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Dedication

الحَمْدُ لله الَّذِي هَدَانَا لِهَذَا وَ مَا كُنَّا لِنَهْتَدِيَ لَوْلَا أَنْ هَدَانَا الله

To my beloved mother, the one who carried me in her heart long before I even knew myself. Your gentle voice, your constant prayers, your silent sacrifices, and your boundless love gave me strength in my weakest moments. Your presence alone is a source of healing, and your love pure and unconditional is the greatest comfort I've ever known. Thank you for everything, Mama. May Allah bless your soul with joy in this world and the next.

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Dedication

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Imane ✨

Summary

General Introduction 1

I. Chapter 1: Introduction to Robotics 4

I.1. Introduction 5

I.2. Robot Fields 5

I.2.1. Industrial Robotics 6

I.2.2. Service Robotics 6

I.2.3. Agricultural Robotics 7

I.2.4. Space Robotics 8

I.2.5. Military and Defense Robotics 9

I.2.6. Entertainment and Social Robotics 10

I.2.7. Environmental Robotics 10

I.2.8. Medical Robotics 10

I.2.8.1. Surgical Robots 12

I.2.8.2. Rehabilitation Robots 12

I.2.8.3. Diagnostic Robots 12

I.2.8.4. Disinfection Robots 12

I.2.8.4.1. Importance of Disinfection Robots 13

I.2.8.4.2. Disinfection Methods 15

a) Ultraviolet-C Radiation (UV-C) 15

b) Hydrogen Peroxide Vapor (HPV) 17

c) Electrostatic Spraying 20

d) Combination of Several Methods 21

I.3. Conclusion 23

II. Chapter 2: Design of disinfection robots 24

II.1. Introduction 25

II.2. General Architecture of the System 25

II.2.1. Power Supply 26

II.2.1.1. Lithium battery 26

II.2.2. Microcontroller 27

II.2.2.1. Arduino Uno Board 27

II.2.3. Driver L293D 34

II.2.4. Emitter 37

II.2.4.1. Ultraviolet LEDs 37

II.2.5. Actuators 40

II.2.5.1. DC Motor ... 40
II.2.5.2. Servo Motor ... 44
II.2.5.3. Stepper Motor ... 46
II.2.5.4. DC Mini Water Pump ... 48
II.2.6. Sensors ... 50
II.2.6.1. Ultrasonic sensor ... 50
II.2.6.2. HC-SR501 PIR Sensor ... 53
II.2.7. Communication ... 56
II.2.7.1. NodeMCU ESP8266 ... 56
II.2.7.2. MIT App Inventor ... 57
II.3. Conclusion: ... 59
III. Chapter 3: Practical Implementation and Experimental Results ... 60
III.1. Introduction ... 61
III.2. Simulation and System Design ... 61
III.2.1. Movement System Simulation ... 61
III.2.1.1. Circuit Design ... 61
III.2.1.2. Algorithmic Flow ... 63
III.2.1.3. Functional Description ... 65
III.2.2. Disinfection System Simulation ... 67
III.2.2.1. Ultraviolet LEDs System ... 67
III.2.2.1.1. Circuit Design ... 67
III.2.2.1.2. Algorithmic Flow ... 68
III.2.2.1.3. Functional Description ... 69
III.2.2.2. Liquid Disinfection System ... 70
III.2.2.2.1. Circuit Design ... 70
III.2.2.2.2. Algorithmic Flow ... 71
III.2.2.2.3. Functional Description ... 72
III.2.3. Communication System Simulation ... 73
III.2.3.1. Circuit Design ... 73
III.2.3.2. Application Interface ... 74
III.2.3.3. Algorithmic Flow ... 77
III.3. Experimental Setup ... 78
III.3.1. Hardware Components ... 79
III.3.2. Testing Environment ... 79
III.3.3. Test Protocol and Methodology ... 80
III.4. Testing of Individual Components ... 80

III.4.1. Accuracy of the Ultrasonic Sensor ... 80
III.4.2. Servo Motor Angle Accuracy ... 85
III.5. Movement System Evaluation ... 88
III.5.1. Smoothness of Movement and Rotation Speed ... 89
III.6. Disinfection System Evaluation ... 91
III.6.1. UV-C LED Disinfection System ... 91
III.6.1.1. Limitations of Implementation and Simulation-Based Validation ... 91
III.7. Full System Integration Test ... 93
III.7.1. Test Procedure ... 93
III.7.2. Results ... 94
III.7.3. Analysis ... 95
III.8. Discussion and Analysis ... 96
III.9. Challenges and Limitations ... 97
III.10. Conclusion ... 98
BUSINESS MODEL CANVA (BMC) ... 99
General Conclusion ... 120
Perspectives ... 122
Bibliography ... 123
Abstract ... 128

Table of Figure

Figure I.1 (a): Classification of industrial robots based on functionality in manufacturing Systems [4], **(b):** Application of the ur10 collaborative robot with onrobot gripper in industrial pick-and-place tasks [5] 6
Figure I.2 Service robot demonstration [7] 7
Figure I.3 Coordinated robot farming systems [9] 7
Figure I.4 Curiosity rover on mars exploration mission [10] 8
Figure I.5 Europa Clipper flight system with solar arrays and reason antennas in close approach configuration [11] 9
Figure I.6 Pitbull with Sig Sauer 338 MMG firing on the move | Photo Credit: General Robotics [13] 9
Figure I.7 (a): Exploring the future of rescue robots: advancements in search and rescue technology [15]. **(b):** Drone delivering first aid kit for disaster response | Image: Shutterstock [16] 10
Figure I.8 Two examples of the da Vinci surgical system 12
Figure I.9 Light spectrum representation and UV-C wavelength range 15
Figure I.10 Formation of thymine dimers under UV-C exposure 16
Figure I.11 Common pathogenic bacteria found in surgical environments 17
Figure I.12 Structural damage to E. coli induced by liquid and vapor-phase hydrogen peroxide 18
Figure I.13 Forms of bio quell and steris hydrogen peroxide vapor systems 19
Figure II.1 Block diagram of disinfection robot design 25
Figure II.2 Samsung INR18650-25R lithium-ion battery cell (3.6V / 2500mAh) [30] 27
Figure II.3 Arduino uno pinout diagram [32] 29
Figure II.4 Interface of Arduino IDE (1- Code editor, 2- Library manager, 3- Serial monitor, 4- Toolbar with buttons for common functions, 5- Verify, 6- Upload, 7- Board manager) 30
Figure II.5 Code and organogram showing DC motor control with $AFMotor.h$ library 31
Figure II.6 Servo motor control using $Servo.h$ library 32
Figure II.7 Serial communication with ESP8266 using $SoftwareSerial.h$ 33
Figure II.8 Distance measurement using ultrasonic sensor without external library 34
Figure II.9 L293D IC pinout [34] 35
Figure II.10 Pinout of the L293D motor driver shield [33] 36
Figure II.11 Package schematic with mechanical dimensions (mm) for 365nm UV LED emitter (LZ1-00U600) [35] 38
Figure II.12 Brushed motor and brushless motor [40] 41
Figure II.13 Schematic diagram of a DC gear motor structure [41] 42
Figure II.14 Overview in servo motor [42] 44
Figure II.15 Servo Motor Internal Diagram [42] 45
Figure II.16 The relation between pulse width and servo motor arm position [42] 45
Figure II.17 (a): Basic structure of a stepper motor showing the rotor (rotating part) and stator (stationary part). **(b):** Illustration of how sequential current flow in coils generates discrete steps in rotor movement. [44] 47
Figure II.18 Diagram of a DC mini water pump showing the internal motor, impeller chamber, inlet and outlet ports. [48] 49
Figure II.19 Examples of different object types encountered by ultrasonic sensors [50] 51
Figure II.20 Ultrasonic sensor front view with pin configuration [50] 52
Figure II.21 The HC-SR501 sensor layout and specs 54

Figure II.22 Pinout diagram of NodeMCU ESP8266EX [53] 57
Figure II.23 Designer and Blocks editor of the platform of MIT App Inventor. (a): Designer, (b): Blocks Editor 58
Figure III.1 Placement of each motor of the robot 62
Figure III.2 Obstacle avoiding robot 62
Figure III.3 Algorithmic flow for an obstacle avoiding robot 63
Figure III.4 Algorithmic flow for $compareDistance()$ function 65
Figure III.5 A Simulation in proteus for the UV LED system 67
Figure III.6 Algorithmic flow for UV LED system 68
Figure III.7 Circuit diagram of the liquid disinfection system 70
Figure III.8 Algorithmic flow for liquid disinfection system 71
Figure III.9 Circuit diagram of the communication part (Black wire is GND, Red wire (from RX of ESP8266 to TX of Arduino Uno), Green wire (from TX of ESP8266 to RX of Arduino Uno)) 74
Figure III.10 Navigation diagram of the mobile application interface 76
Figure III.11 Algorithmic flow of the communication between mobile app, ESP8266, and Arduino uno boards. 77
Figure III.12 The test place of the precision and accuracy of the ultrasonic sensor (HC-SR04) 81
Figure III.13 Graph of measured distance versus actual distance using MATLAB 83
Figure III.14 Graph of relative and absolute error versus actual distance using MATLAB 84
Figure III.15 Test of servo motor angle accuracy 85
Figure III.16 Graph of average measured angle versus commanded angle 87
Figure III.17 Graph of error versus commanded angle 88
Figure III.18 Effect of motor speed on rotation time for 90° turn 90
Figure III.19 Diagram of the simulated system in the inactive state 92
Figure III.20 System in the active disinfection state (no motion detected) 92
Figure III.21 System in the standby state (motion detected, LED off). 93
Figure III.22 Prototype of the disinfection robot during integration test 94
Figure III.23 Overhead view for prototype of the disinfection robot during integration test 94

