system more robust so that this doesn't happen in the first place, but ROS makes it easier for your robot to continue doing its thing even if two sensors and an arm motor have died (for example).

Concurrent resource handling : Without ROS, reading/writing to resources quickly becomes a mess with large multi-threaded systems (i.e. virtually any robotics application). Again, there are ways to deal with this, but ROS simplifies the whole process by ensuring that your threads aren't actually trying to read and write to shared resources, but are rather just publishing and subscribing to messages.

Vibrant Community : Over the past several years, ROS has grown to include a large community of users worldwide. Historically, the majority of the users were in research labs, but increasingly we are seeing adoption in the commercial sector, particularly in industrial and service robotics.

Collaborative Environment : ROS by itself offers a lot of value to most robotics projects, but it also presents an opportunity to network and collaborate with the world class roboticists that are part of the ROS community. One of the core philosophies in ROS is shared development of common components.

Interested reader can find more information,material, and much more at: www.ros.org/core-components

4.1.2. ROS Package

Software in ROS is organized in packages. A package might contain ROS nodes, a ROS-independent library, a dataset, configuration files, a third-party piece of software, or anything else that logically constitutes a useful module. The goal of these packages is to provide this useful functionality in an easy-to-consume manner so that software can be easily reused. In general, ROS packages follow a "Goldilocks" principle: enough functionality to be useful, but not too much that the package is heavyweight and difficult to use from other software.

Packages are easy to create by hand or with tools like `catkin_create_pkg`. A ROS package is simply a directory descended from `ROS_PACKAGE_PATH` (see ROS Environment Variables) that has a `package.xml` file in it. Packages are the most atomic unit of build and the unit of release. This means that a package is the smallest individual thing you can build in ROS and it is the way software is bundled for release (meaning, for example, there is one debian package for each ROS package), respectively.

4.1.3. ROS Node

A node is a process that performs computation. Nodes are combined together into a graph and communicate with one another using streaming topics, RPC services, and the Parameter Server. These nodes are meant to operate at a fine-grained scale; a robot control system will usually comprise many nodes. For example, one node controls a laser range-finder, one Node controls the robot's wheel motors, one node performs localization, one node performs path planning, one node provides a graphical view of the system, and so on.

The use of nodes in ROS provides several benefits to the overall system. There is additional fault tolerance as crashes are isolated to individual nodes. Code complexity is reduced in comparison to monolithic systems. Implementation details are also well hidden as the nodes expose a minimal API to the rest of the graph and alternate implementations, even in other programming languages, can easily be substituted.

All running nodes have a graph resource name that uniquely identifies them to the rest of the system. For example, `/hokuyo_node` could be the name of a Hokuyo driver broadcasting laser scans. Nodes also have a node type, that simplifies the process of referring to a node executable on the filesystem. These node types are package resource names with the name of the node's package and the name of the node executable file. In order to resolve a node type, ROS searches for all executables in the package with the specified name and chooses the first that it finds. As such, you need to be careful and not produce different executables with the same name in the same package. Finally, a ROS node is written with the use of a ROS client library, such as `roscpp` or `rospy`.

4.1.4. Publisher/Subscriber

The Publisher object represents a publisher on the ROS network. The object publishes to an available topic or to a topic that it creates. This topic has an associated message type. When the Publisher object publishes a message to the topic, all subscribers to the topic receive this message. The same topic can have multiple publishers and subscribers.

The primary mechanism for ROS nodes to exchange data is to send and receive messages. Messages are transmitted on a topic and each topic has a unique name in the ROS network. If a node wants to share information, it will use a publisher to send data to a topic. A node that wants to receive that information will use a subscriber to that same topic. Besides its unique name, each topic also has a message type, which determines the types of messages that are allowed to be transmitted.

This publisher/subscriber communication has the following characteristics:

1. Topics are used for many-to-many communication. Many publishers can send messages to the same topic and many subscribers can receive them.
2. Publisher and subscribers are decoupled through topics and can be created and destroyed in any order. A message can be published to a topic even if there are no active subscribers.

The concept of topics, publishers, and subscribers is illustrated in the figure.??.

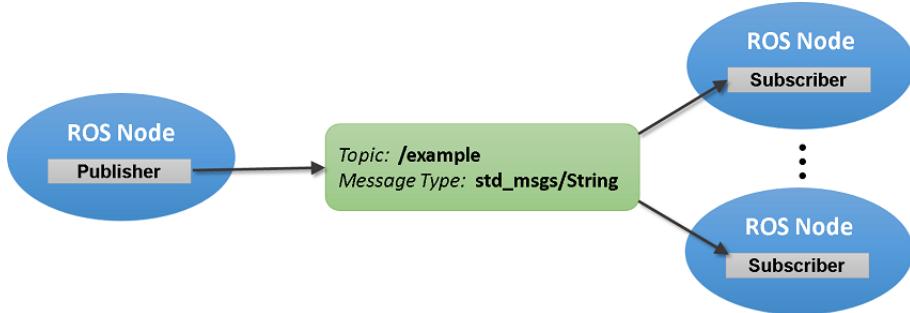


Figure 4.1.: Outline of control systems.

4.1.5. ROS Topic

Topics are named buses over which nodes exchange messages. Topics have anonymous publish/subscribe semantics, which decouples the production of information from its consumption. In general, nodes are not aware of who they are communicating with. Instead, nodes that are interested in data subscribe to the relevant topic; nodes that generate data publish to the relevant topic. There can be multiple publishers and subscribers to a topic.

Topics are intended for unidirectional, streaming communication. Nodes that need to perform remote procedure calls, i.e. receive a response to a request, should use services instead. There is also the Parameter Server for maintaining small amounts of state.

Each topic is strongly typed by the ROS message type used to publish to it and nodes can only receive messages with a matching type. The Master does not enforce type consistency among the publishers, but subscribers will not establish message transport unless the types match. Furthermore, all ROS clients check to make sure that an MD5 computed from the msg files match. This check ensures that the ROS Nodes were compiled from consistent code bases.

with a simple words we can define this terms:

Nodes: A node is an executable that uses ROS to communicate with other nodes.
Topics: Nodes can publish messages to a topic as well as subscribe to a topic to receive messages.
Messages: ROS data type used when subscribing or publishing to a topic.
Master: The ROS Master provides name registration and lookup to the rest of the Computation Graph. Without the Master, nodes would not be able to find each other, exchange messages, or invoke services.
roscore: is a collection of nodes and programs that are pre-requisites of a ROS-based system. You must have a roscore running in order for ROS nodes to communicate. It is launched using the roscore command.

4.1.6. Can we access ROS form a remote computer?

ROS is a distributed computing environment. A running ROS system can comprise dozens, even hundreds of nodes, spread across multiple machines. Depending on how the system is configured, any node may need to communicate with any other node, at any time.

- There must be complete, bi-directional connectivity between all pairs of machines, on all ports.
- Each machine must advertise itself by a name that all other machines can resolve.

