Design of a Miniature Quadruped Multi-Robot System for Environment Exploration

Chapter 1
Introduction

1.1 Introduction

The exploration of unknown environments has always been a difficult engineering challenge. This is because the human body is so fragile in extreme environments that they can't explore deeply. With the development of sensor and robot technology, people began to rely on various robots instead of going personally in environment exploration. This demand has led to the progress of a branch of robotics which is called filed robots. Compared with industrial robots, which are designed for customized workspaces, the purpose of field robots is summarized to operate in a complex, harsh and anomalistic environment (Thorpe et al., 2001). Field robots are deployed in farmland, wild, underwater, air and even outer space to conduct exploration, acquisition and surveillance. Although robots have appeared in the deep sea (submersible Jiaolong) and even on other planets (rover Curiosity), their huge size and high cost make them temporarily unable to be used in areas other than national plans. Environment exploration is not limited to adventure in uncharted territory, but also in the civilized society. Many areas of man-made buildings are too narrow, so that some survey work is very difficult for humans, such as the excavation of ancient ruins or the maintenance of urban pipeline systems.

According to a report of the commercial robot market, the development of a miniature field robot that can operate in various situations has huge commercial potential and application prospects (Mordor Intelligence, 2020). It can be used in post-disaster rescue, city maintenance, archaeological survey and house security. Their small size and low cost can not only bring new solutions to these engineering problems, but also reduce labour costs.

Figure 1.1: Three types of robot with different functions in the system.

Based on the personal understanding of project title which is miniature exploration robots, this project has designed a robot system that can conduct exploration activities in different narrow environments by multi-robot. In this report, all technical points, algorithms design and simulation results will be described in detail. Figure 1.1 shows three types of robots as the main components of this system. Their design is based on the same prototype and equipped with different sensors to perform different tasks.

1.2 Aims

In order to meet the requirements of the above-mentioned situations, the design of the miniature exploration robot should meet the following technical points:

- Can move freely in narrow environments such as ruins or pipelines.
- Has a certain obstacle crossing ability, athletic ability will not be affected by rough roads.
- Equipped with a variety of sensors, and can send back real-time image, sound and temperature data from the scene.
- The modular design of the sensor can be replaced according to the site conditions.
- It can establish a virtual map while exploring the environment autonomously, and perform positioning and path planning on this basis at the same time.
- Collect target data in unknown environments and automatically return when necessary.
- Acceptable cost.

1.3 Objectives

In order to make the design of the robot reach the required technical level, it should include the complete design scheme of both hardware and software. For the hardware part, there should be CAD models, evaluation and analysis of components and feasibility tests of the robot. The software part should analyse the kinematic of robot and provide a program that can effectively control the robot. Considering that the robot needs to be intelligent, it also needs the analysis and implementation of related algorithms. Finally, there should be valid simulation results.

For this project, the specific objectives should be as follows:

1. Reasonable robot design and corresponding CAD models.
2. Robot control scheme supported by results.
3. Algorithms design that make robots work intelligently.

4. The simulation results that can be used as a theoretical basis.

1.4 Change in project scope (covid-19 response)

When this project was just started, the main purpose was to design a mini spider-shaped bionic walking robot. The specific task is to analyse the existing hexapod and quadruped robots, and realize the miniaturization of the robot while ensuring that the leg structure of the robot still has a certain degree of freedom. At this stage, the focus of the project is on industrial design and robotic manufacturing and the final expected result of the project is a working robot prototype. Obviously, this relies on actual engineering validation tests rather than simulation. At the same time, the demand for 3D printing and robotic materials led this project to obtain permission to use the relevant laboratory of the School of Mechanical Engineering.

However, due to the spread of the covid-19 coronavirus. All school facilities were forced to close in March, which caused the project to lose support from school resources. Based on the above reasons, the author of the project had some discussions with supervisor on the research direction. After reaching a consensus, the scope of the project changed from a complete mechanical and electronic design to a robotic system design.

In the new project scope, the actual robot prototype is no longer a necessary result of the project. This allows researcher to do more algorithmic research and simulation works with limited resources. From the results, this change has brought a positive impact on the project. It realizes the design of a robot system involving multiple disciplines instead of an individual robot design that was expected at the very beginning.

1.5 Project Report Layout

Chapter 1 has introduced the research purpose of the project, aims and specific objectives. It also explained the impact of the covid-19 coronavirus on the project.
Chapter 2 is the literary review, which will analyse and evaluate existing research results from the requirements of robot design. Some of these studies and theories may form the basis of the project results.

Chapter 3 and Chapter 4 will focus on the design details of the entire robot system. Chapter 3 involves the mechanical design of the robot, the technical description of actuators and sensors and the simulation of robot control. This provides hardware theoretical support for the realization of various algorithms in the robot system. Chapter 4 uses these robots as the theoretical basis and describes the framework of the robot system in detail. It also analyses the task requirements in different situations and proposes corresponding response strategies of the robot system. All response modes are given control algorithms as theoretical support, and realize the simulation of the most important algorithm in robot system.

The report concludes with Chapter 5, discussing the validity of the results and the findings during the working process. The project still has some shortcomings, but it also gives possibility of any further work may be conduct in the future.

Chapter 2
Literature review

2.1 Introduction

Robot technology has experienced rapid development in the past ten years and a large number of outstanding designs and ideas have been born from it. Now is the era of advocating modular design. It is obviously unrealistic to design a robot that completely adopts new ideas. Therefore, it is very important to sum up experience and technology from the research results of others. In this chapter, the main points and useful knowledge of all articles, books and documents read for the project will be briefly described. Some of these studies and designs pointed out the critical paths for the project, while others had limitations but the improvements based on them became some important results of the project. The scope of literature review will start from broad industry research, reveal the general background of robotics. Then gradually lead to specific technical issues which will be the most severe challenge faced by this project.

2.2 The Application of Robots in Exploration

The title of the project gives a conceptual vocabulary: "Miniature Exploration Robots". It is easy to extract the two keywords "miniature" and "exploration", which can be regarded as an overview of the robot design and main function respectively. Starting with functionality is a shortcut for robot design. However, in the process of reading various literatures, it is found that exploring robotics is actually a very broad field.

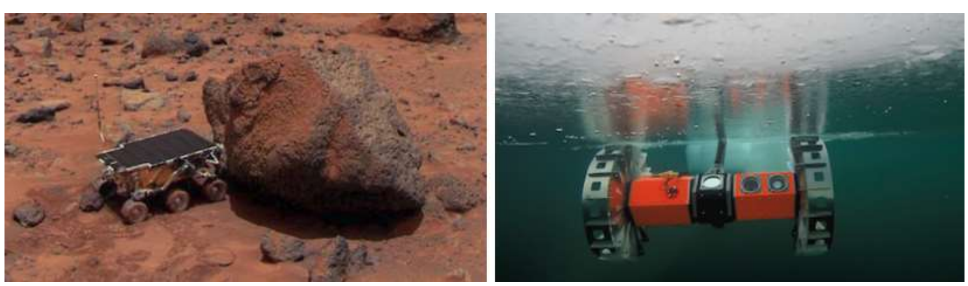


Figure 2.1: Exploration robots developed by NASA (NASA, 2017).

In articles related to exploration robots, more than half of the research is about the design of robots for space exploration. Followed by underwater robots, used for ocean exploration. This may be because space and deep sea are the last two places that have not been fully explored by humans. Even in the early preparation phase of the project, the help of these studies is very limited. The main reasons are too advanced concepts and lack of research on miniaturization.

If the definition of exploration is taken into consideration, the scope of the robot will be greatly increased. Almost all robots are equipped with sensors that can collect environmental information as feedback. Some of these technologies have appeared in daily lives, such as robot vacuum cleaners. It can detect the environment of the house and construct a virtual map. Furthermore, self-driving cars can also be regarded as an exploration robot because they can recognize the surrounding environment.

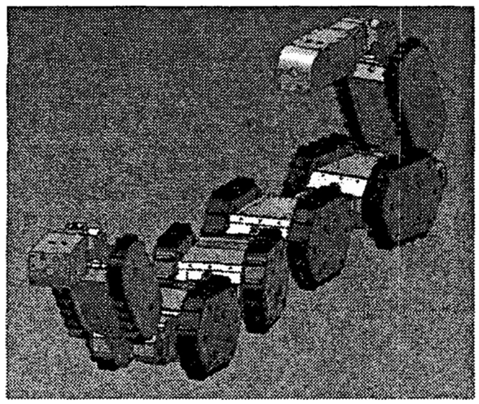


Figure 2.1 The design of “KOHGA” is based on the imitation of snakes (Kamegawa et al., 2004).