Table of Tables

Table I.1 Examples of Recent Advances in Biomedical Engineering [17] 11
Table I.2 Comparison of Automated Disinfection Systems for Contact-Free Room Sanitization [23] 14
Table I.3 Minimum UV-C Exposure Doses ($D90$) for Effective Surface Disinfection.......... 16
Table I.4 Comparison of Automated Room Disinfection (ARD) Systems 22
Table II.1 The Arduino Uno technical specifications 28
Table II.2 Configuration of Arduino Uno Pins [32] 29
Table II.3 Comparison between UV Lamps and UV LEDs... 39
Table II.4 Characteristics of some UV LEDs [35], [36], [37].. 40
Table II.5 Performance Parameters and Operational Features of a Stepper Motor 47
Table II.6 Advantages and Limitations of the mini water pump... 50
Table II.7 The Specifications and Features of the HC-SR501 PIR Sensor 55
Table III.1 User Interface Screenshots of the Mobile Application 75
Table III.2 Table of Results of Measured Distance Absolute Error and Relative Error......... 82
Table III.3 Commanded vs Measured Angles 86
Table III.4 Robot Rotation Behavior at Various Motor Speeds for 90° Turn 89

Abbreviations

UV-C: Ultraviolet type C

LED: Light Emitting Diode

HPV: Hydrogen Peroxide Vapor

DC: Direct Current

MIT: Massachusetts Institute of Technology

Cobots: Collaborative Robots

COVID-19: Corona Virus Disease 2019

HAIs: Hospital-Acquired Infections

NTD: No-Touch Disinfection

H_2O_2: Hydrogen Peroxide

PX-UV: Pulsed Xenon Ultraviolet

Log: Logarithmic Measure

DNA: Deoxyribonucleic Acid

RNA: Ribonucleic Acid

MRSA: Methicillin-Resistant Staphylococcus Aureus

ROS: Reactive Oxygen Species

DHP: Dry Hydrogen Peroxide

AHP: Accelerated Hydrogen Peroxide

PIR: Passive Infrared

I/O: Input / Output

SRAM: Static Random-Access Memory

EEPROM: Electrically Erasable Programmable Read-Only Memory

USB: Universal Serial Bus

PWM: Pulse Width Modulated

UART: Universal Asynchronous Receiver/ Transmitter

I2C: Inter Integrated Circuit (Inter to Circuit)

SPI: Serial Peripheral Interface

IDE: Integrated Development Environment

IC: Integrated Circuit

EMF: Electromotive Force

ESD: Electrostatic Discharge.

MCPCBs: Metal Core Printed Circuit Boards

PCBs: Printed Circuit Boards

RPM: Revolutions Per Minute

T: Torque

GR: Gear Ratio

3D: Three Dimensional

NPN: Negative-Positive-Negative

DIY: Do It Yourself

TTL: Transistor-Transistor Logic

IoT: Internet of Things

TCP: Transmission Control Protocol

IP: Internet Protocol

RISC processor: Reduced Instruction Set Computer

I2S: Inter-IC Sound (Inter to Sound)

Wi-Fi: Wireless Fidelity

IEEE: Institute of Electrical and Electronics Engineers

WPA/WPA2 security: Wi-Fi Protected Access/ Wi-Fi Protected Access 2

HTTP: Hyper Text Transfer Protocol

JBT: Junction Bipolar Transistor

GND: Ground

General Introduction

General Introduction:

In recent years, healthcare systems have faced unprecedented challenges in ensuring infection control, especially in hospital environments. One of the most critical issues is the persistence of pathogens on surfaces and the high risk of transmission through direct or indirect contact. Traditional manual disinfection methods, though widely practiced, remain subject to human error and do not guarantee complete coverage, particularly in shaded or hard-to-reach areas.

With the advancement of robotic technologies, there has been growing interest in automating disinfection processes to improve safety, efficiency, and reliability. Robots can operate continuously, avoid fatigue, and minimize the need for human involvement in high-risk environments. In this context, the present project aims to design and implement a hospital disinfection robot capable of operating autonomously using dual disinfection technologies: UV-C LED (Ultraviolet type C Light Emitting Diode) radiation and liquid-based spraying with an integrated drying system.

Furthermore, the robot is designed to include a safety mode that ensures it halts operation in the presence of nearby individuals to avoid potential harm, and it can be remotely controlled via a mobile application. This system is expected to reduce the workload on medical personnel, allowing them to focus on critical care tasks rather than routine sterilization duties.

It is hypothesized that combining UV-C and liquid disinfection methods in a mobile autonomous robot will ensure broader and more effective surface sterilization in hospital environments. Additionally, incorporating a human safety mode and remote control via smartphone is expected to enhance usability and reduce risks associated with manual disinfection.

Manual disinfection methods in hospitals pose risks due to human error and exposure to harmful agents. With the rising need for contactless solutions, one may ask:

How can robotic technologies be leveraged to develop an autonomous, efficient, and safe disinfection system for hospitals?

To answer this question, the project has been structured into three main chapters.

The first chapter provides a comprehensive overview of the field of robotics, with a focus on medical robots and particularly disinfection robots. It explores various disinfection methods such as UV-C radiation, hydrogen peroxide vapor (HPV), and electrostatic spraying, discussing their benefits and limitations.

Chapter II focuses on the design of the disinfection robot, presenting the overall system architecture including power supply, microcontroller (Arduino Uno), actuators (DC motors, stepper motor, water pump), sensors, ultraviolet LED emitters, and the communication module (ESP8266 and MIT App Inventor).

Chapter III covers the simulation, practical implementation, and experimental validation of the robot, highlighting sensor accuracy, movement efficiency, disinfection performance, and full system integration, along with a discussion of challenges and comparisons between simulation and real-world application.

The expected outcome of this project is a prototype of a fully functional autonomous robot capable of performing disinfection using two distinct methods: (1) UV-C LED disinfection, equipped with a safety mechanism that stops the robot when human presence is detected, and (2) a spraying system using sterilizing solutions such as hydrogen peroxide, with an integrated drying mechanism. Additionally, the robot should be controllable remotely via a smartphone application for manual navigation and activation of disinfection modes.

I. Chapter 1: Introduction to Robotics

I.1. Introduction

Robotics brings together many disciplines from engineering, computer science and artificial intelligence. This field focuses on understanding and developing how robots operate and control [1]. Robots are programmable machines capable of executing a series of actions (commands) autonomously or semi-autonomously in coordination with humans. Robots are often tasked with tasks that are either inaccessible to humans, dangerous places, difficult tasks and even repetitive tasks.

Since the inception of this field (Robotics), it has been in continuous and significant development, thanks to the development of sensors, actuators, control systems, and machine learning algorithms.

Since the first appearance of the term robot, early automation and mechanical devices were the precursor to modern robotics. They have evolved to become ubiquitous in our lives, playing an important role in many areas such as transportation, industry, agriculture, space exploration, healthcare and many others [2], revolutionizing the way tasks are performed and problems are solved.

I.2. Robot Fields

In this section, we will take a look at the key areas where robotics has made a significant impact. Robotics has expanded far beyond its industrial origins, penetrating every aspect of modern life.

I.2.1. Industrial Robotics

Industrial robots have been a cornerstone of modern manufacturing by automating repetitive, precise, and dangerous tasks. Collaborative robots (cobots) work alongside humans in smart factories to enhance productivity and safety. They can efficiently perform assembly, welding, and material handling tasks thanks to their advanced sensors, adaptive control systems, and machine learning algorithms. This integration into the manufacturing sector has reduced costs and improved product quality. [3]

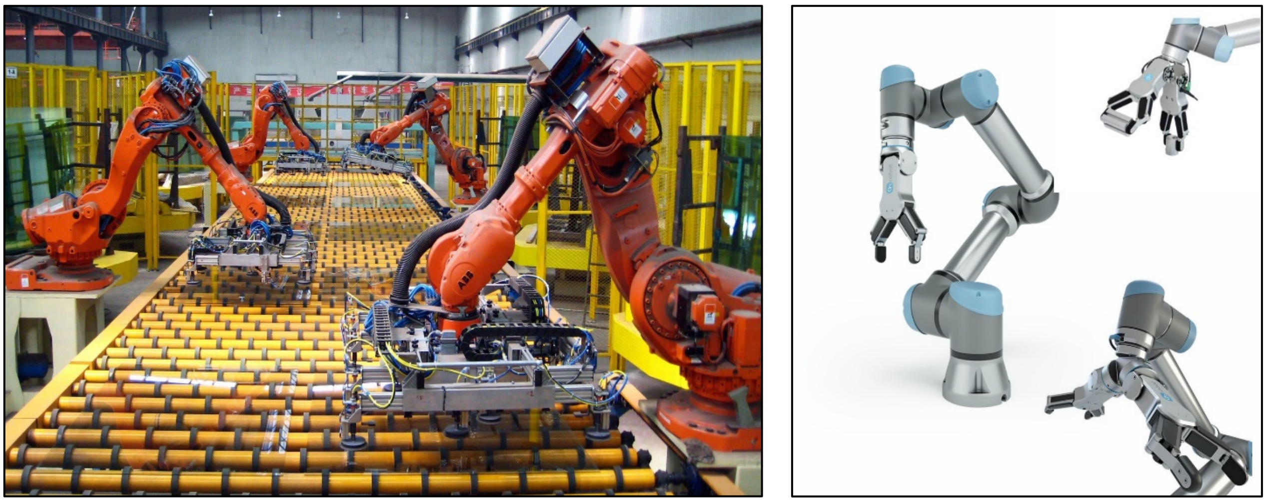


Figure I.1 (a): Classification of industrial robots based on functionality in manufacturing Systems [4], **(b):** Application of the ur10 collaborative robot with onrobot gripper in industrial pick-and-place tasks [5]

I.2.2. Service Robotics

The field of human-robot companionship is one of the basic fields designed to assist humans in daily tasks (personal and professional). According to Ahmed et al. (2024), the development of robots to provide social interaction, emotional support and assistance to individuals is driven by advances in artificial intelligence, natural language processing and affective computing, enabling them to simulate understanding emotions and respond effectively.