More information can be found at: wiki.ros.org/ROS/NetworkSetup

4.2. Linux

4.3. General View Of The Control System

The control system of the robot can be divided into two parts:

- Raspberry Pi - High level -

- Arduino - Low level -

All computing and control operation is done on RP that lies on the robot to insure the speed of control and precision. The sensors data send from mobile App to the RP through TCP/IP connection and to a computer also, RP receive this data and process it to be aware with its environment and make a decision upon it, the computer show this data on a GUI to the operator/user so he can also make a decision using the reading form sensors and the camera. When a order form an operator using Joystick/Bluetooth to move the robot the RP take this order and send it to the Arduino through a serial port, using a C++ program in Arduino we compute the angles to move to the desired direction with minimal error. FigureFigure 4.2 show an Outline for the control system.

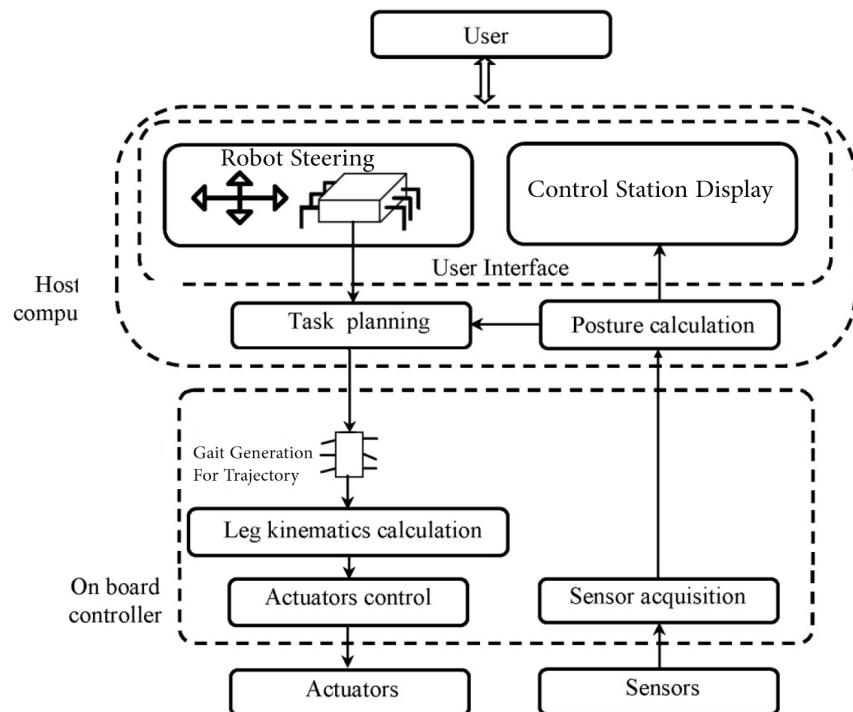


Figure 4.2.: Outline of control systems.

4.3.1. Raspberry Pi

A Raspberry Pi is a credit card-sized computer originally designed for education, inspired by the 1981 BBC Micro. Creator Eben Upton's goal was to create a low-cost device that would improve programming skills and hardware understanding. But thanks to its small size and accessible price, it was quickly adopted by tinkerers, makers, and electronics enthusiasts for projects that require more than a basic microcontroller.

The Raspberry Pi is slower than a modern laptop or desktop but is still a complete Linux computer and can provide all the expected abilities that implies, at a low-power consumption level.

The Raspberry Pi is open hardware, with the exception of the primary chip on the Raspberry Pi, the Broadcom SoC (System on a Chip), which runs many of the main components of the board—CPU, graphics, memory, the USB controller, etc. Many of the projects made with a Raspberry Pi are open and well-documented as well and are things you can build and modify yourself.

- What kind of operating system does the Raspberry Pi run?

The Raspberry Pi was designed for the Linux operating system, and many Linux distributions now have a version optimized for the Raspberry Pi.

Two of the most popular options are Raspbian, which is based on the Debian operating system, and Pidora, which is based on the Fedora operating system. For beginners, either of these two work well; which one you choose to use is a matter of personal preference. A good practice might be to go with the one which most closely resembles an operating system you're familiar with, in either a desktop or server environment.

If you would like to experiment with multiple Linux distributions and aren't sure which one you want, or you just want an easier experience in case something goes wrong, try NOOBS, which stands for New Out Of Box Software. When you first boot from the SD card, you will be given a menu with multiple distributions (including Raspbian and Pidora) to choose from. If you decide to try a different one, or if something goes wrong with your system, you simply hold the Shift key at boot to return to this menu and start over.

There are, of course, lots of other choices. OpenELEC and RaspBMC are both operating system distributions based on Linux that are targeted towards using the Raspberry Pi as a media center. There are also non-Linux systems, like RISC OS, which run on the Pi. Some enthusiasts have even used the Raspberry Pi to learn about operating systems by designing their own.

Raspberry Pi 3 Model B specification The Raspberry Pi 3 Model B is the third generation Raspberry Pi. This powerful credit-card sized single board computer can be used for many applications and supersedes the original Raspberry Pi Model B+ and Raspberry Pi 2 Model B. Whilst maintaining the popular board format the Raspberry Pi 3 Model B brings you a more powerful processor, 10x faster than the first generation Raspberry Pi. Additionally it adds wireless LAN & Bluetooth connectivity making it the ideal solution for powerful connected designs.

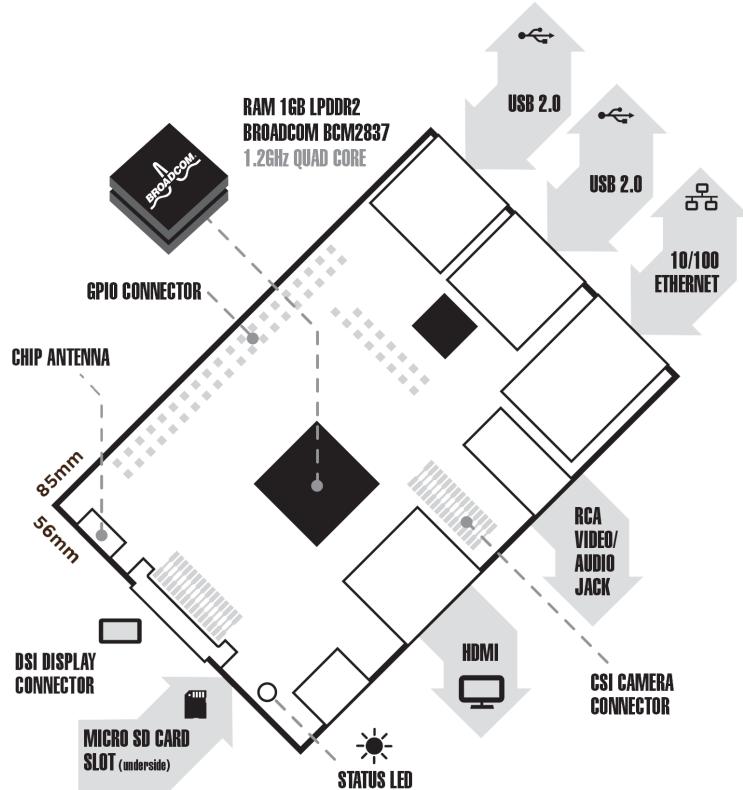


Figure 4.3.: Outline of control systems.