Among the many types of robots that rely on sensors to reflect the field environment, rescue robots are the most concerned. After entering the 21st century, people began to consider to use robotics to perform search and rescue activities (Liu et al., 2007). In the "9.11" incident, search and rescue robots were used for the first time to carry out rescue operations. Show the feasibility of this type of robot. Affected by this incident, some researchers began to design more versatile and efficient rescue robots. Some of these designs are very inspiring. For example, the snake-like rescue robot designed by researchers from Tokyo Institute of Technology (Kamegawa et al., 2004). It was designed to be able to enter the complex ruins after the earthquake. Figure 2.1 shows the structural design of “KOHGA” based on bionics. In subsequent research, a follow-up model of this robot was also developed. The "KOHGA3" in Figure 2.2 was even successfully applied in the rescue after the 2011 Japan earthquake. "KOGHA3" does not inherit the design idea of "KOGHA", but the variable track of provides more advantageous than the traditional transmission structure in the ability to overcome obstacles.

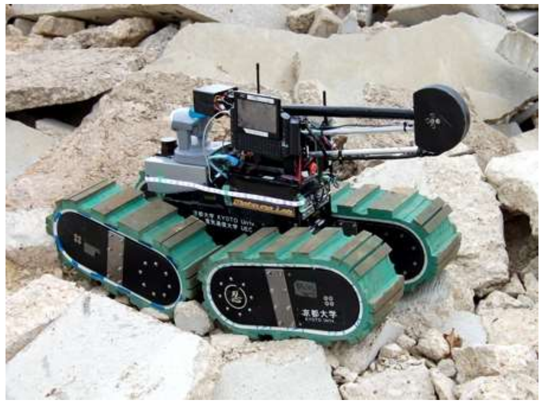


Figure 2.2 The “KOHGA3” ground robot developed by Japanese roboticists (Erico, 2011).

The characteristics of such robots enable them to be used in rescue activities as well as in other fields. The robotics group at the University of Leeds has developed and designed a variety of exploration robots for archaeology and urban maintenance. In this field, Professor Robert Richardson, the supervisor of this project, has made rich achievements. In 2013, Richardson et al. (2013) designed a robot called "Djedi" that can pass through the narrow passage inside the Pyramid of Khufu for an archaeological project in Egypt. As shown in Figure 2.3, this robot discovered writing that had been hidden for thousands of years without harming some of the fragile structures of the pyramid. This has brought new breakthroughs to archaeological work.

Figure 2.3 The robot "Djedi" used to explore the inside of the pyramid (Richardson, 2011).

Similar robots are also used in the Self Repairing Cities project led by the University of Leeds, a collaboration that uses various robots for city maintenance. A study by (2012) presents a robot that can move freely in a pipeline system. Figure 2.4 shows the amazing dynamic structure. This robot is expected to perform automatic inspection and maintenance of the pipeline system.

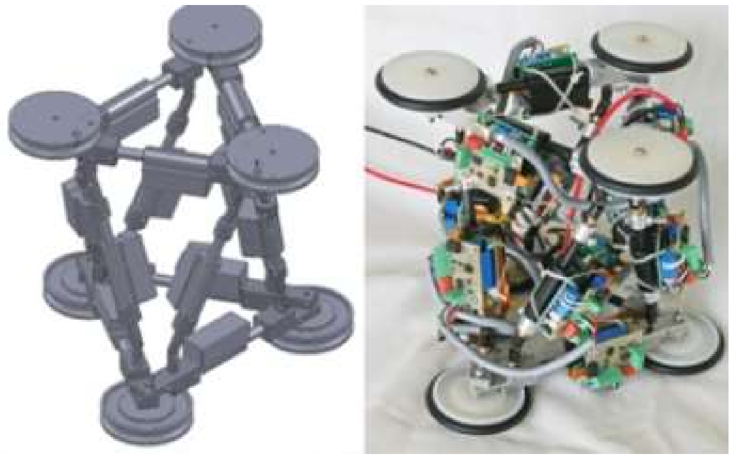


Figure 2.4 A pipe inspection robot (Bekhit et al., 2012).

Although the robots discussed above all have outstanding engineering achievements, they still have some limitations. The first is their lack of versatility. It can be seen from their special structure that they are designed for specific tasks or environments. This will cause some problems for cost and research cycle. In this project, versatility should be actively incorporated into the design considerations.

2.3 Miniaturization & Bionics

In the discussion of existing exploration robots in the previous section, the importance of miniaturization for this type of robot has been discovered. In addition to space and underwater exploration, other exploration missions all occur in fragile or space-limited places. In order not to cause permanent damage to the environment, researchers have tried their best to achieve miniaturization of the robot.

Even though these robots have different shapes, most of them have animal-like prototypes. It is the so-called bionics. The bodies of animals and insects are very reasonable and efficient structures. Many researches on biology have brought inspiration and profound influence to engineering. Snake-like and reptile-like robots have already been introduced. As mentioned before, they lack versatility. On the other hand, these special structures have not received a lot of technical demonstrations, and complex structures are often accompanied by lower reliability.

In the initial concept of the project theme, a robot prototype with the appearance of insects or spiders has always occupied the centre of the discussion. Robotics from the University of Leeds also made many contributions to such research. In the Self Repairing Cities, the project led by Professor Richardson, contains a miniature robot called “DORA”as shown in Figure 2.5. It is moved by mechanically driven six legs and has a very small body. But it is foreseeable that because the leg design of "DORA" does not contain a high level of freedom, the athletic ability will be limited. At the same time, it cannot carry non-customized sensors.

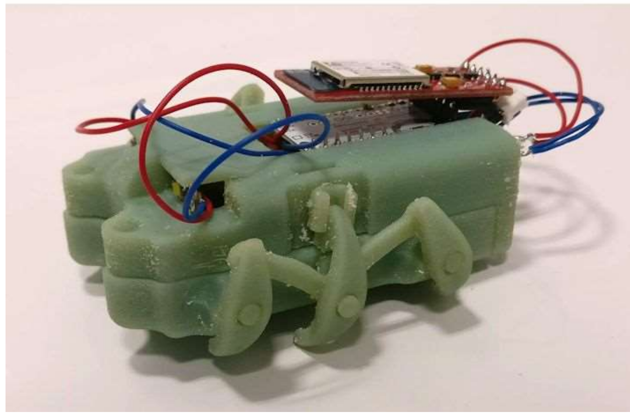


Figure 2.5 The Deployable Robot Assistant (DORA) (SELF REPAIRING CITIES, 2018).

In another project, Pipebots, also led by Professor Richardson, a micro-robot for underground pipelines was proposed (Pipebots, 2019). In the demonstration video of the Pipebots project (Pipebots 2, 2019), the depiction of the robot concept left a deep impression. This impression eventually became the original framework of miniature exploration robot. The screenshots of videos are shown in Figure 2.6.

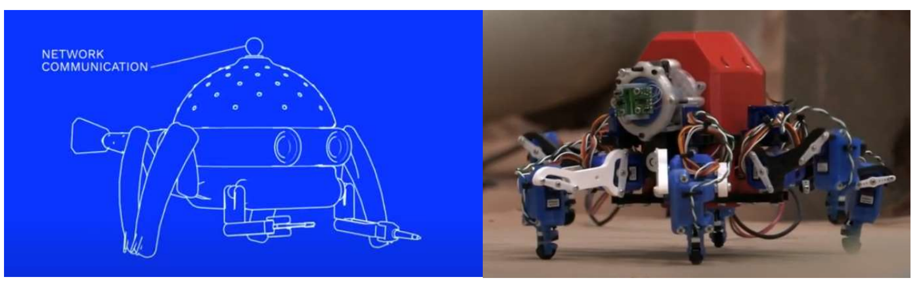


Figure 2.6 The Conceptual design (Pipebots 2, 2019) and engineering prototype (Pipebots on the BBC!, 2019) of Pipebots.

2.4 Walking Robots

Even if the design of the project is clearly identified as a walking robot with legged structure, the scope of articles for reference has not been reduced too much. At present, the power part of most robots still uses a wheeled structure which often encounter problems on non-paved roads. This situation seems to ignite designers' enthusiasm for the design of walking robots.

In the general design of many walking robots, although the robot dog is the most popular research direction nowadays, this project quickly abandoned articles about it because it seems currently no possible to miniaturize. In contrast, numerous researches and designs of hexapod robots and quadruped robots became the reference of the project. Figure 2.7 shows typical hexapod and quadruped robots. They are robots with a leg structure driven by a servo motors, which are easy to develop and expand.