Among the applications that service robots include: elderly care, child education and customer service.... [6]

Figure I.2 Service robot demonstration [7]

I.2.3. Agricultural Robotics

Agricultural robotics continue to play a pivotal role, especially as global demand for food increases. Their integration into agriculture not only boosts productivity, but by optimizing resource use (water and fertilizer), it supports sustainable agriculture while reducing environmental impact. Sensors and data analytics are at the core of enabling precision agriculture technologies such as tractors, autonomous tillers, planting and harvesting crops, and drones to monitor crop health, soil conditions and water requirements while providing real-time data to farmers. [8]

Figure I.3 Coordinated robot farming systems [9]

I.2.4. Space Robotics

Space is one of the places that are difficult for humans to reach and may pose a danger to them. Therefore, space robots are one of the basic tools for space exploration. According to Mahfuz (2018), rovers on the surface of Mars and self-maintaining satellites are some of the early practical examples of autonomous robots in space that laid the foundation for modern exploration technologies (**Figure I.4**). The necessity of using these robots for space exploration lies in the advanced autonomous systems that they rely on to navigate and perform tasks in harsh conditions. [10]

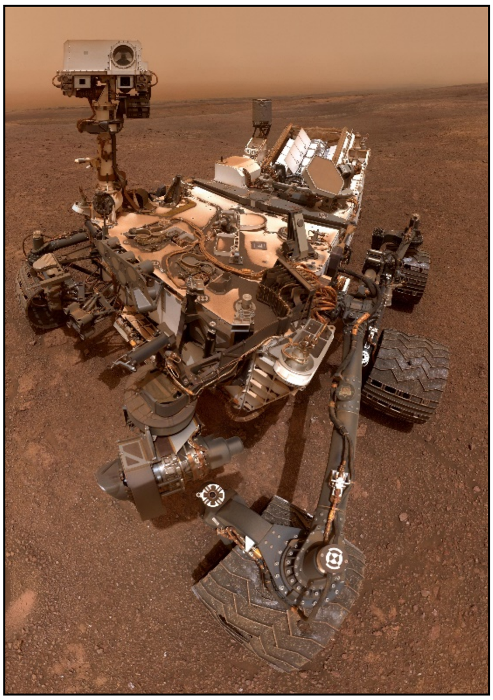


Figure I.4 Curiosity rover on mars exploration mission [10]

The Europa Clipper mission (2024) demonstrates the technological advancements in space robotics in terms of efficiency and capability. This mission features advanced robotic systems that allow autonomous navigation and the collection of accurate scientific data about Jupiter's moon 'Europa'. Which is believed to contain an ocean under its ice (**Figure I.5**). [11]

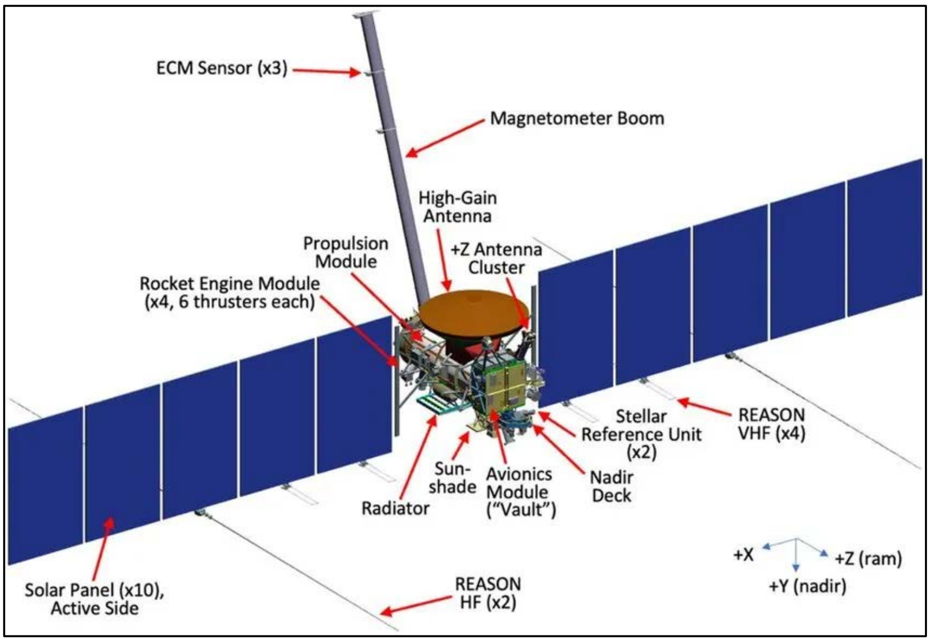


Figure I.5 Europa Clipper flight system with solar arrays and reason antennas in close approach configuration [11]

I.2.5. Military and Defense Robotics

According to Kamil and Kaja (2023), to avoid psychological effects and ethical issues on the battlefield, military robots should not be designed to resemble humans. Instead, they should be designed according to the required tasks, such as drones and ground robots that operate in difficult conditions, and are also used in tasks such as surveillance, reconnaissance, and mine clearance. [12]

Figure I.6 Pitbull with Sig Sauer 338 MMG firing on the move | Photo Credit: General Robotics [13]

I.2.6. Entertainment and Social Robotics

This field, as discussed by Ahmed et al. (2024), focuses on creating robots that provide entertainment, emotional support, and social interaction, making them popular in both home and public settings as toy robots and social robots. Also, to support human well-being, they are increasingly being used in amusement parks and live performances. [6]

I.2.7. Environmental Robotics

In environmental disasters such as earthquakes and floods, search and rescue operations are enhanced by robots, which contribute to saving lives and reducing the risks to human rescue teams. According to H. Mugo Moses (2024), robots are used to assess damage in environmental disaster areas, discover survivors under rubble, and transport medical supplies. [14]

Figure I.7 (a): Exploring the future of rescue robots: advancements in search and rescue technology [15].
(b): Drone delivering first aid kit for disaster response | Image: Shutterstock [16]

I.2.8. Medical Robotics

By assisting in surgery, diagnosis, patient care and disinfection, medical robots enhance accuracy, reduce human error and improve outcomes in complex medical procedures.

Medical robots are revolutionizing patient care. The integration of robots into healthcare has led to important innovations, such as AI-powered diagnostic tools and robot-assisted surgeries. This is what is shown in the following table, which presents some examples of modern developments in biomedical engineering.

Table I.1 Examples of Recent Advances in Biomedical Engineering [17]

Recent Advances in Biomedical Engineering	
Diagnostics	
Imaging Modalities	Computed Tomography, Magnetic Resonance Imaging, Positron Emission Tomography, and Ultrasound, Nuclear Image Reconstruction
Monitoring	Sensors and Transducers (Intensive Care Unit, e. g. , Pulse Oximeter)
Instruments and Devices	Clinical Laboratory
Therapeutics	
Sensory/ Motor	Intraocular Lens and Cochlear Implants
	Implantable Nerve Stimulators
Cardiovascular	Defibrillators and Pacemakers (Implantable and Programmable)
	Ventricular Assist Devices
	Catheter — Based Ablation and Balloon Pumps
	Stents
Renal/ Respiratory	Kidney Dialysis
	Artificial Lungs and Blood Gas Exchange Devices
Tissue/ Organ Failure	Organ Transplantation, New Materials
	Kidney Dialysis
	Prostheses and Implants (e. g. , Total Joints)
Tissue Engineering	Artificial Skin (First Product), Progress in Cartilage Repair, Bone, Liver, Kidney, Skeletal Muscle, and the Nervous System
Biotechnology and Biomaterials	Monoclonal Antibodies and Protein Engineering
	Vaccines, Gene Therapy
	Natural and Synthetic Materials, Biodegradables
Surgery and Rehabilitation	
Devices and Procedures	Minimally Invasive Surgery (e. g. , Arthroscopy, Laparoscopy, Endoscopy)
	Prostheses and Orthotics, Sensory Augmentation and Substitution, New Materials, Wheelchair Mobility

Global health challenges such as the COVID-19 pandemic as discussed by Gao et alii (2024), have highlighted the crucial role played by robots in disinfection and telemedicine to reduce healthcare-associated infections. The increasing demand for medical robots, especially in disinfection, has confirmed their potential in addressing healthcare challenges. [18]

I.2.8.1. Surgical Robots

In performing minimally invasive surgeries, robots help surgeons with high precision. The da Vinci Surgical System is one of the most widely used examples for operations such as prostatectomy and hysterectomy **(Figure I.8)**. [17]