Processor	Broadcom BCM2837 chipset. 1.2GHz Quad-Core ARM Cortex-A53 802.11 b/g/n Wireless LAN and Bluetooth 4.1 (Bluetooth Classic and LE)
GPU	Dual Core VideoCore IV® Multimedia Co-Processor. Provides OpenGL ES 2.0, hardware-accelerated OpenVG, and 1080p30 H.264 high-profile decode.
Memory	1GB LPDDR2
Operating System	Boots from Micro SD card, running a version of the Linux operating system
Dimensions	85 x 56 x 17mm
Power	Micro USB socket 5V1, 2.5A
Ethernet	10/100 BaseT Ethernet socket
Video Output	HDMI (rev 1.3 & 1.4 Composite RCA (PAL and NTSC)
Audio Output	Audio Output 3.5mm jack, HDMI
USB	4 x USB 2.0 Connector
GPIO Connector	40-pin 2.54 mm (100 mil) expansion header: 2x20 strip Providing 27 GPIO pins as well as +3.3 V, +5 V and GND supply lines
Camera Connector	15-pin MIPI Camera Serial Interface (CSI-2)
Display Connector	Display Serial Interface (DSI) 15 way flat flex cable connector with two data lanes and a clock lane
Memory Card	Slot Push/pull Micro SDIO

4.3.1.1. Ubuntu MATE with Raspberry Pi

Ubuntu MATE is a stable, easy-to-use operating system with a configurable desktop environment. It is ideal for those who want the most out of their computers and prefer a traditional desktop metaphor. With modest hardware requirements it is suitable for modern workstations, single board computers and older hardware alike. Ubuntu MATE makes modern computers fast and old computers usable.

The MATE desktop is essentially a continuation of the traditional Gnome 2 desktop environment. Combining the MATE desktop with Ubuntu gives you an experience that is almost identical to the early days of Ubuntu, prior to the switch to Unity.

Martin Wimpress and Rohith Madhavan have made an Ubuntu MATE image for the Raspberry Pi 2 and Raspberry Pi 3 based on the regular Ubuntu armhf base, not the new Ubuntu “Snappy” Core, which means that the installation procedure for applications uses the traditional tools, ie apt-get with highly recommended microSDHC Class 6 or Class 10 microSDHC card. Ubuntu MATE 16.04 also fully supports the built-in Bluetooth and Wifi on the Raspberry Pi 3 and features hardware accelerated video playback in VLC and hardware accelerated decoding and encoding in ffmpeg

To installing Ubuntu MATE onto Raspberry Pi 3, starting by download the OS into microSD then the partition is automatically resized to fill your microSD card when the pi is powered up for the first time, typical guided installer is shown up. Installation takes several minutes and finally the system reboots and you arrive at the desktop. A Welcome app provides some good information on Ubuntu MATE, including a section specific for the Raspberry Pi.

The Welcome app explains that the while the system is based on Ubuntu MATE and uses Ubuntu armhf base, it is in fact using the same kernel as Raspian. It also turns out that a whole set of Raspian software has been ported over such as raspi-config, rpi gpio, sonic-pi, python-sent-hat, omxplayer, etc.

[ubuntu-mate.org/blog/ubuntu-mate-xenial-raspberry-pi]

4.3.1.2. Raspberry Pi with ROS

4.3.2. Arduino Mega

Arduino is an open-source platform used for building electronics projects. Arduino consists of both a physical programmable circuit board (often referred to as a micro-controller) and a piece of software, or IDE (Integrated Development Environment) that runs on your computer, used to write and upload computer code to the physical board.

The Arduino platform has become quite popular with people just starting out with electronics, and for good reason. Unlike most previous programmable circuit boards, the Arduino does not need a separate piece of hardware (called a programmer) in order to load new code onto the board – you can simply use a USB cable. Additionally,

the Arduino IDE uses a simplified version of C++, making it easier to program. Finally, Arduino provides a standard form factor that breaks out the functions of the microcontroller into a more accessible package.

The Arduino Mega 2560 is a microcontroller board based on the ATmega2560. It has 54 of digital input/output pins (14 can be used as PWM outputs), 16 analog inputs, a USB connection, a power jack, a 16 MHz crystal oscillator, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The large number of pins make this board very handy for projects that require a bunch of digital inputs or outputs.

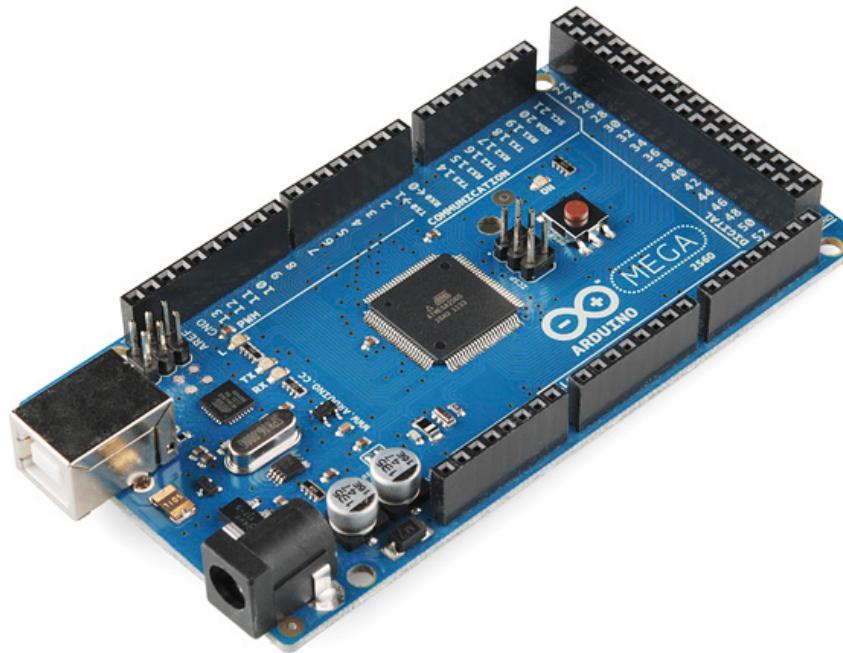


Figure 4.4.: Outline of control systems.

Arduino Mega specification

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage	(recommended) 7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

4.3.2.1. Arduino whit Raspberry Pi

4.3.2.2. Arduino PWM to Servo Motors

4.4. Mobile Application

4.5. Communication Types

Firstly, the wireless joystick communicates with the Raspberry Pi, using a ROS node called ‘joy’, and send a keystroke to it. Then the Raspberry Pi find the key pressed using a python library called ‘pygame’ and send a proper character on the serial port to the Arduino, our low-level interface with the servomotors. Lastly, the Arduino checks the received character and perform the needed action. Another line of communication is between our control station and an Android smart phone mounted on the robot through a TCP/IP client server application.

4.5.1. Joystick

4.5.2. Bluetooth

4.5.3. Wi-Fi

- What is TCP/IP? When two computers follow the same protocols—the same set of rules—they can understand each other and exchange data. TCP/IP (Transmission Control Protocol/Internet Protocol) is the basic communication language or protocol of the Internet that use this concept to communicate through the internet and become standard terminology for referring to this suite of protocols. TCP/IP

architecture omits some features found under the OSI model, combines the features of some adjacent OSI layers and splits other layers apart. The 4-layer structure of TCP/IP is built as information is passed down from applications to the physical network layer. When data is sent, each layer treats all of the information it receives from the upper layer as data, adds control information (header) to the front of that data and then pass it to the lower layer. When data is received, the opposite procedure takes place as each layer processes and removes its header before passing the data to the upper layer.