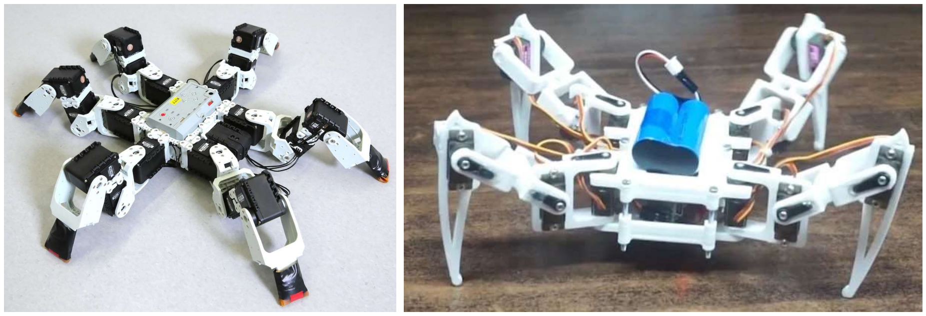


Figure 2.7 A hexapod robot from EPFL in Switzerland (Ackerman, 2017) and a Raspberry Pi quadruped robot (Horsey, 2019).

Many researchers and enthusiasts have provided a large number of development projects for these two types of robots. Vincross's commercial product HEXA proves that this type of robot can maintain ability of movement on any ground (Simon, 2017). On the other hand, an open source project on quadruped robots demonstrates the potential for miniaturization using existing materials (Jason Workshop, 2020). The interest thing is that most of these robots are still above 30cm in size, which is difficult to reach the standard of miniature. For those designs that use mini servo motors to miniaturize the robots, the results are only used as advanced toys, and there is no further work to add functionality by install sensors. The innovation in this point can be the focus of the next project work.

2.5 Multi-robot Cooperation

The miniaturization of robots will bring another technical issue. Mini robots cannot carry many common types of sensors, or even all the parts necessary to explore the environment. A size that is too small will also have a negative impact on work efficiency. It is very easy to find a solution that is to deploy many robots at the same time and let them carry different sensors and then share data between all robots. With the support of IoT and low-latency communication technology, this is a very promising direction.

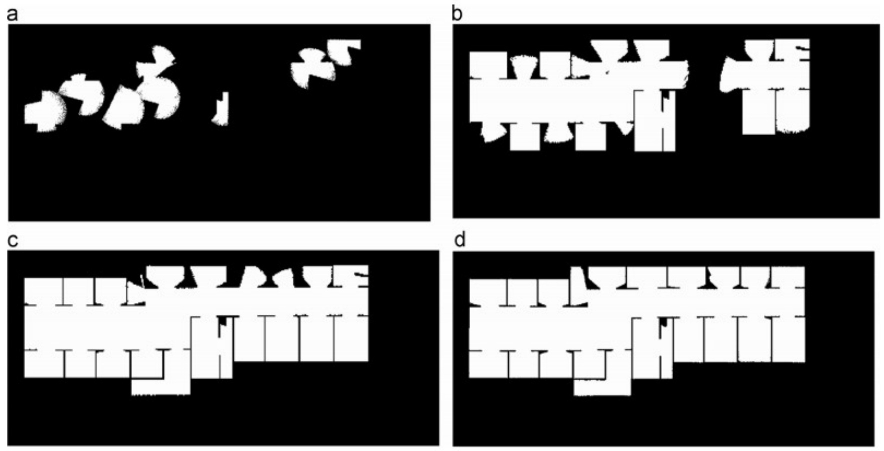


Figure 2.8 The environment exploration simulation using multiple robots equipped with lidar. (Wang et al., 2015).

A number of studies have shown that the idea of realizing multi-robots to explore the environment through data exchange is effective (Burgard, 2005; Nieto-Granda, 2014; Al-khawaldah, 2012; Rekleitis et al., 1997; Wang et al., 2015). The simulation results of one of the studies are shown in Figure 2.8.

However, most simulations only exist as experimental results. In order for the project design to be experimentally demonstrated, how to reproduce this type of simulation with personal hardware and equipment will become one of the most difficult parts of the project.

In addition, the control of multiple robots can also be run by formation control. The formation control algorithm can make the robots or drones quickly arrange in a specific formation. But this algorithm is not suitable for controlling robots in unknown environments. Because the effective transformation of the formation depends on a known and stable environment.

2.6 Automatic Navigation in Unknown Environments

The primary task of the exploration robot is to collect data of various parameters in the field environment. The main control method used by the exploration robot has always been remote control, wired or radio for many years. The operator receives data through the operating terminal and gives control commands to the robot. But with the rapid development of deep learning and AI technology, people are beginning to expect robots to be autonomous and intelligent. But with the rapid development of deep learning and AI technology, people are beginning to expect robots to be autonomous and intelligent. Not to mention that in an environment that is not easy to receive radio signals such as urban pipeline systems and ruins, robots often need to make autonomous judgments by their own.

Among the many problems that robots need to deal with autonomously, the most basic and critical one is how to make a robot to locate, navigate and plan the path in an unknown environment. It seems that robots can rely on satellite positioning, but GPS signals are difficult to receive indoors and underground, and the accuracy is not enough. What the robot needs is centimetre-level or even millimetre-level precise positioning.

Although this requirement seems very strict, in fact, robots that developed by this technology have been widely used in people's daily lives. It can even be said to be the first domestic robot to enter the consumer field. Although this requirement seems very strict, in fact, robots that use this technology have been widely used in people's daily lives. It can even be said to be the first domestic robot to enter the consumer field, that is, the robotic vacuums.

Many people are curious about how robotic vacuums adapt to their new home. The early model used hundreds of collisions against the wall to draw a bordered map. For the past few years, the answer is that they have been installed Lidar and used an algorithm called simultaneous localization and mapping (SLAM). This algorithm allows the robot to measure distance, identify obstacles through lidar or camera and draw a virtual map in the system. At the same time, it can also determine the own position on the map through the results of recognition by lidar or camera to realize autonomous positioning. The intuitive working process of SLAM is shown in Figure 2.9.

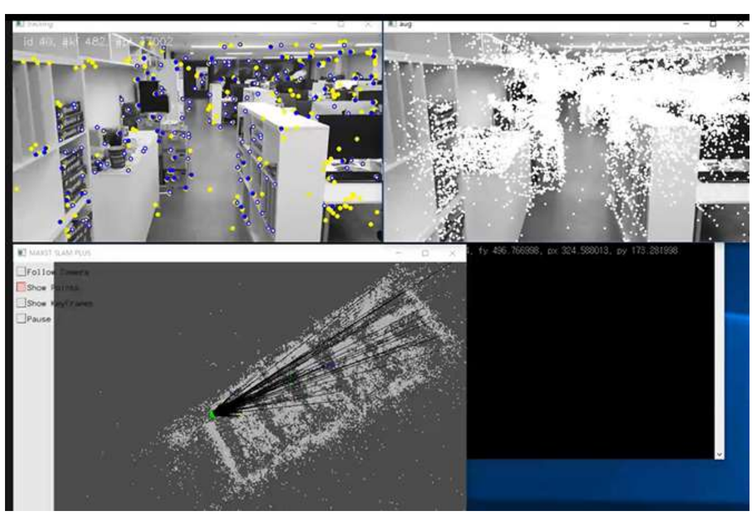


Figure 2.9 A visual SLAM algorithm recognizes the environment and performs real-time mapping. (Park, 2019).

In fact, most of the researches mentioned previously on robot cooperation are all about multi-robot SLAM simulation. The idea of using multiple robots to cooperatively explore the environment is still being actively studied. As mentioned before, the design and simulation of this algorithm will be the most difficult part of the project.

2.7 Development Tools

Through the description of the previous sections, three specific tasks can be obtained:

1. Three-dimensional model design of the robot.
2. Writing the control program of robot and conducting locomotion simulation.
3. Multi-robot cooperation and SLAM simulation.

Based on previous development experience, the CAD model can be completed through Solidworks and Rhino, reliable professional CAD design tools. The control program of the robot can be developed in C++ or Python, which are the languages most commonly used by robot development. There are many development tools available for robot control and locomotion simulation. For the research needs of robot locomotion, a realistic physics engine is necessary. Considering that most robot simulation software requires systematic learning and this will affect the progress of the work, Unity 3D can be used as a simulation tool for robot control. After Stanford University released Robot Operating System (ROS), an open source robot development tool. Almost all SLAM development is based on ROS and supporting tools, which makes ROS became the only choice of SLAM development. This is a new tool that I have never touched before, but it is also an indispensable and important tool in modern robot development.