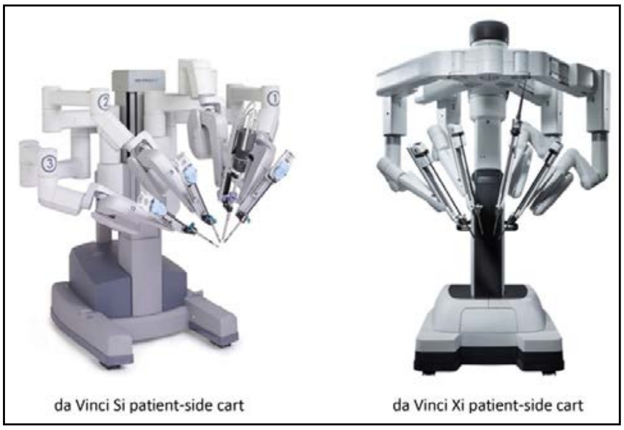


Figure I.8 Two examples of the da Vinci surgical system

I.2.8.2. Rehabilitation Robots

Rehabilitation robots are particularly useful for spinal cord injuries and stroke patients, designed to help them regain movement and strength. Rehabilitation robots include prosthetics and exoskeletons. [18]

I.2.8.3. Diagnostic Robots

Diagnostic robots support artificial intelligence and advanced imaging technologies for early and accurate detection of diseases. Such as robotic systems being developed for automated cancer screening and analysis. [17]

I.2.8.4. Disinfection Robots

According to the article '*Health Care Environmental Hygiene'* (2021), disinfection robots reduce the risk of healthcare-associated infections by effectively eliminating pathogens from surfaces and air. Hence, due to the necessity of maintaining a sterile hospital environment, disinfection robots such as ultraviolet robots and hydrogen peroxide vapor robots are used... [19]

I.2.8.4.1. **Importance of Disinfection Robots**

Disinfection robots have become essential in minimizing the spread of infectious diseases, particularly in healthcare and public settings. Their significance is highlighted through the following key points:

a) **Enhanced Safety:** By reducing human involvement in the disinfection process, these robots limit exposure to harmful pathogens, particularly in hospitals, public transport, and contaminated environments. [20], [21]
b) **Rapid and Efficient Sanitization:** Disinfection robots can sanitize large areas in minutes, significantly reducing cleaning time compared to manual methods. For instance, UV-C robots disinfect an entire hospital room within 10-15 minutes. [21], [22]
c) **Comprehensive Coverage:** Equipped with autonomous navigation systems, these robots can reach hard-to-access areas like under hospital beds, behind curtains, and around medical equipment, ensuring thorough disinfection. [21]
d) **Cost-Effectiveness Over Time:** While the initial cost of robotic disinfection systems can be high, they reduce long-term expenses by lowering labor costs and minimizing the frequency of hospital-acquired infections (HAIs), which reduce patient readmission rates and healthcare expenses. [22]
e) **Seamless Integration with Existing Systems:** Modern disinfection robots can be remotely operated, programmed to work within existing cleaning schedules, and connected to hospital management systems for efficient deployment. [22]
f) **Technological Advancements:** Innovations such as AI-driven navigation, IoT connectivity, and real-time monitoring continue to enhance the effectiveness of disinfection robots, making them smarter and more autonomous. [21], [22]
g) **Public Confidence and Health Security:** The visible presence of disinfection robots in hospitals, offices, and public spaces boosts public trust by demonstrating active measures to maintain hygiene and safety. [20]

Several sterilization systems were compared according to the ideal NTD (No-Touch Disinfection) system, and the results are shown in the following table.

Table I.2 Comparison of Automated Disinfection Systems for Contact-Free Room Sanitization [23]

The 'ideal' NTD system	Aerosolized hydrogen peroxide (aHP)	H_2O_2 Vapor	UVC	Pulsed xenon UV (PX-UV)
Short cycle time (< 1 h)	✗	✗	✓	✓
High level of microbial efficacy (6-log sporicidal reduction)	✗/✓	✓	✗	✗
Pathogens not culturable from surfaces after the cycle	✗	✓	✗	✗
Easy to operate	✓	✗	✓	✓
Fully automated operation	✓	✓	✗/✓	✗
Immediate room entry available [a]	✗	✗	✓	✓
No requirement of room sealing	✗	✗	✓	✓
Homogeneous distribution	✗	✓	✗	✗
Evidence of clinical impact	✗/✓	✓	✓	✗/✓

NTD: No-Touch Disinfection

✓: does meet the characteristic of the 'ideal' NTD system.

✗: does not meet the characteristic of the 'ideal' NTD system.

✗/✓: it is not clear whether or not the characteristic of the 'ideal' NTD system is met.

[a]: Immediate room entry may be advantageous in the event of an emergency.

Disinfection robots significantly improve infection control efforts, providing a safer, faster, and more cost-efficient alternative to traditional cleaning methods. As technology advances, their role in disease prevention and public health will only continue to grow.

I.2.8.4.2. **Disinfection Methods**

a) Ultraviolet-C Radiation (UV-C)

Principle of UV-C Disinfection

Ultraviolet-C (UV-C) radiation, with a wavelength range of **200–280 nm**, is a potent germicidal technology used in various environments such as hospitals, laboratories, and public spaces. It effectively eliminates pathogens by damaging ***microbial DNA and RNA***, preventing their replication and ensuring disinfection. [24]

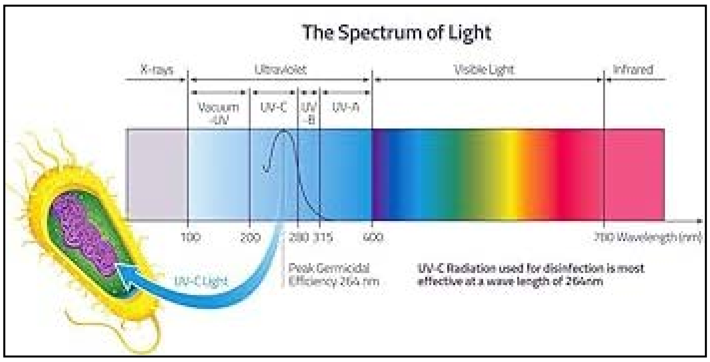


Figure I.9 Light spectrum representation and UV-C wavelength range

The spectrum of light **(Figure I.9.)** illustrates the range of electromagnetic wavelengths, highlighting the UV-C band (200–280 nm) used for germicidal purposes. [24]

Mathematical Model for UV-C Dosage Calculation

For effective sterilization, the required UV dose D is determined by:

$$D = \sqrt{k} \times I_t \qquad \text{(I.1)}$$

where:

- D is the UV dose (mJ/cm²),
- k is a constant dependent on environmental conditions and pathogen type,
- I_t is the intensity of the UV-C radiation over time. [25]

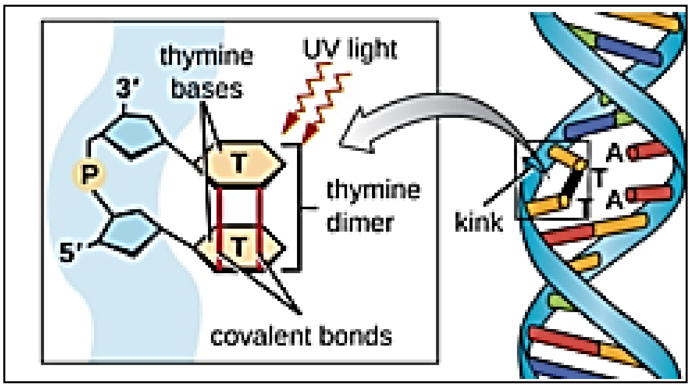


Figure I.10 Formation of thymine dimers under UV-C exposure

The formation of thymine dimers under UV-C exposure is depicted in **Figure I.10**, illustrating the damage mechanism to microbial DNA that prevents replication. [24]

UV Dose Requirements for Pathogen Elimination

Table I-3. summarizes the UV dose requirements for various pathogens, showing the energy needed to neutralize different microorganisms effectively. [25]

Table I.3 Minimum UV-C Exposure Doses (D_{90}) for Effective Surface Disinfection

Pathogen	Required UV Dose (J/m^2)
Bacteria (Average UV Dose)	54
Viruses (Average UV Dose)	73
SARS-COV-2 (COVID-19 virus)	27

Calculated Time for Disinfection

The disinfection time T can be estimated using:

$$T = \frac{D}{I} \qquad \text{(I.2)}$$

where:

-T is the required exposure time (seconds),

-I is the UV intensity (mW/cm²).