- Application Layer The Application Layer in TCP/IP groups the functions of OSI Application, Presentation Layer and Session Layer. Therefore any process above the transport layer is called an Application in the TCP/IP architecture. In TCP/IP socket and port are used to describe the path over which applications communicate. Most application level protocols are associated with one or more port number.
- Transport Layer In TCP/IP architecture, there are two Transport Layer protocols. The Transmission Control Protocol (TCP) guarantees information transmission. The User Datagram Protocol (UDP) transports datagram without end-to-end reliability checking. Both protocols are useful for different applications.
- Network Layer The Internet Protocol (IP) is the primary protocol in the TCP/IP Network Layer. All upper and lower layer communications must travel through IP as they are passed through the TCP/IP protocol stack. In addition, there are many supporting protocols in the Network Layer, such as ICMP, to facilitate and manage the routing process.
- Network Access Layer In the TCP/IP architecture, the Data Link Layer and Physical Layer are normally grouped together to become the Network Access layer. TCP/IP makes use of existing Data Link and Physical Layer standards rather than defining its own. Many RFCs describe how IP utilizes and interfaces with the existing data link protocols such as Ethernet, Token Ring, FDDI, HSSI, and ATM. The physical layer, which defines the hardware communication properties, is not often directly interfaced with the TCP/IP protocols in the network layer and above. []

TCP/IP uses the client/server model of communication in which a computer user (a client) requests and is provided a service (such as sending a Web page) by another computer (a server) in the network. TCP/IP communication is primarily point-to-point, meaning each communication is from one point (or host computer) in the network to another point or host computer. TCP/IP and the higher-level applications that use it are collectively said to be "stateless" because each client request is considered a new request unrelated to any previous one (unlike ordinary phone conversations that require a dedicated connection for the call duration). Being stateless frees network paths so that everyone can use them continuously. (Note that the TCP layer itself is not stateless as far as any one message is concerned. Its connection remains in place until all packets in a message have

been received.)

- Protocol A protocol is the special set of rules that end points in a telecommunication connection use when they communicate. Protocols specify interactions between the communicating entities. Protocols exist at several levels in a telecommunication connection. For example, there are protocols for the data interchange at the hardware device level and protocols for data interchange at the application program level. In the standard model known as Open Systems Interconnection (OSI), there are one or more protocols at each layer in the telecommunication exchange that both ends of the exchange must recognize and observe. Protocols are often described in an industry or international standard.

The TCP/IP Internet protocols, a common example, consist of: Transmission Control Protocol (TCP), which uses a set of rules to exchange messages with other Internet points at the information packet level Internet Protocol (IP), which uses a set of rules to send and receive messages at the Internet address level Additional protocols that include the Hypertext Transfer Protocol (HTTP) and File Transfer Protocol (FTP), each with defined sets of rules to use with corresponding programs elsewhere on the Internet

- The Protocol Used In ZagHexa Robot

4.6. GUI

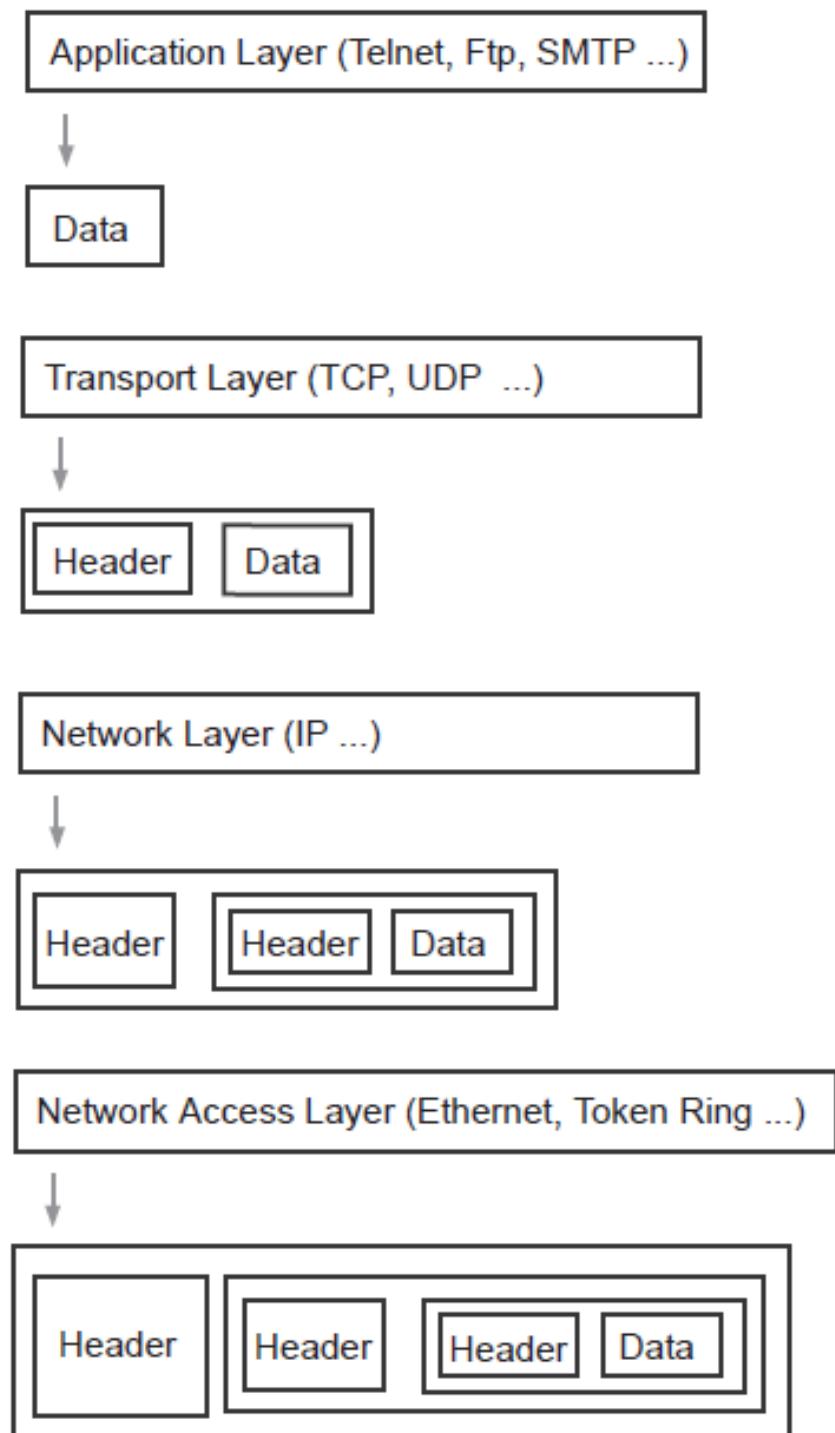


Figure 4.5.: Outline of control systems.

“A computer would deserve to be called intelligent if it could deceive a human into believing that it was human.”