2.8 Conclusion

In the literature review, the conceptual design of the robot was established by disassembling the keywords in the project title and analysing them one by one. A miniature multi-robot system for environment exploration. The background of all key point in project design were introduced in detail. For some of the difficult parts, it focuses on analysing the work that has been done by other researchers and what can be improved. In general, it is a serious and brand-new engineering challenge to deploy miniature multi-robots to corporately complete exploration tasks in complex environments.

Chapter 3
Robot Design

3.1 Introduction

This chapter will focus on the hardware components and design of the robot. Why did the robot adopt this design; what influence did the component selection have caused on the design; can robot really walk and why the robot eventually formed three variants. All these questions will be answered in detail using intuitive images. Some special ideas and the work done for it will be described. Although some of the robot designs may be confusing, all of them are the basis of the next chapter of control theory.

3.2 Demand Analysis

This project already has a basic design framework, a walking robot with 4 or 6 legs drove by servo motors. But in order to achieve a specific design, a detailed demand analysis is still necessary. In the literature review, many exploration robots have demonstrated their unique functions. These functions, such as rescue and sample collection, rely on customized actuators. The design of this kind of actuator is also a complex project. For this reason, the functional design of the robot should focus on basic exploration tasks. This requires that the robot can at least perform simultaneous localization and mapping; detect temperature and humidity; return live images and sound information from field. Figure 3.1 shows these tasks that robots should complete in environmental exploration. In the design, suitable sensors can be selected based on these requirements.

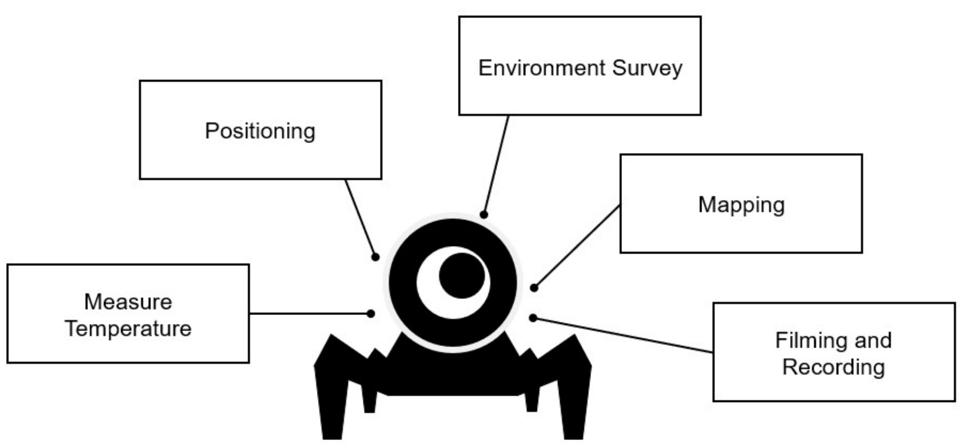


Figure 3.1: Information that the robot should obtain when exploring the unknown environment.

In terms of robot control, it is obvious that the robot needs at least one single-board microcontroller, a complete microcontroller built on a single circuit board, to control the servo motors and receive signals from the sensors. However, mainstream single-board microcontrollers, such as Arduino, cannot handle complex calculations and data. Therefore, the robot also needs a single-board computer to run various algorithms needed for intelligence and many applications of Robot Operating System (ROS).

In addition, the robot must also have the function of communication to return data and be controlled by remote terminal. More importantly, it has to be miniaturized.

3.3 Design Framework

This section will introduce how several key designs of the robot are determined, and explain the working principle of the robot from the system level.

3.3.1 System Block Diagram

A block diagram of robot system can make people better understand how the robot works. As shown in Figure 3.2, it shows the structure of the robot system and the communication relationship between each individual module.

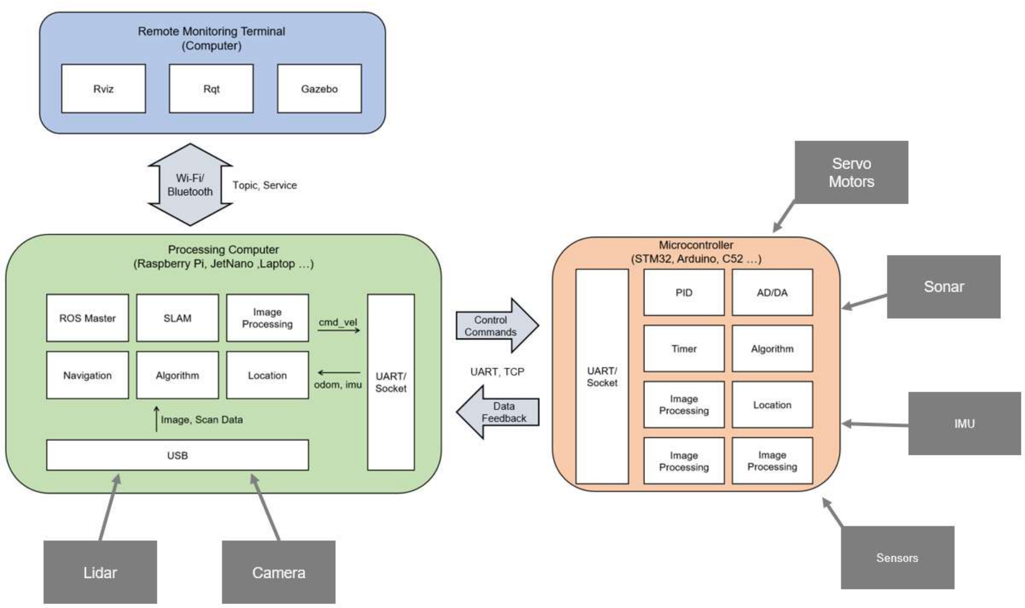


Figure 3.2: The system block diagram of the robot.

As the control components of the robot, the microcomputer and the microcontroller are responsible for different parts. Although microcontrollers like Arduino cannot run operating systems and complex applications, their digital I/O interfaces can effectively control small actuators such as servo motors. In addition, it can also be used as a receiving terminal for various sensors and send data to the upper computer or remote monitoring terminal for processing. It is worth noting that in this robot system, the sonar is also connected to the microcontroller. This is because the locomotion device control program of the robot is stored and run in the microcontroller, and the data of sonar is an important parameter of the control program to avoid the robot from hitting obstacles. This is part of the bottom-level control of the robot, not the function of environmental exploration.

The microcomputer will process the data from the lidar, camera and all micro controllers. They communicate directly through common communication protocols, UART (Universal asynchronous receiver-transmitter) or TCP (Transmission Control Protocol). While receiving data, the microcomputer will also send control commands to the microcontroller based on the processing results of the algorithms. The relationship between them is like the brain and the cerebellum. Although the microcontroller can control the robot to walk, run or jump, it still needs a microcomputer to tell the robot where to go, how fast to go, or whether to walk over.

The remote control terminal can connect with the robot through Wi-Fi or Bluetooth to monitor and receive real-time data or directly control the robot.

3.3.2 Locomotion Device

The locomotion device of the robot will affect the final motion capability and the size of the robot. Deciding whether to adopt hexapod or quadruped design and how many degrees of freedom (DOF) the leg structure has is the focus of robot design. However, this work can also be translated into how to achieve the miniaturization of existing robots.

The parameters of a typical hexapod robot can be summarized as:

- Six legs.
- Each leg has 3 DOF and is driven by a total of 18 powerful servo motors.

In order not to weaken the motion ability too much, the size of the robot can be reduced in the following ways:

- Reduce the legs to four.
- Reduce the degree of freedom of each leg to 2 DOF.
- Replaced by mini servo motors.
- Redesign of structural components aimed at miniaturization.

3.4 Components Selection

This section will show the components used in the robot design and the reasons for selection.

3.4.1 Servomotor

The choice of servo motor will determine the design of the robot and the control program that needs to be written. So, it was considered first.

Figure 3.3: The SG90 servo motor.

In conclusion, the robot uses the SG90 servo motor as shown in Figure 3.3. This is basically the smallest model in the market, with a size of only about 2cm but can output a torque of 2.0kg/cm, which can provide enough power for the robot. Most importantly, it has been used in some hexapod and quadruped robot projects with good results (Jason Workshop, 2020; Liang, 2012).

3.4.2 Lidar

Lidar is a complex and expensive component. Even though the growth of the robotic vacuum cleaner market drives the development of lidar products, there are still not many options. Most lidars are designed for robotic vacuum cleaners, and their size is too large. This project chose TFmini plus, a unidirectional lidar. As shown in Figure 3.4, it is very small. Although the scanning capability is not as good as the 360° lidar, it can be made up for by the control theory described in the next chapter.

Figure 3.4: TFmini plus and a typical lidar.