Experimental results indicate that for a UV intensity of 5 mW/cm^2, eliminating MRSA (Methicillin-Resistant Staphylococcus Aureus, a highly resistant bacterial strain) requires 1.3 seconds, while C. difficile spores need approximately *7.2 seconds* of exposure. [24]

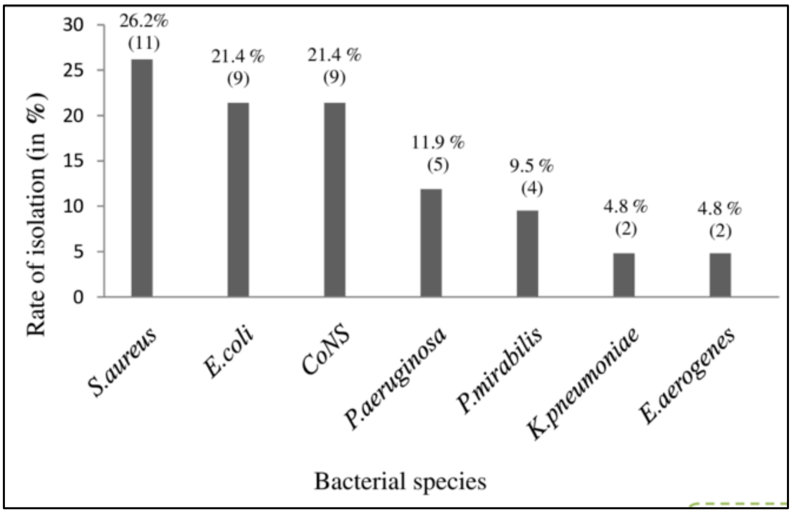


Figure I.11 Common pathogenic bacteria found in surgical environments

Figure I.11 illustrates common pathogenic bacteria found in surgical environments, highlighting the primary microorganisms responsible for hospital-acquired infections. [24]

b) Hydrogen Peroxide Vapor (HPV)

Mechanism of Action

Hydrogen Peroxide Vapor (HPV) is a widely used disinfection method that effectively eliminates microorganisms by producing reactive oxygen species (ROS). When released into the environment, HPV undergoes decomposition, generating hydroxyl radicals (OH•) that attack cellular components, including proteins, lipids, and nucleic acids. This process leads to oxidative damage, disrupting microbial structures and ultimately causing cell death. [26]

HPV is particularly effective against a broad spectrum of pathogens, including bacteria, viruses, fungi, and spores. Unlike conventional liquid disinfectants, HPV can reach hidden and hard-to-access surfaces, making it suitable for hospital environments where complete sterilization is required. [27]

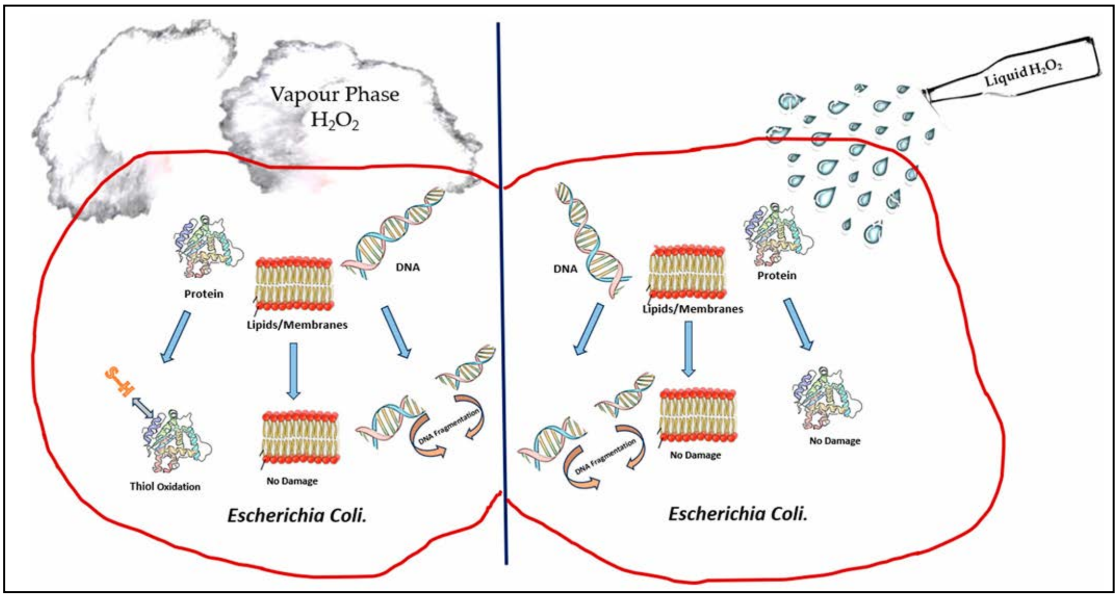


Figure I.12 Structural damage to E. coli induced by liquid and vapor-phase hydrogen peroxide

Figure I.12 illustrates the mechanism of action, highlighting how reactive oxygen species disrupt microbial integrity. [26]

Systems Utilizing HPV for Disinfection

Several automated systems have been developed to apply HPV in controlled settings, mainly in healthcare and laboratory environments. These systems vary in design but typically include the following components:

- Vapor Generation Unit: Converts liquid hydrogen peroxide into vapor.
- Distribution Mechanism: Ensures even dispersion throughout the targeted area.
- Aeration System: Facilitates the removal of residual peroxide after disinfection.

The main types of hydrogen peroxide application methods include:

1. Dry Hydrogen Peroxide (DHP): Delivers micro aerosols of HPV without condensation, maintaining low humidity and preventing surface damage. [27]

2. Condensed Hydrogen Peroxide Vapor (HPV) Systems: Create a fine mist that condenses on surfaces, ensuring prolonged contact time and improved efficacy. [23]

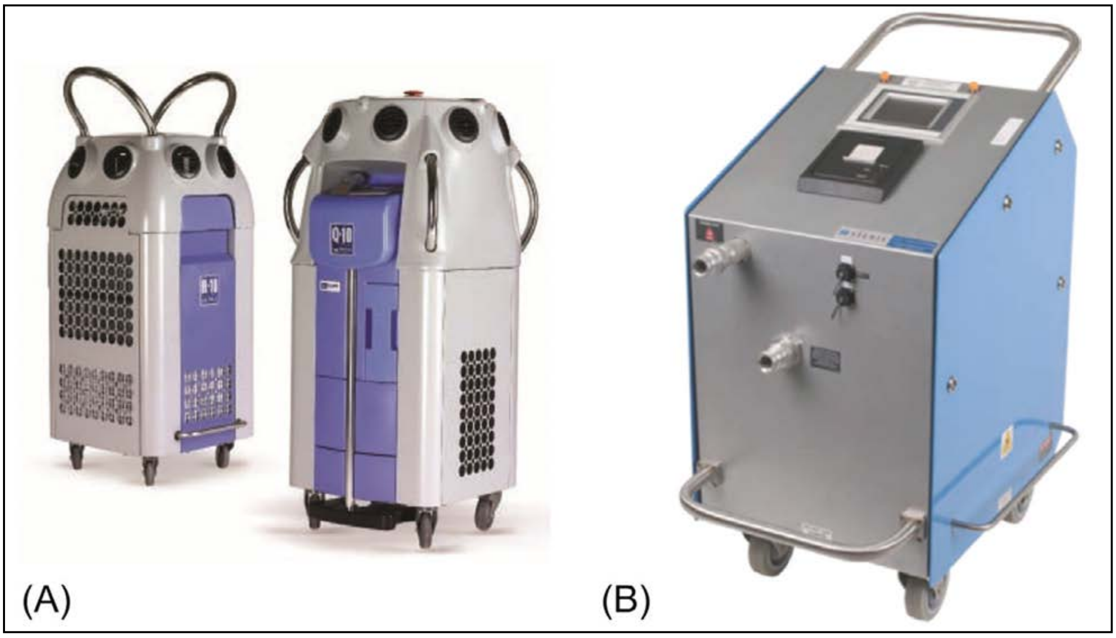


Figure I.13 Forms of bio quell and steris hydrogen peroxide vapor systems

Figure I.13 provides an overview of how HPV is applied in healthcare environments. [23]

Effects of HPV on Surfaces and Environment

While HPV is a highly effective disinfectant, its interaction with materials must be carefully considered. Studies indicate that prolonged exposure to HPV may cause oxidation-related degradation of certain materials, including:

-*Rubber and plastics:* May experience brittleness and discoloration.

-*Metals:* Susceptible to corrosion if exposed to high concentrations.

To mitigate potential material damage, facilities employing HPV disinfection often implement controlled aeration cycles to remove residual peroxide post-disinfection. [23]. Furthermore, HPV is considered environmentally friendly as it decomposes into oxygen and water, leaving no toxic residues. [26]

c) Electrostatic Spraying

Mechanism of Action

Electrostatic spraying is an advanced disinfection technology that enhances the application of liquid disinfectants by charging droplets electrostatically before they are dispersed. This process allows the disinfectant to wrap around and evenly coat surfaces, ensuring comprehensive coverage. [23]

The electrostatic charge is applied to liquid droplets using a high-voltage electrode nozzle, which induces a negative or positive charge. These charged droplets are then attracted to surfaces, including hard-to-reach areas, improving adhesion and reducing waste. [28]

Systems Utilizing Electrostatic Spraying for Disinfection

Electrostatic spraying is commonly used in hospitals, public transportation, and industrial environments. The main components of an electrostatic spraying system include:

Electrostatic Nozzle: Imparts a charge to the disinfectant droplets.

High-Pressure Pump: Ensures fine mist generation (10–50 microns in size).

Disinfectant Tank: Holds the chemical solution to be sprayed.