— Alan Turing, (British pioneering computer scientist, cryptanalyst, ..., and philosopher, 1912–1954)

Chapter 5

Mechanical Design

ZagHexa was first implemented in SolidWorks to verify its mechanical structure and produce the required workshop drawings to develop and cut its metal and plastic parts. In addition, some preliminary motion analysis simulations were also conducted. The final resulting design is given in Figure 5.1. To further develop the kinematic model of

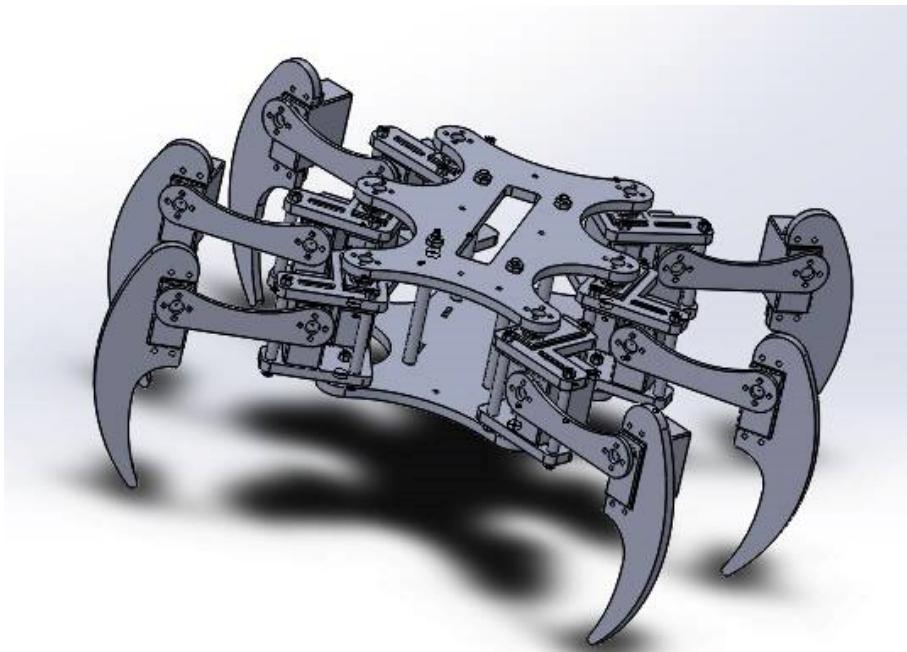


Figure 5.1.: CAD rendering of the robot.

the robot, the coordinate systems (Cartesian frames [?]) for all parts of the robot need to be identified. Next, the detailed development of such frames is given.

5.0.1. Robot body frame

The origin of the robot base frame will be in the center of the body, structured with Z-axis pointing up, the X-axis positioning right and Y-axis pointing forwards with respect to the robot front side as depicted in Figure 5.2.

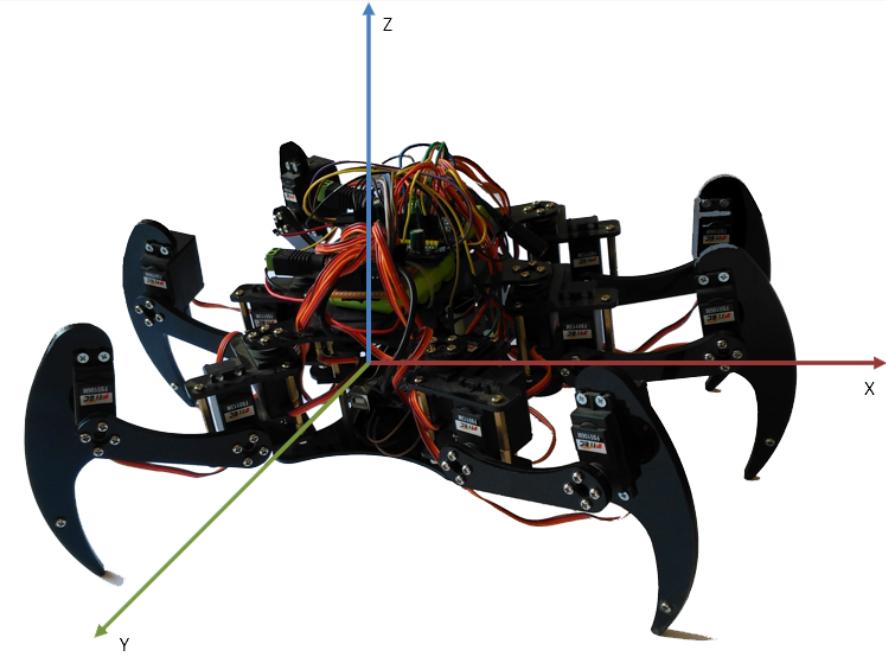


Figure 5.2.: Location of body frame relative to robot hardware.

5.0.2. Leg frames and notations

The design of hexapod constitutes the kinematic configuration of a hexapod robot, with each leg acting as an independent serial manipulator with three degrees of freedom. Figure Figure 1.1 shows the actual prototype of our robot.

The final leg design and its links and joints notations are given in Figure 5.3. The robot leg is made of links and joints as noted on Figure 5.4, different links of robot leg are called Femur, Tibia and Tarsus. As depicted in figure, the robot leg frame starts with link 0, which is the point where the leg is attached to the body, link 1, is Femur, link 2 is the Tibia and link 3 is Tarsus. The joints are located at the inner end of their respective link. Frames are attached to outer end of their respective links, this means that joint 2 rotates about the Z-axis of frame 1.

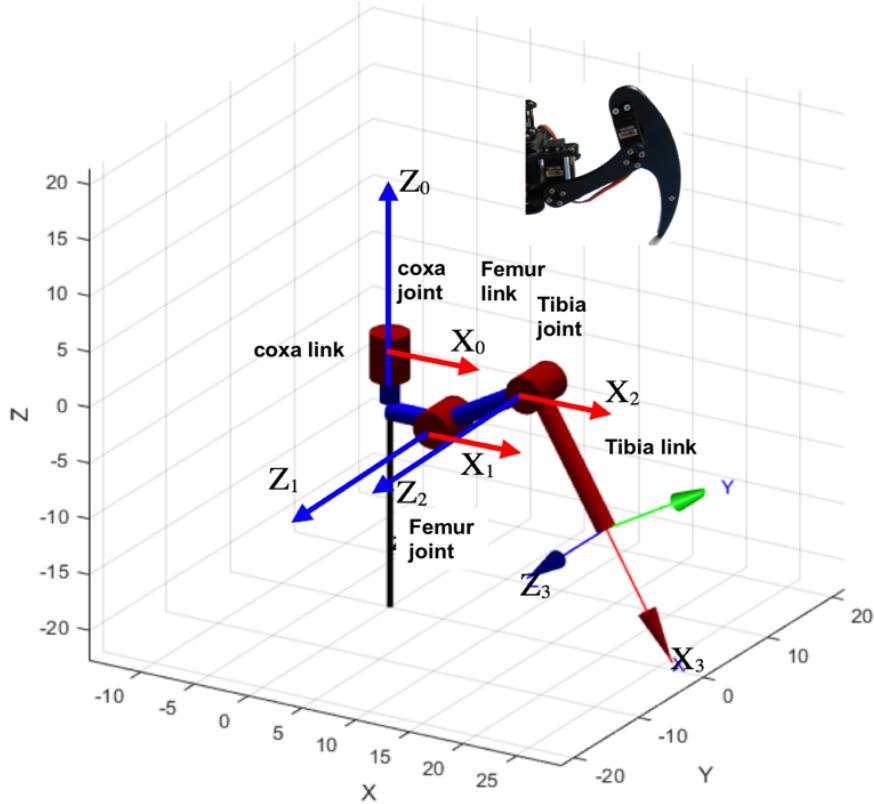


Figure 5.3.: Final leg design (top right) and its notations, reference frames, joints and links.