3.4.3 Controller

As mentioned before, the robot needs at least two microprocessors. The upper-level controller for data processing and algorithms uses Raspberry Pi 3 Model B, a single-board computer widely used in robot development.

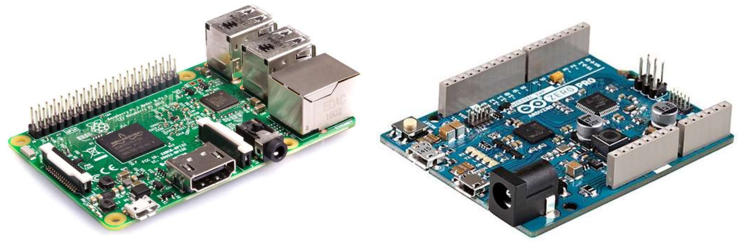


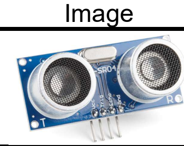
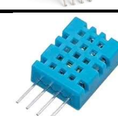
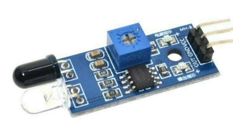
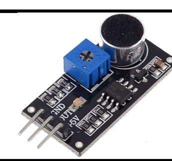
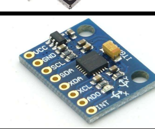
Figure 3.5: Raspberry Pi 3 Model B and Arduino ZERO.

The choice of microcontroller is a problem. Because it needs to control 8 servo motors at the same time, and the servo motors are controlled by PWM signals. Therefore, the microcontroller must have at least 8 pins that can output PWM signals. The initial choice of Arduino UNO was later proved to be completely unable to meet the requirements. But powerful Arduino models are often accompanied by large sizes. Finally, Arduino ZERO is the best choice because of the same size as UNO and abundant signal output. The controllers are shown in Figure 3.5.

3.4.4 Sensors

Some electronic sensors are used in the design to reflect the environment information. They are general products and can be easily used in any mini controller with digital I/O pins. For specific models, please refer to Table 3.1.

Table 3.1: The list of sensors used in robots

Model	Function Description	Image
HC-SR04	Ultrasonic Distance Sensor	
DHT11	Temperature and Humidity Sensor	
Geekcreit	Infrared Obstacle Avoidance Sensor	
LM393	Sound Sensor Microphone	
MPU6050	Inertial Measurement Unit	
OV5647	Camera for Raspberry	

3.5 Prototype

After referring to the work of Liang (2012) and MEGA DAS (2018), the first prototype was designed based on the robot in an open source project published by Jason Workshop. The design and dimensions of the robot prototype are shown in Figure 3.6.

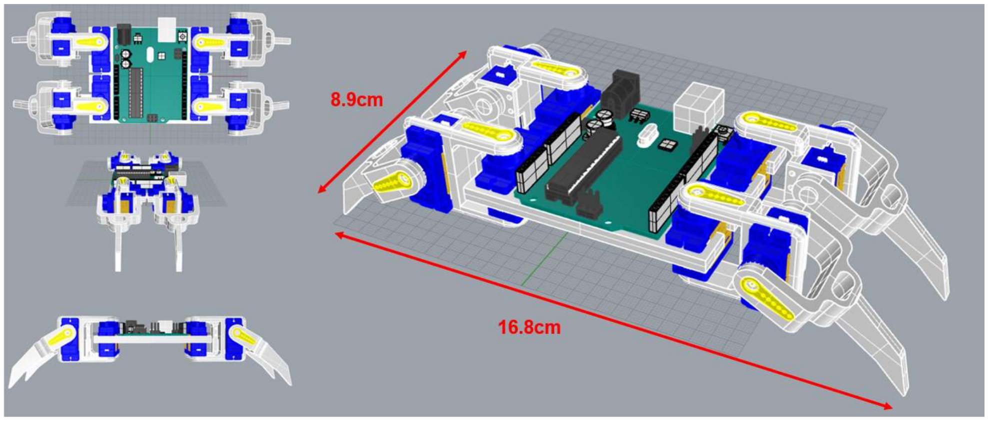


Figure 3.6: The robot prototype.

The prototype has a complete robot structure and an Arduino circuit board for control, which is used as the model for the motion capability verification and control experiment. It was also used as a reference for other robot models designed in this project. The quadruped structure of the prototype allows it to move and turn around freely in different surfaces. The size of the prototype is almost as a human palm, and it can easily enter most pipes and the voids of ruins.

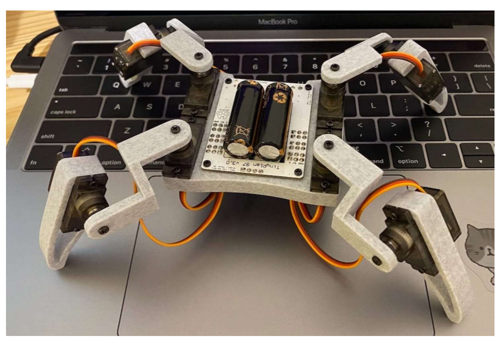


Figure 3.7: Q1 lite 3 (Jason Workshop, 2020).

This design mainly refers to Q1 lite 3, an open source project launched by Jason Workshop (2020). This is shown in Figure 3.7. However, in order for this design to be used for environmental exploration, many places have been improved and redesigned. Their microcontrollers are not the same. Their microcontrollers are not the same. The microcontroller used in Q1 lite 3 is difficult to install other sensors. In addition, the biggest difference lies in the transmission structure of the legs. The leg structure of Q1 lite 3 is too fragile, and the installation position of the servo motor is also prone to break.

In the design of the prototype, a stronger and reasonable leg structure was used to deal with these deficiencies.

3.6 Locomotion Simulation

In this section, a locomotion simulation will be used to prove that the robot design is effective. At the same time, simulation can also prove that the control program written in this project is successful.

The control program of the robot is based on the research of Raheem and Flayyih (2018) on the gait of quadruped robots and a work about quadruped robot development (Atique et al., 2018). The core function of the code is to realize the independent movement of the legs through the separate control of each motor servo. If all four legs can move with the correct gait, then the robot can walk and complete more actions. Figure 3.8 shows a complete gait cycle of the quadruped robot.

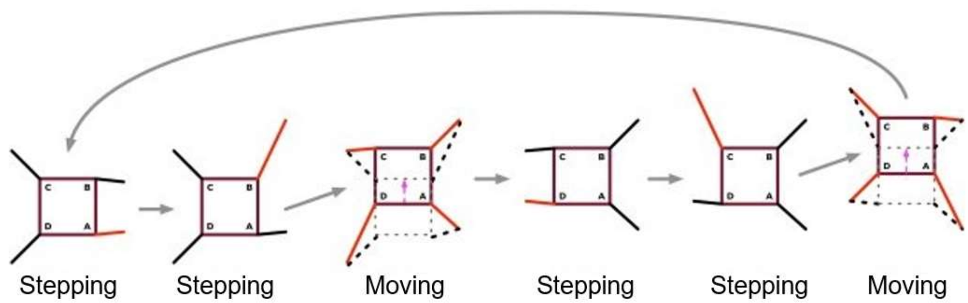


Figure 3.8: A gait cycle of the robot.

The realization of the simulation refers to the hexapod robot project of Cella (2017), which used Unity to perform locomotion control. This project modified part of the code so that they can also work on quadruped robots. The gait of a hexapod robot and a quadruped robot are not the same. For this reason, the code of the gait control part was rewritten. The complete code is attached in Appendix B.

Figure 3.9 shows the simulation process. The collision model of the robot can execute walking and turning instructions under the control of the program in an environment with real physical effects. The design of the prototype and the effectiveness of the control program have been proved by the success of the simulation.

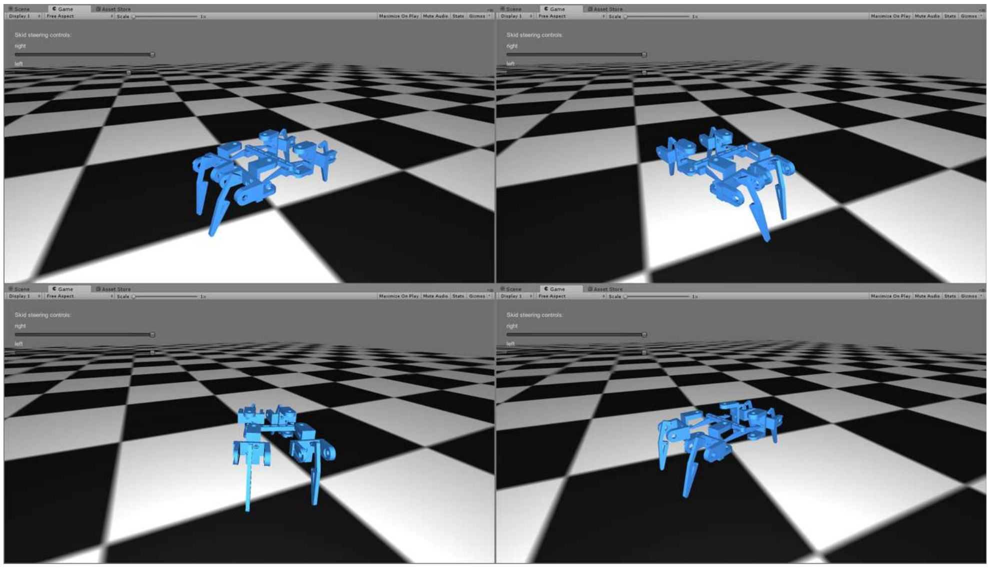


Figure 3.9: The locomotion simulation of Prototype.