Battery or Electric Power Source: Supplies energy for charging and spraying. [28]

Advantages of Electrostatic Spraying

- ✓ Even Distribution: Charged droplets adhere uniformly to surfaces.
- ✓ Increased Efficiency: Reduces the amount of disinfectant needed.
- ✓ Faster Application: Covers large areas in less time compared to manual wiping.
- ✓ Hard-to-Reach Areas: Wraps around objects, reaching areas that traditional spraying methods miss. [23]

Limitations and Considerations

- × Not Suitable for All Disinfectants: Some chemical solutions are not compatible with electrostatic application.
- × Surface Residue: May leave a thin film that requires wiping in certain environments.
- × Humidity Dependency: Performance may vary based on environmental conditions. [23]

d) Combination of Several Methods

The Need for Combining Disinfection Methods

Different disinfection techniques have their strengths and limitations. While **“UV-C radiation”** is effective against airborne and surface pathogens, it struggles with shadowed areas. **“Hydrogen Peroxide Vapor (HPV)”** ensures thorough decontamination but requires longer processing times. **“Electrostatic spraying”**, on the other hand, enhances coverage but may not be effective on its own. Combining multiple methods helps achieve higher efficacy and broader pathogen elimination. [23]

Hybrid Disinfection Systems

Healthcare facilities and industrial settings increasingly use hybrid disinfection systems to maximize microbial inactivation. Some common combinations include:

- **UV-C and Hydrogen Peroxide Vapor (HPV):** UV-C provides rapid decontamination, while Hydrogen Peroxide Vapor (HPV) ensures complete sterilization of hidden surfaces. [23]
- **Electrostatic Spraying and UV-C:** Electrostatic spraying distributes disinfectant evenly, and UV-C enhances microbial inactivation. [23]
- **Hydrogen Peroxide Vapor (HPV) and Chemical Disinfectants:** A combination of hydrogen peroxide vapor and peracetic acid improves overall disinfection efficiency. [23]

Advantages of Combining Methods

- ✓ **Improved Coverage:** Ensures disinfection in areas where a single method may be ineffective.
- ✓ **Enhanced Microbial Elimination:** Reduces the risk of residual contamination.
- ✓ **Increased Efficiency:** Optimizes disinfection time without compromising thoroughness.
- ✓ **Redundancy for Safety:** If one method fails to eliminate a particular pathogen, the second method compensates. [23]

Table I.4 Comparison of Automated Room Disinfection (ARD) Systems

	HPV 30% – 35% H_2O_2 vapor	**AHP 5% – 6% $H_2O_2 + Ag$ aerosol**	**UVC UVC (280 nm)**	**PX-UV Pulsed-xenon UV**
Efficacy	1 > 6-log reduction	2 ~ 4-log reduction	3 ~ 2-4- log reduction	4 ~ 1-3-log reduction
Distribution	1 Homogeneous	2 Nonhomogeneous	3 Line of sight issues	3 Line of sight issues
Ease of use	4 Multiple units; sealing/ monitoring	3 Sealing & monitoring	2 Multiple positions; no sealing/ monitoring	2 Multiple positions; no sealing/ monitoring
Cycle time	3 ~ 1.5h single room	4 > 2h single room	1 ~ 10-30 min	1 ~ 10-30 min
Purchase cost	2	1	3	3
Running cost	4	3	1	1

Note: *Log reduction is a logarithmic measure used to evaluate the effectiveness of disinfection. Each 1-log reduction corresponds to a* ***90% decrease*** *in the number of microorganisms, meaning a 2-log reduction equals* ***99%****, a 3-log reduction equals* ***99.9%****, and so on. Higher log reductions indicate greater microbial elimination. This measure is widely used to assess disinfection methods like* ***UV-C Light and hydrogen peroxide vapor*** *in medical and industrial applications.*

The **Table I-4** provides an overview of how different methods perform in terms of microbial efficacy, ease of use, and operational efficiency. [23]

I.3. Conclusion

The integration of robotics in disinfection has significantly improved hygiene standards in healthcare and public environments. This chapter explored key disinfection methods, including UV-C radiation, Hydrogen Peroxide Vapor (HPV), and Electrostatic Spraying, highlighting their individual benefits and limitations.

While each method has its strengths, combining multiple approaches has proven to be the most effective strategy for achieving comprehensive disinfection. Hybrid systems ensure better coverage, enhanced microbial elimination, and increased efficiency in various applications.

Having explored the fundamental disinfection methods and their integration with robotics, the next chapter presents the detailed design of a disinfection robot, focusing on its system architecture, key components, and functional organization.

II. Chapter 2: Design of disinfection robots

II.1. Introduction

This chapter presents the complete design of a hospital disinfection robot, focusing on the architecture and interconnection of its key subsystems. The robot is composed of various hardware components that work together to ensure autonomous movement and effective disinfection. These include the power supply system (based on a lithium battery), the central microcontroller (Arduino Uno), the L293D motor driver, and a set of actuators such as DC motors, servo motors, stepper motors, and a mini water pump.

The disinfection capability is achieved through ultraviolet LEDs and a liquid-based system, both of which are discussed in terms of components and integration. The sensing system, consisting of ultrasonic and PIR sensors, plays a key role in environment detection and control. Communication between the robot and the user is enabled via the NodeMCU ESP8266 module and a mobile application developed using MIT App Inventor.

Each section of this chapter details the function, structure, and role of these components within the system.

II.2. General Architecture of the System

the system contains six blocs which are: power supply block, a microcontroller block, a motor driver block, Sensors block, actuator block, and an autonomous communication block.

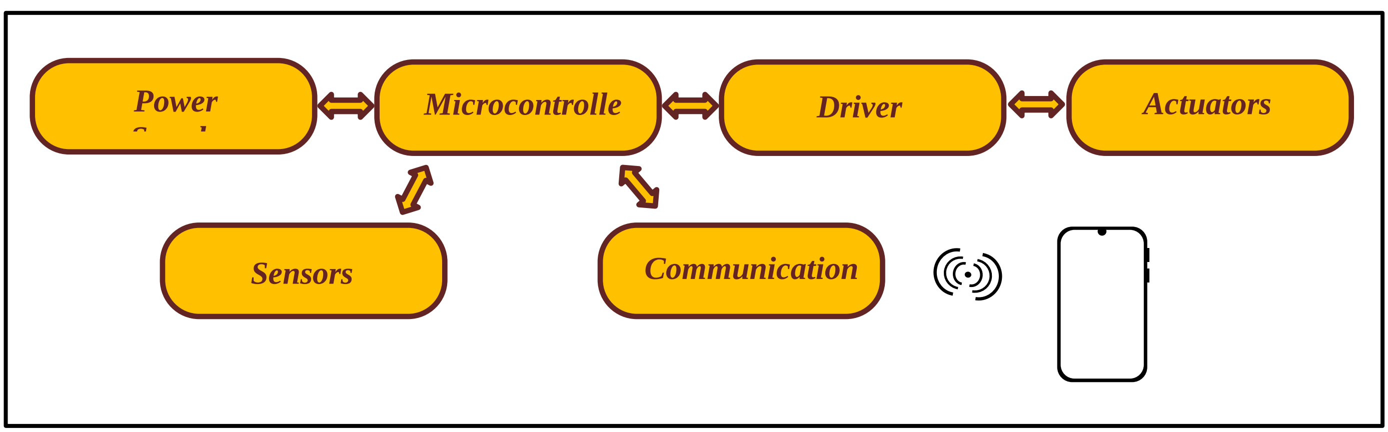


Figure II.1 Block diagram of disinfection robot design

II.2.1. Power Supply

II.2.1.1. Lithium battery

Electrochemical Working Principle

Lithium-ion batteries provide a reliable and efficient power supply due to their high energy density, stable voltage output, and low self-discharge. Each cell typically delivers 3.6V, which is ideal for powering modern devices like phones and laptops without needing multiple cells.

These batteries can be optimized as:

- Energy Cells (for long runtime),
- Power Cells (for high current output), or
- Hybrid Cells (a balance of both).

They are built using:

- A graphite anode (negative electrode),
- A metal oxide cathode (positive electrode),
- An electrolyte (lithium salt in organic solvent),
- And a separator to prevent short circuits.

To supply power safely, they require protection circuits to control voltage and current, and prevent overheating or thermal runaway.

Their advantages include:

- High performance with minimal maintenance,
- A flat discharge curve (stable voltage),
- And low internal resistance.

However, they:

- Must be protected from overcharging and overheating,
- Cannot be charged in freezing conditions,
- And are subject to shipping regulations in bulk. [29]

This image shows a Samsung INR18650-25R rechargeable lithium-ion cell. It belongs to the 18650 cylindrical format (18 mm diameter × 65 mm length), commonly used in high-drain devices such as power tools, electric vehicles, and battery packs. This specific model provides 3.6–3.7V nominal voltage and a 2500mAh capacity, known for its balance of energy density and discharge performance.

Figure II.2 Samsung INR18650-25R lithium-ion battery cell (3.6V / 2500mAh) [30]

II.2.2. Microcontroller

II.2.2.1. Arduino Uno Board

The Arduino Uno is an open-source microcontroller board based on the ATmega328P, widely used for educational, prototyping, and embedded system applications due to its simplicity and flexibility. It provides digital and analog I/O pins to connect with sensors, actuators, and communication modules. In disinfection robots, it serves as the central control unit—managing motor movements, processing sensor data, and enabling wireless communication via modules like ESP8266. Its popularity is supported by strong community backing, rich libraries, and open hardware/software architecture. [31]

Technical Specification

The Arduino Uno is powered by the ATmega328P microcontroller and offers a range of features suitable for embedded system applications such as robotics, automation, and IoT. The board is designed to balance performance, usability, and expandability. [31]

The table below summarizes the key technical specifications of the Arduino Uno:

Table II.1 The Arduino Uno technical specifications

Feature	Specification
Microcontroller	ATmega382P
Operating Voltage	5 V
Input Voltage (recommended)	7-12 V
Input Voltage (limit)	6-20 V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	20 mA
Flash Memory	32 KB (0.5 KB used by bootloader)
SRAM	2 KB
EEPROM	1 KB
Clock Speed	16 MHz
USB Connection	Type B (via ATmega382P for serial conversion)

These specifications ensure that the Arduino Uno can:

- Perform stable operations at 16 MHz clock speed.
- Handle basic tasks like reading sensors and controlling actuators.
- Retain persistent data through its EEPROM.
- Interface easily with USB for programming and communication. [31]

Pin Configuration and Layout

Understanding the pinout is crucial when integrating components such as sensors, motors, and communication modules in a disinfection robot.