5.0.3. Robot Leg Parameters

Following the well-known Denavit-Hartenberg (DH) notation, coordinate frames for the robot leg are assigned. The assigned frames are shown in Figure 5.4. In figure, the body b and the zeroth 0 reference frames are attached to the stationary robot body. Therefore, they can be both considered as inertial frames. The axes of the body frame are arranged to be in accord with the actual robot-body orientation. The DH link parameters based on Figure 5.4 are given in Table II.

The resulting homogeneous transformation matrices between the body and the zeroth frame and between the sequential link frames are given in (1). In the formulas, the variables represented by a stand for the length of the i^{th} link (namely, the length of the portion of the link between the origins of $(i-1)^{th}$ and i^{th} reference frames). The variables represented by θ_{ij} mean the sum of the i^{th} and j^{th} joint angles ($\theta_{ij} = \theta_i + \theta_j$). C and S are for $\cos(\cdot)$ and $\sin(\cdot)$ functions, respectively. The exact values of these variables corresponding to ZagHexa robot are: $\psi = 45^\circ$, $a_1 = 5\text{cm}$, $a_2 = 9\text{cm}$, $a_3 = 18\text{cm}$

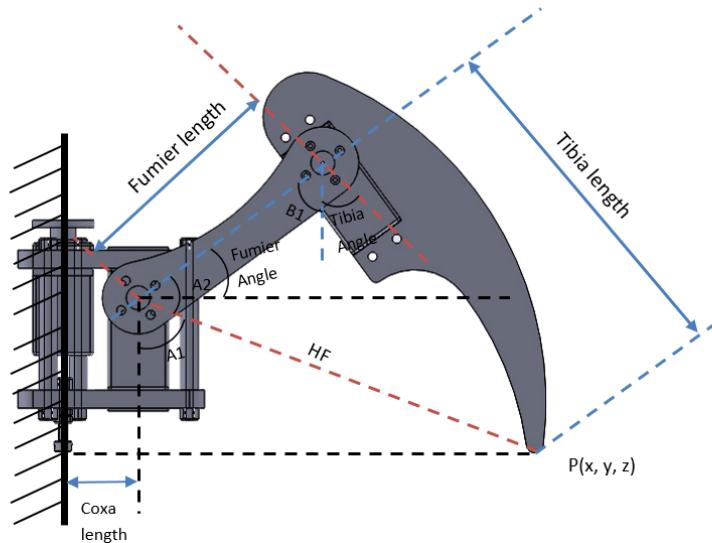


Figure 5.4.: Final leg design (top right) and its notations, reference frames, joints and links.

Joint	θ_i	α_i	a_i	d_i
1	θ_1	$\pi/2$	a_1	0
2	θ_2	0	a_2	0
3	θ_3	0	a_3	0

Homogeneous matrices are used in derivation of positional relations between the successive frames. In (3) the leg tip point position with respect to the body frame is given. The rotation matrices between the frames are given in (2). These rotation matrices are used in vector equations, especially while deriving the dynamic equations.

$$H^{(b,0)} = \begin{bmatrix} 0 & \cos(\psi) & \sin(\psi) & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$H^{(K-1,K)} = \begin{bmatrix} \cos \theta_k & -\cos \alpha_k \sin \theta_k & \sin \alpha_k \sin \theta_k & a_k \cos \theta_k \\ \sin \theta_k & \cos \alpha_k \cos \theta_k & -\sin \alpha_k \cos \theta_k & a_k \sin \theta_k \\ 0 & \sin \alpha_k & \cos \alpha_k & d_k \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5.1)$$

$$H^{(0,3)} = H^{(0,1)} H^{(1,2)} H^{(2,3)} H^{(b,3)} = H^{(b,0)} H^{(0,3)}$$

$$C^{(b,0)} = \begin{bmatrix} 0 & \cos(\psi) & \sin(\psi) \\ -1 & 0 & 0 \\ 0 & -\sin(\psi) & \cos(\psi) \end{bmatrix}$$

$$C^{(K-1,K)} = \begin{bmatrix} \cos \theta_k & -\cos \alpha_k \sin \theta_k & \sin \alpha_k \sin \theta_k \\ \sin \theta_k & \cos \alpha_k \cos \theta_k & -\sin \alpha_k \cos \theta_k \\ 0 & \sin \alpha_k & \cos \alpha_k \end{bmatrix} \quad (5.2)$$

$$P_e^{(K-1,K)}(\theta) = \begin{bmatrix} C\psi(a_1S\theta_1 + a_2S\theta_1C\theta_2 + a_3S\theta_1C\theta_{23}) + S\psi(a_2S\theta_2 + a_3\theta_{23}) \\ -(a_1C\theta_1 + a_2C\theta_1C\theta_2 + a_3C\theta_1C\theta_{23}) \\ -S\psi(a_1S\theta_1 + a_2S\theta_1C\theta_2 + a_3S\theta_1C\theta_{23}) + C\psi(a_2S\theta_2 + a_3\theta_{23}) \end{bmatrix} \quad (5.3)$$

To derive the dynamic equations, first the inertia matrices of the links should be determined. Since the k^{th} reference frame is stationary with respect to the k^{th} link, the inertia tensor of the k^{th} link around its center of mass appears to be a constant matrix with respect to the k^{th} reference frame, as in (4). The values used in these formulations belong to the Hexapod robot. The resulting matrices for each link are in the form of (5).

$$\{J_K\}^{(K)} = J_K^{(K)} = J_K \quad (5.4)$$

$$J_K = \begin{bmatrix} J_{K1} & 0 & 0 \\ 0 & J_{K2} & 0 \\ 0 & 0 & J_{K3} \end{bmatrix} \quad (5.5)$$

5.0.4. Inverse kinematics

The forward kinematics (FK) is a simple equation used to calculate the position of the end effectors for the leg in the robot base frame, by injecting values of each joint angle. But the reverse operation, namely inverse kinematics (IK), is more complex. IK is employed to find all the joint angles given the position of the end effectors. In general, solving the IK equations can be a bit of a challenge. Some positions cannot be reached at all, as the physical system is unable to get there, and some end effectors positions can have more than one solution, and not all of them are desirable.

We solve the IK problem for each leg separately, as this makes it possible to solve it geometrically, by setting up some constraints. The first constraint for solving the IK equations due to the fact that all robot joints allow rotation about one axis only. The second constraint is that the Femur, Tibia joints always rotate on parallel axes. The third set of constraints arises from the physical limitations for each joint, giving us some angular interval for each joint in which the servos can actually rotate the link. In Figure 5.4, the angles of movement are shown. First, the coxa angle can be found directly by knowing the end effectors position then simply using $\text{atan2}(y, x)$ to calculate it. Equations (6) through (14) are used to find the individual joint angles.