3.7 Variants

In the subsequent design work, a difficult problem emerged. The prototype cannot carry too many sensors for environmental exploration, and the power of a small battery cannot drive too many components at the same time. This plight changed the design from a single individual robot to a robot exploration system with various types of robots cooperate with each other. This section will introduce the design of three variants of robots developed from the prototype. The specific working principle will be explained in the next chapter.

3.7.1 "Perceiver"

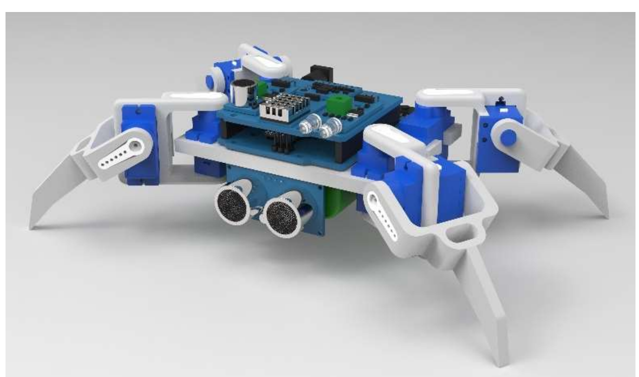


Figure 3.10: The Perceiver.

Perceiver is the most numerous and most basic unit in the system. It is installed an expansion board with ESP8266 WiFi module on the Arduino to realize the communication function. There are two ultrasonic distance sensors in front and behind separately to detect obstacles and avoid collisions with other robot units. The temperature and humidity sensor, microphone module, inertial measurement unit and infrared detector are installed on the expansion board. The data of these sensors can reflect the abnormal conditions in most situations. The structure of Perceiver is shown in Figure 3.11.

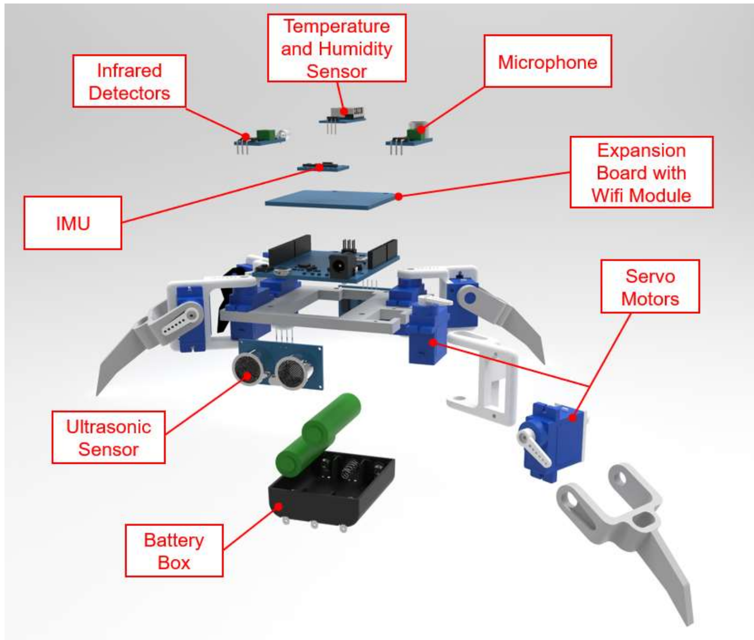


Figure 3.11: The structure of Perceiver.

The Perceiver does not have a Raspberry Pi as the system processor, which makes the Perceiver act like a worker ant. The Perceiver will not judge where to go by themselves, but can get instructions from other robot units or remote control terminals through WiFi communication. The data detected by a large number of Perceivers will become an important part of the entire robot system.

3.7.2 "Seeker"

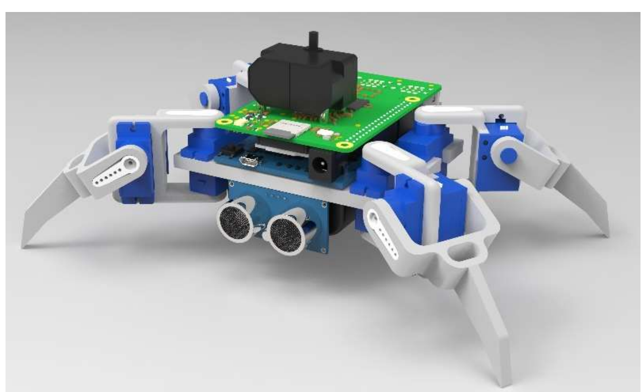


Figure 3.12: The Seeker.

Seeker is the most important part of the entire system. As a scout, the mission of Seeker is to explore the physical features of the environment through the lidar on the back and generate an accurate map by SLAM. This map will become an important basis for system deployment of robots and evaluation of exploration progress. Compared with the perceiver, as shown in Figure 3.12,Seeker has only two sensors: ultrasonic distance sensor and lidar, but it is equipped with a raspberry pie as a processor for SLAM and ROS. This also means that Seeker can generate maps on its own to realize autonomous exploration.

3.7.2 "Watcher"

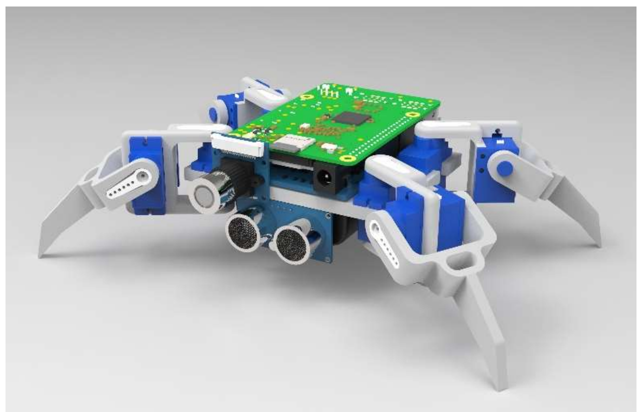


Figure 3.12: The Watcher.

Watcher is almost the same as Seeker, the difference is that Watcher removed the lidar and installed a wide-angle camera dedicated to the Raspberry Pi. Watcher can transmit live video to a remote control terminal, which is complex data that Arduino cannot handle, and take pictures. These image data often become key materials for environmental exploration. Because there is a Raspberry Pi as the processor, Watcher can also run ROS. Since all Seekers have to perform SLAM data processing all the time, they cannot effectively calculate other algorithms. At this time, Watcher can act as the commander of the entire robot system and give instructions to other robot units to complete environmental exploration based on the results of algorithms.

3.8 Discussions

This chapter mainly introduced the design of the robots and proved feasibility. The design of the three robot variants is the most important work. Although the design has improved the degree of completion as much as possible, due to the lack of relevant resources and actual hardware development, all the results can only be regarded as conceptual designs under ideal conditions.

In the robot design, there may be many technical problems that only occur in the actual manufacturing and experiment process, such as the communication delay between the Arduino and the Raspberry Pi, or the accuracy of the sensor cannot meet the requirements.

However, these are not very fatal flaws. The whole work demonstrated the core concept of modular design from the very beginning. Both Arduino and Raspberry Pi are used for robot control by many robot projects individually or simultaneously. In this project, a large number of interfaces are also reserved, which provides the possibility for sensor replacement or expansion. This makes this project to offer a effective robot development framework even though it only completed the conceptual design.

Chapter 4

Control Theory

4.1 Introduction

The number of robots has increased significantly since the beginning of this century. How to control a large number of robots at the same time has become a hot research topic. After understanding the design of the robot, this chapter will focus on how the three variants of robot work as a system.

4.2 System overview

In the theoretical design of the system, In the theoretical design of the system, the core concept is to complete the exploration of the environment through the cooperation of multiple robots. This idea is also reflected in the design of the robot. The ideal work processing of the system should like shown in Figure 4.1.