The following diagram illustrates the Arduino Uno pinout, providing a visual reference to support accurate and efficient wiring of your components.

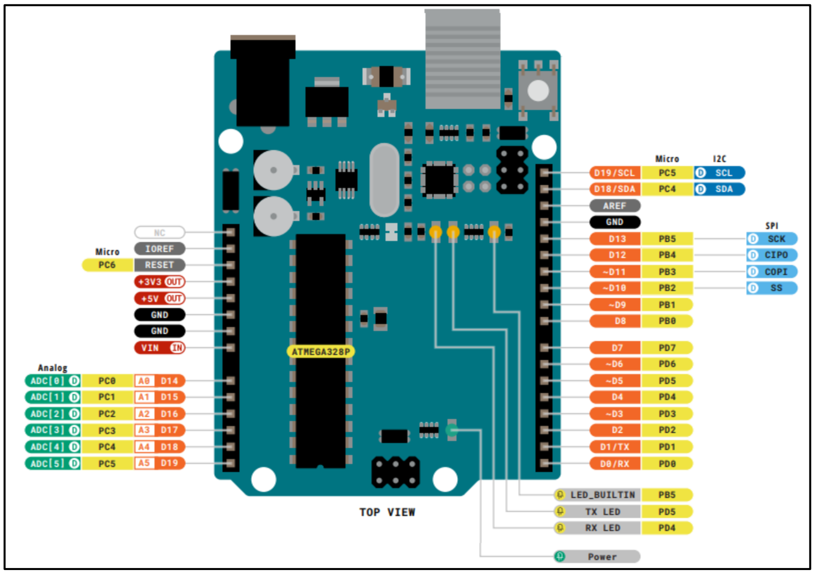


Figure II.3 Arduino uno pinout diagram [32]

We can summarize the Pin Configuration in the following table:

Table II.2 Configuration of Arduino Uno Pins *[32]*

Pin Type	Pins	Description
Digital I/O	$D0 - D13$	General-purpose digital input/output
PWM Output	$D3, D5, D6, D9 - D11$	Used for speed control or dimming
Analog Inputs	$A0 - A5$	Reads voltage from sensors (0-5V)
Serial (UART)	$D0\ (RX), D1\ (TX)$	Serial communication
I2C	$A4(SDA), A5\ (SCL)$	For I2C sensors or displays
SPI	$D10 - D13$	For SPI modules
Power Supply Pins	$Vin, 5V, 3.3\ V, GND$	Power connections

Programming Environment

The Arduino Uno is programmed using the Arduino Integrated Development Environment (IDE), a cross-platform application designed to simplify writing, compiling, and uploading code to the board. It supports Arduino C/C++, a user-friendly language built on top of standard C++ with simplified syntax and a rich set of libraries tailored for embedded systems.

Arduino IDE

- *Interface:* The IDE includes a code editor, a compiler, a serial monitor for real-time data visualization, and a board manager.

The image below highlights the main features of the Arduino IDE interface, corresponding to the components mentioned above for easier identification and navigation.

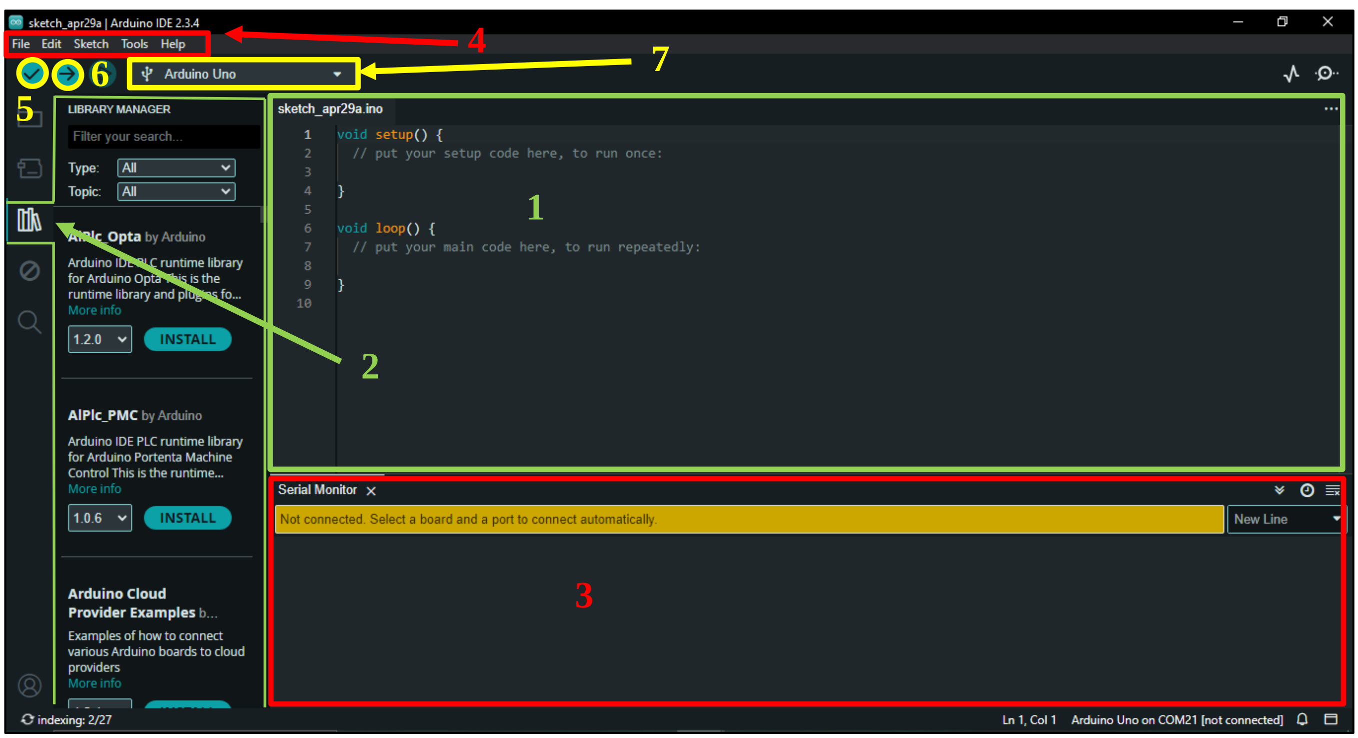


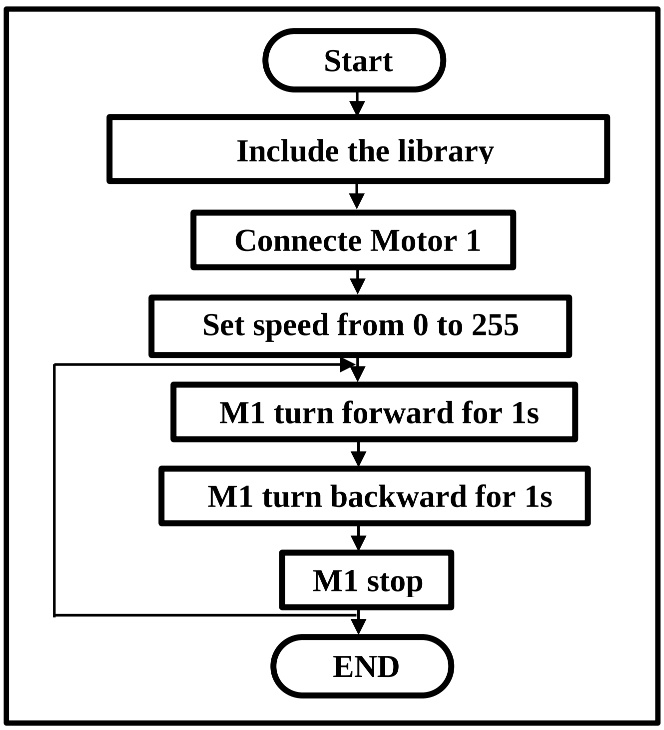
Figure II.4 Interface of Arduino IDE (1- Code editor, 2- Library manager, 3- Serial monitor, 4- Toolbar with buttons for common functions, 5- Verify, 6- Upload, 7- Board manager)

- *Platform Support:* Compatible with Windows, macOS, and Linux.
- *Code Upload:* Programs (called sketches) are uploaded via the USB connection using the onboard ATmega16U2 serial converter.
- *Library Manager:* Offers easy integration of external libraries for components like motors, sensors, and communication modules.

Important Libraries Used in This Project

In the context of a disinfection robot, the following libraries are essential to interface with actuators and modules:

- ***AFMotor.h***: For controlling DC motors via motor drivers like L293D.