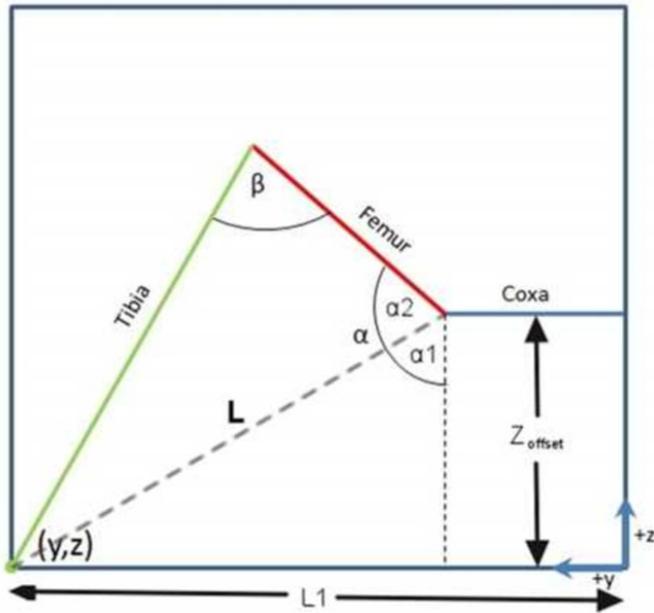


Figure 5.5.: Illustration of the 2D triangle with vertices in the coxa, the femur, and tibia link from origin.

$$\frac{x}{y} = \tan(y) \rightarrow \gamma = \tan^{-1} \frac{x}{y} \quad (5.6)$$

$$L = \sqrt{Z_{offset}^2 + (L_1 + \cos A)^2} \quad (5.7)$$

$$a_L = \cos^{-1} \left(\frac{Z_{offset}}{L} \right) \quad (5.8)$$

$$Tibia^2 = Femar^2 + L^2 - 2(Femar)(L)\cos\alpha_2 \quad (5.9)$$

$$\alpha_2 = \cos^{-1} \left(\frac{Tibia^2 - Femar^2 - L^2}{-2(Femar)(L)} \right) \quad (5.10)$$

$$\alpha = \alpha_1 + \alpha_2 \quad (5.11)$$

$$\alpha = \cos^{-1} \left(\frac{Z_{offset}}{L} \right) + \cos^{-1} \left(\frac{Tibia^2 - Femar^2 - L^2}{-2(Femar)(L)} \right) \quad (5.12)$$

$$\beta = \cos^{-1} \left(\frac{L^2 - Femar^2 - Tibia^2}{-2(Femar)(Tibia)} \right) \quad (5.13)$$

5.1. Walking Pattern

In this section, the generation of the robot gait will be described. We provided the robot with a group of programmed gait sequences used for different purposes. For example, a Tripedal gait is used as the basic movement for the robot which provide

speed and longer traverse length. Metachronical gait is used for rough terrain traverse which provide better stability but slower motion [?, ?]. Main types of gaits used in ZagHexa robot are shown in Figure 5.6. The description of these gaits is given next.

5.1.1. Wave gait (Metachronical Gait)

In this gait mode, the robot move one leg at a time, it starts by lifting one leg and then lowering it down gradually until the foot touches the ground and then the next leg starts to move, as mentioned before this gait sequence is rather slow but it provides maximum stability for the robot, and it enables the robot to walk on rough terrain. This is illustrated in Figure 5.6.

5.1.2. Ripple gait (Two wave Gait)

In this gait, two legs move at a time, since it has two independent wave gaits. The opposite sides legs are 180 degrees out of phase and it needs three beats to complete one cycle. Figure 5.6. shows the Ripple gait.

5.1.3. Tripedal Gait

This gait is the fast gait for the hexapod; it completes a cycle in two beats. In this gait, the robot lift three legs simultaneously while leaving three legs on the ground, which keeps the robot stable. Figure 5.6. shows Tripedal gait reaction [?].

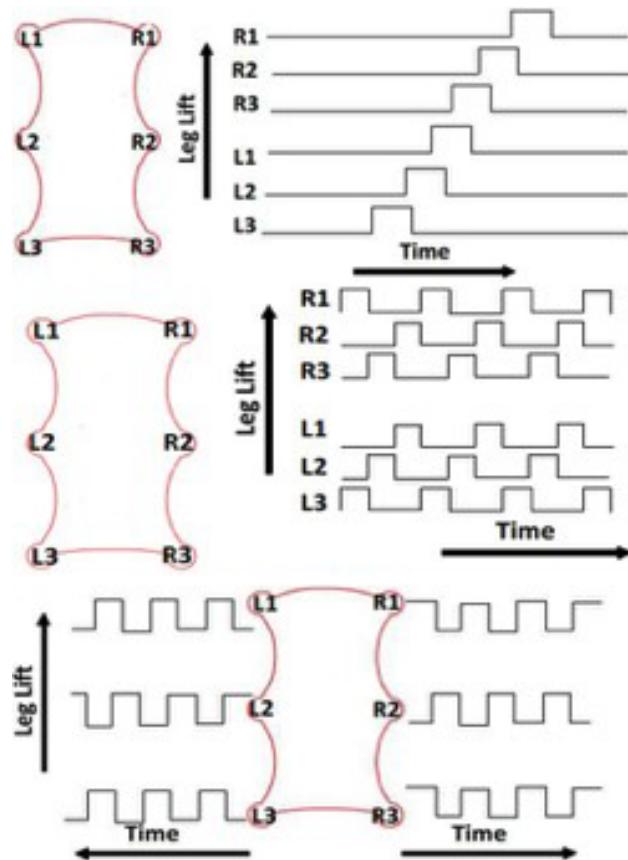


Figure 5.6.: Different walking gaits: wave (top), ripple (middle), and tripod (middle).

“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are. If it doesn’t agree with experiment, it’s wrong.”

— Richard P. Feynman, (American theoretical physicist, 1918–1988)

Chapter 6

Experiments and Results

To verify the designed and constructed robot as well as its software framework and control methods, a series of field experiments were performed. The first set of experiments was to test the robot basic movements (such as forward, backward walking and right and left turn). Some results of these experiments are shown in Figure 6.1 (top). The second set was to test the implemented body kinematics. Example results such experiments are given in Figure 6.1 (bottom) which shows the robot raising and lowering its body height.