Figure 4.1: Cooperation of multiple robots in environmental exploration.

When the robot system is deployed, Seekers which carry lidar will first conduct an ergodic exploration of the environment. Generating a virtual map by SLAM. For a single robot, it will consume a lot of time to map the entire environment through ergodic exploration. If this is a post-disaster search and rescue operation, then the efficiency of exploration must first be considered. The biggest advantage of multiple robots is reflected in the efficiency of exploration. Seekers can explore in different directions and realize multi-robot SLAM through mutual communication. This multi-robot SLAM algorithm can greatly reduce the exploration time and has a huge advantage in time-sensitive exploration activities. On the other hand, Seekers can also be used for positioning other robots. The fact is that only Seeker can confirm their position on the virtual map at any time through lidar. But as long as there are three Seekers that can communicate with WiFi, the precise position of each robot unit can be achieved through the trilateration technique. This WiFi-based indoor positioning technology has been proven feasible (Ilci et al., 2015).

For Watchers, in addition to being instructed by the terminal to send back image data to a specific location when necessary, they also act as commanders and signal relay towers. Since each robot unit can maintain a real-time connection via WiFi, the virtual map is shared in the entire robot system. Watch can assign a large number of Perceivers to every corner of the environment through the virtual map to detect whether there are temperature or sound abnormalities.

The relationship between the various units in the system can be summarized as Figure 4.2.

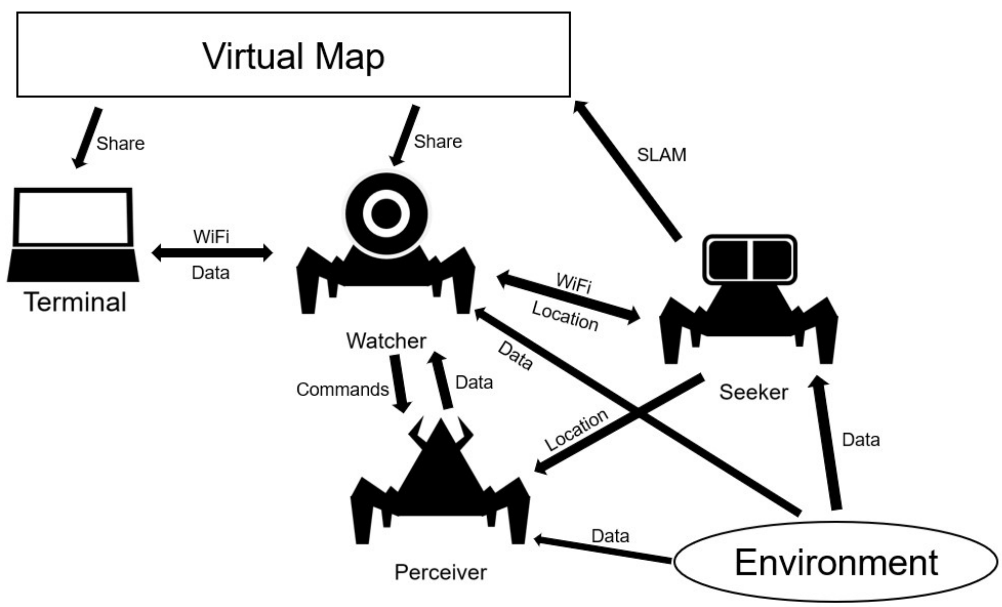


Figure 4.2: Block diagram of the system.

4.3 Algorithm theories

The system principles described above seems too complicated to be realized, but in fact every step of the action can be completed by a specific algorithm. Such as the control behaviour of watcher. It is very difficult for Watcher to give Perceiver a specific order. But Watcher can use the ant colony optimization to assign where Perceiver should go. Ant colony optimization is often used for path finding or path planning in the field of robotics. But in an environment where a large number of robots are deployed, it is more likely to be used to achieve the original function.

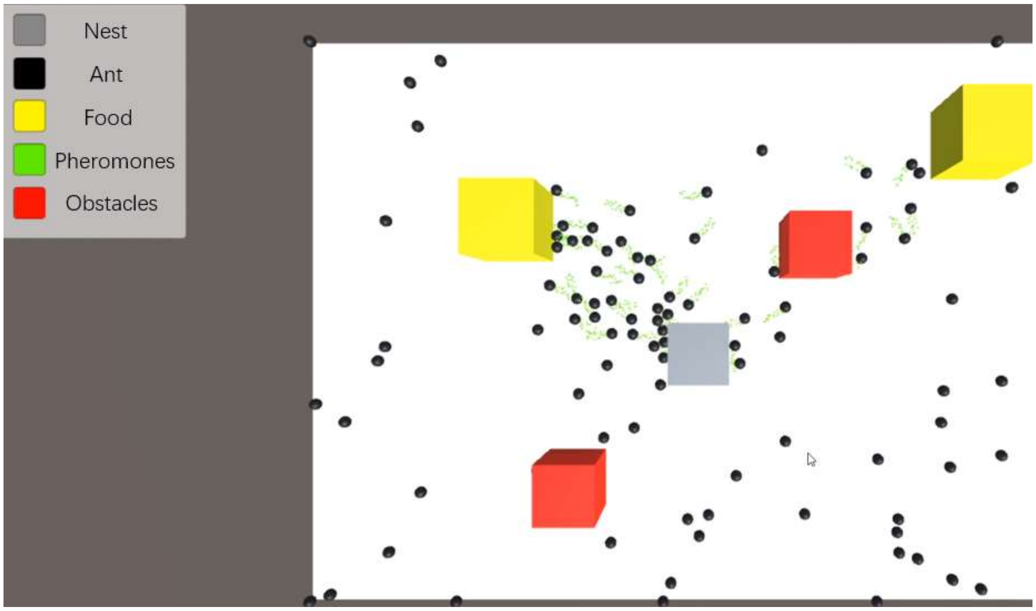


Figure 4.3: The simulation of ant colony algorithm.

After referring to a research on ant colony algorithm simulation (Cheng et al., 2017), this project tried to reproduce the simulation effect in the research. Figure 4.3 Shows the reproduction of this simulation. It can be found that the ants in the simulation will walk around between the food and the nest because of the pheromone. In environmental exploration, food can be replaced with feature points, such as abnormal high temperature and sound, so that the robot has higher efficiency than ergodic search.

In addition, many behaviours described in the system principle are similar to some activities of social insects such as ants or bees. This is very similar to the concept of swarm intelligence.

4.4 Automatic SLAM simulation of Multi-robot

From the system concepts described in the previous sections, it can be found that the multi-robot SLAM performed by Seeker is the foundation of the entire system. Only after Seekers generate virtual maps through SLAM, Watcher and Perceiver can take the next action. In order for the system design of this project to have some experimental data or results as evidence for the discussion, this section will focus on the simulation of multi-robot autonomous SLAM.

4.4.1 Simulation Preparing

SLAM technology has been widely used in robotic vacuum cleaners and self-driving cars. But most of these projects are individual SLAM. In the research of multi-robot SLAM, many algorithms have been proposed (Atanasov et al., 2015; Lee et al., 2009; Abdulgalil et al, 2017). The most commonly implemented algorithm is to directly merge multiple robots through the maps generated by SLAM. The autonomous exploration and path planning of SLAM robots is also a focus of the SLAM algorithm. The simulation plan is to try to use two ROS packages, multirobot_map_merge and explore_lite, in the built virtual environment. They are all ROS packages published and maintained by Horner (2019). Explore_lite use greedy frontier-based exploration to make the robot automatically explore the environment greedily. Multirobot_map_merge can provide a global map for multiple robots. It can merge the maps of any number of SLAM robots.

4.4.2 Building Simulation Environment

The robot model used in the simulation is Turtlebot3, a SLAM robot officially developed by ROS. The robot model used in the simulation is Turtlebot3, a SLAM robot officially developed by ROS. It has a 360° lidar and is very similar to the robot in the project on the system framework. The virtual environment used the house environment in turtlebot package, and three turtlebot3-burgers were deployed in it as shown in Figure4.4.

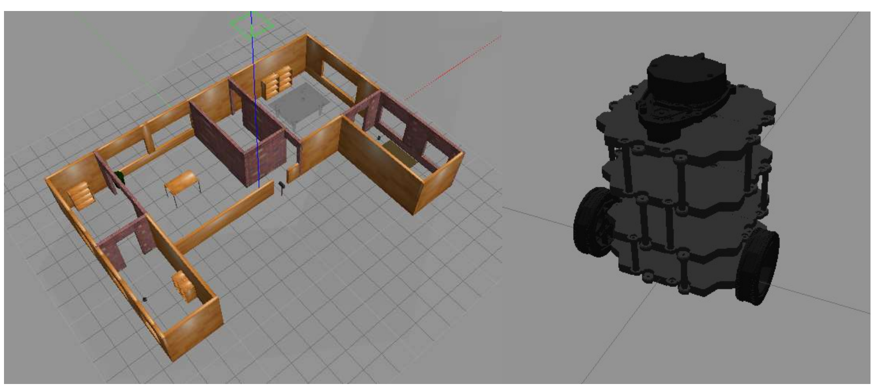


Figure 4.4: The simulation environment and model of turtlebot 3.

4.4.3 Simulation Result

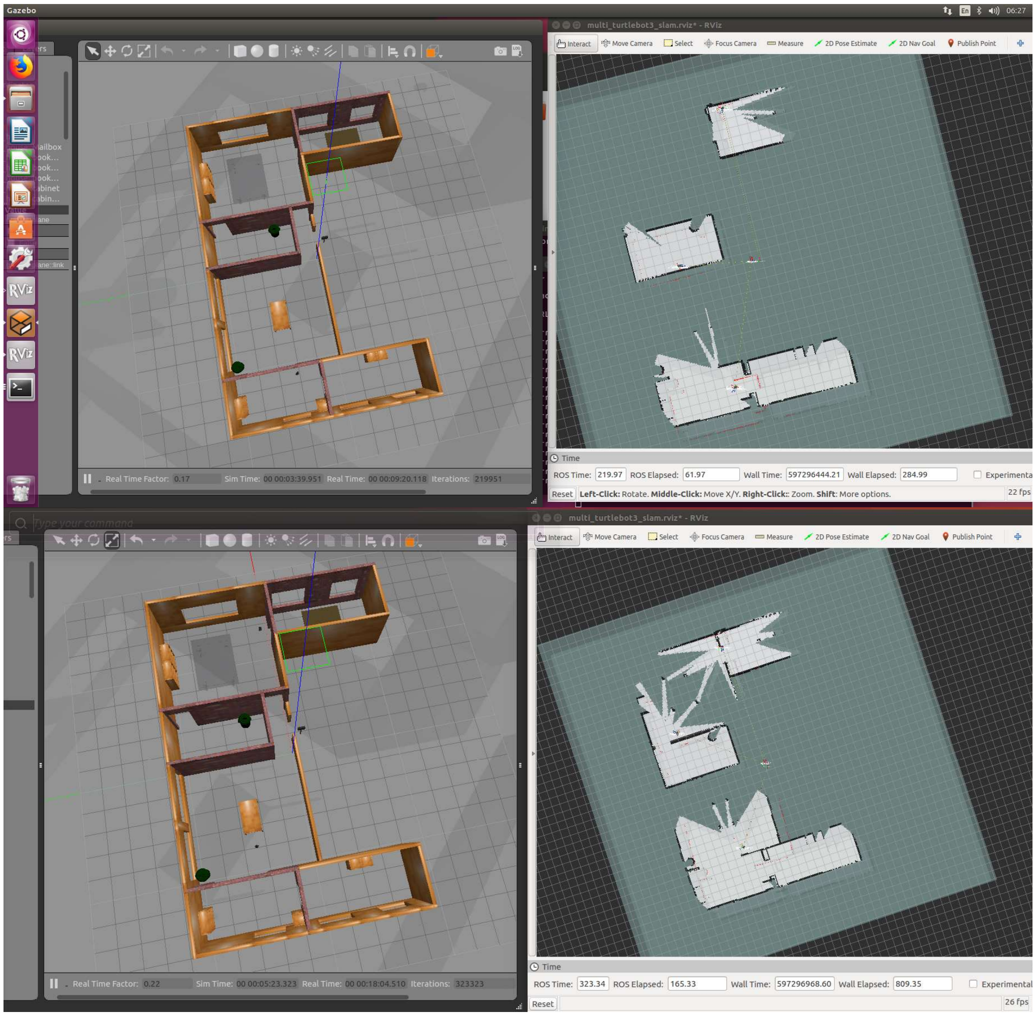


Figure 4.5: a) Simulation Start. b) Automatic Exploration.

Figure 4.5a shows that at the beginning of the simulation, the SLAM maps of the three robots were merged to form a global map. At the same moment, turtlebot3 began to explore the environment autonomously. Figure 4.5b shows the process of drawing the house map gradually. At this time, the node structure diagram of ROS is shown in Figure 4.6.

This simulation shows that the multi-robot SLAM is completely feasible and easy to implement, making the actual development of the multi-robot exploration system possible.

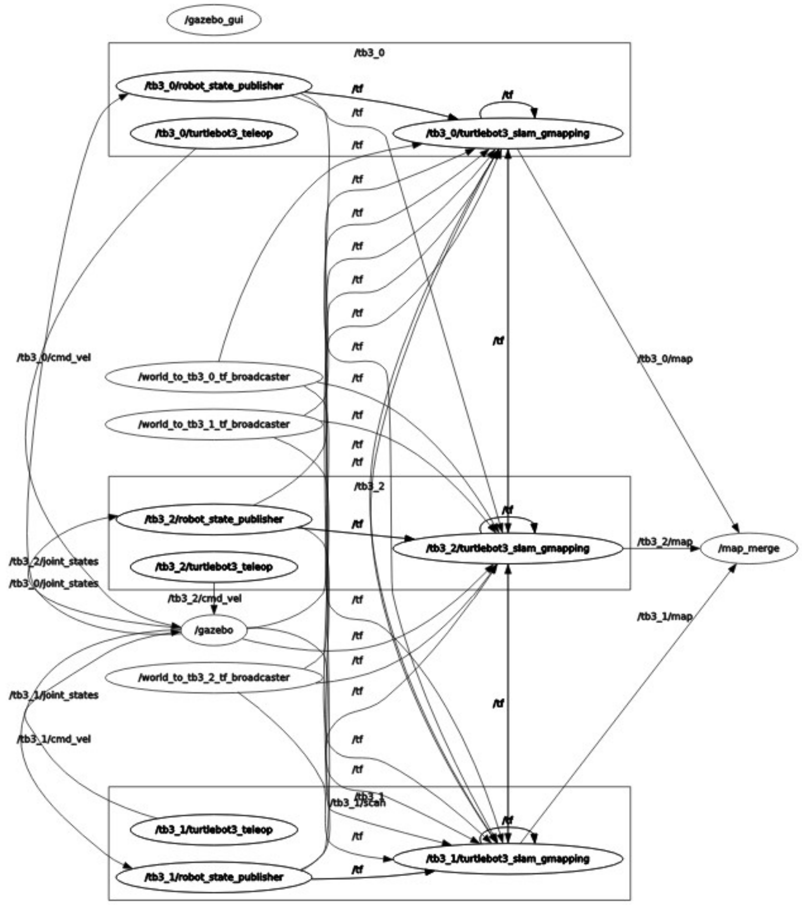


Figure 4.6: The node structure of ROS when simulation.

4.5 Discussions

From the system concepts described in the previous sections, it can be found that the This chapter details how the multi-robot exploration system works. It involves some concepts of swarm intelligence and the simulation of several key algorithms. Similar to the design of the robot itself, too many concepts will make the design less convincing.

However, the idea of allowing different types of robots to cooperate in environmental exploration is still novel. The simulation of multi-robot SLAM also enhances the theoretical foundation of the system design.

Chapter 5
Conclusion

5.1 Achievements

In this professional project, the achievements are as follows:

1. The design of three types of mini exploration robots.
2. Design and simulation of robot locomotion control program.
3. Framework design of multi-robot exploration system.
4. Realization of multi-robot SLAM simulation.

All the objectives mentioned in the first chapter have been completed, and the results even exceeded the initial expectations.

5.2 Discussions

As discussed at the end of the previous two chapters, the design of this project contains too many concepts, making the design less convincing. However, some of these concepts are supported by simulation results, which greatly increases the feasibility of the design. In general, this is a conceptual design that requires more future work.

5.3 Conclusions

This project has completed the design of a multi-robot exploration system through various aspects of work. Some of the technologies involved in the work, such as ROS and SLAM, are the first time to learn and use. The inspiration of emerging technologies and the images caused by Covid-19 have changed the working direction and design ideas of the project several times. This made the structure of the project not very complete. However, with the support of simulation results, this design still has great potential.

5.4 Future work

The multi-robot exploration system still has a lot of work to be done. The first thing is to make real Seeker, Watcher and Perceiver through the material and component list. There are many problems that only appear in the actual manufacturing process. On the other hand, many algorithms designed in the system design have not yet been verified. This work may turn the final project into a large engineering project that is several times more complex than it is now.

Appendix A

The Three-view Drawing of the Robot