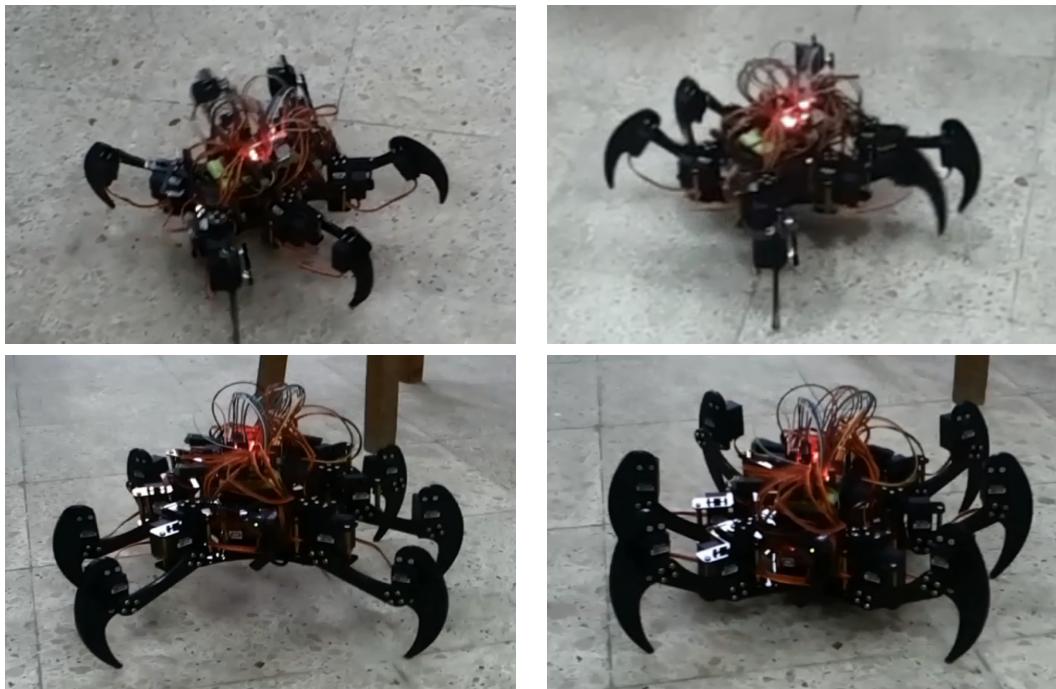


Figure 6.1.: Experiment results: forward and backward move (top) and raising and lowering the body height (bottom).

6.1. Simulation

To help test the design robot and verify software modules and the overall behaviour, the robot is modelled and simulated. The first model for the whole robot is performed in Rviz to test the different ROS nodes and the whole software framework. Rviz is one of ROS tools. It is capable of visualizing many different kinds of information in the same interface. You can load visualization plugins. In the parameters of these plugins you generally define the topic name to which the plugin subscribes, this is fairly straightforward. Rviz configuration file is provided with the sources and started by default in the launch file. Within our ROS-Rviz setup, we simulated the robot movement to test it in different conditions. That made it much easier and faster than apply all the scenarios on the real robot.

In the second simulation, we modelled the robot in MATLAB and employing the Robotics Toolbox. The main purpose of this simulation is to calculate and simulate the kinematics of robot. To create the six-legged walking robot, we started by creating a three-axis robot arm that we used as a leg. Then we implemented a trajectory for the leg that is suitable for walking. Finally, we instantiated six instances of the leg to create the walking robot. The equations given in Sec.4 are programmed first for one leg and tested on successful working, the whole body kinematics were also programmed and tested. The results were very useful in modifying the walking gaits of the robot which then implemented in the real robot. Figure 10 shows one such simulations in which the same experiment performed on the real robot to test the whole body kinematics for raising and lowering the body height.

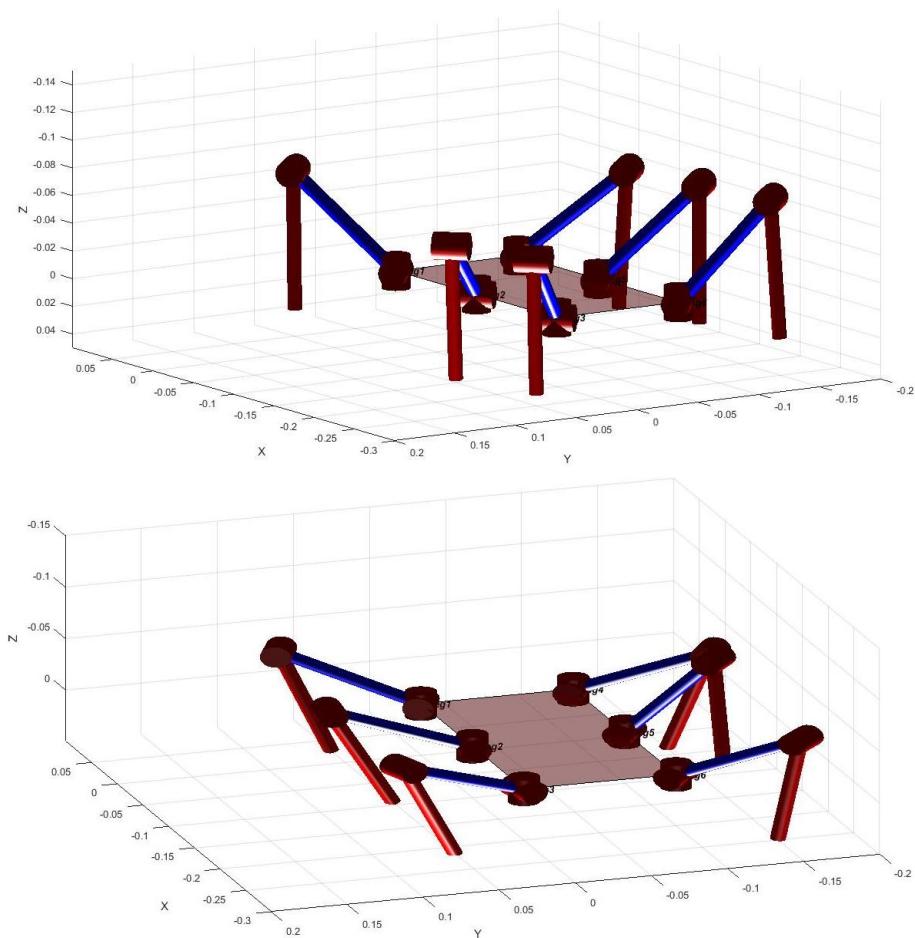


Figure 6.2.: Hexapod robot Simulation.

The true function of philosophy is to educate us in the principles of reasoning and not to put an end to further reasoning by the introduction of fixed conclusions.

— George Henry Lewes, (English philosopher and critic of literature, 1817–1878)

Chapter 7

Conclusions and Future Outlook

This paper presents a system description and the main aspects related to the design, construction, and implementation of six-leg robot named ZagHexa. The robot is a legged robot for search and rescue missions. It benefits from the reliability of its legged locomotion with the flexibility and versatility required to operate in different types of surface. The robot was constructed and tested to walk using tripod, wave and ripple gaits, can rotate and it is equipped with different sensors.

The robot was tested on different surfaces and in rugged terrain. The repeatability of the robot movement as well as the sensor system was also tested. These features are mainly achieved due to its original movement that make it deal with different surfaces. Additionally, its shape and weight give it more stability, and its ability to continue with its moving and sensing capabilities after collisions or even small falls.

However, more tests and experiments to improve and validate the design and sensor performance are to be carried out to optimize the system performance. Finally, we are working on tackling some issues should to have fully autonomous operation and integration into a heterogeneous system. To make the integration of ZagHexa into different missions easier, an effort is being carried to provide it with a standard connectivity over the ROS framework.

Appendix A

This is My Appendix Title

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