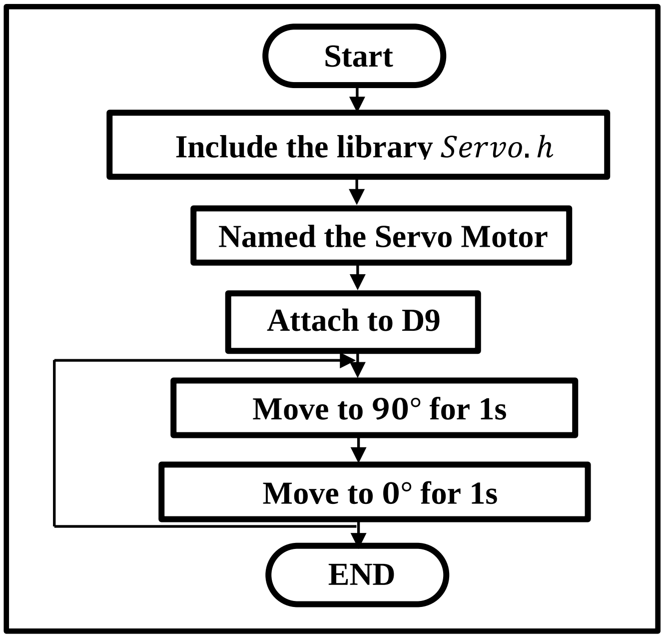

```
#include <AFMotor.h>  // Call the Library

AF_DCMotor motor1(1);  // Motor connected to port M1

void setup() {
  motor1.setSpeed(200); // Speed from 0 to 255
}

void loop() {
  motor1.run(FORWARD);
  delay(1000);
  motor1.run(BACKWARD);
  delay(1000);
  motor1.run(RELEASE);  // Stop M1
}
```

Figure II.5 Code and organogram showing DC motor control with *AFMotor.h* library

This code demonstrates how to control a DC motor using the *AFMotor.h* library with an Arduino Uno. The motor alternates between forward and backward motion, then stops.

- ***Servo.h***: To control servo motors, such as for rotating an ultrasonic sensor.

The following diagram illustrates the control flow of a servo motor using the *Servo.h* library, demonstrating its role in managing rotation functions.



```
#include <Servo.h>  // Call the Library

Servo myServo; // Give a name for Servo Motor

void setup() {
  myServo.attach(9);   // Attach to digital pin 9
}

void loop() {
  myServo.write(90);   // Move to 90°
  delay(1000);
  myServo.write(0);    // Move to 0°
  delay(1000);
}
```

Figure II.6 Servo motor control using $Servo.h$ library

This example uses the $Servo.h$ library to control a servo motor connected to pin 9. The motor rotates between 0° and 90° at one-second intervals.

- $\boldsymbol{SoftwareSerial.h}$: To establish serial communication with modules like the ESP8266, freeing the default hardware serial.

The diagram below outlines how the $SoftwareSerial.h$ library facilitates serial communication with the ESP8266 module, enabling data exchange without occupying the hardware serial port.

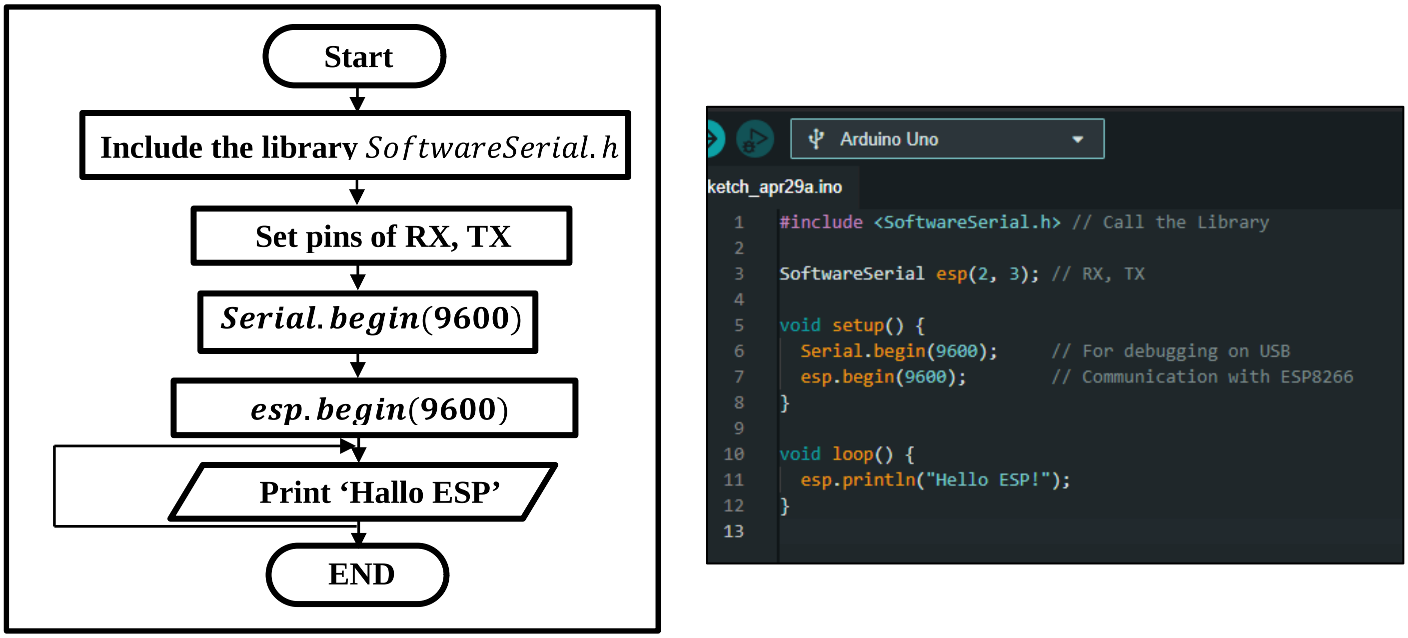
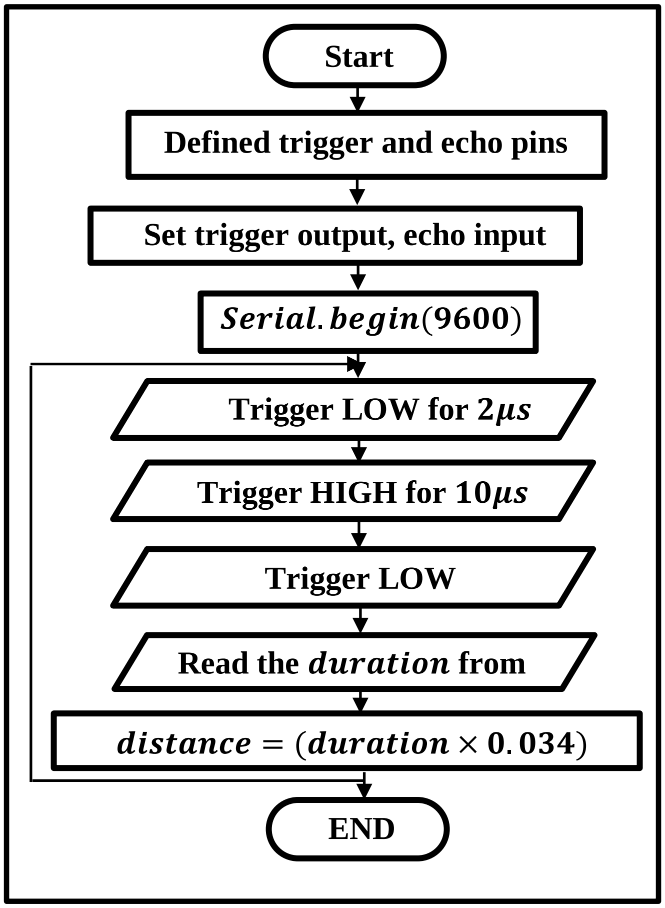


Figure II.7 Serial communication with ESP8266 using $SoftwareSerial.h$

This sketch runs on the Arduino Uno and sends serial data to the ESP8266 via digital pins 2 and 3. The $SoftwareSerial.h$ library is used to establish this communication. A separate sketch must be written and uploaded to the ESP8266 to handle the received data independently.

- ***Ultrasonic Sensor (HC-SR04) without a Library:*** by using $pulseIn()$ to measure the echo signal duration and compute distance.

The following diagram demonstrates the process of measuring distance using the HC-SR04 ultrasonic sensor without relying on an external library, utilizing the $pulseIn()$ function to capture echo duration.




```
const int trigPin = 7; // Trigger pin defined as connected to D7
const int echoPin = 6; // Echo pin defined as connected to D6

void setup() {
  pinMode(trigPin, OUTPUT);
  pinMode(echoPin, INPUT);
  Serial.begin(9600);
}

void loop() {
  // Sending an ultrasound wave
  digitalWrite(trigPin, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);

  long duration = pulseIn(echoPin, HIGH); // Ultrasound wave reception
  float distance = duration * 0.034 / 2;  // Convert to distance
}
```

Figure II.8 Distance measurement using ultrasonic sensor without external library

This Arduino Uno organogram measures distance using an ultrasonic sensor (e.g., HC-SR04) by manually controlling the trigger and echo pins. It calculates the distance based on the time it takes for the sound wave to return. This approach offers full control without relying on external libraries.

II.2.3. Driver L293D

The L293D is a popular motor driver integrated circuit (IC) designed for controlling the direction and speed of DC motors and stepper motors. It can simultaneously control two DC motors independently, offering bidirectional drive capabilities. It operates by using two H-bridge circuits inside the chip, allowing the application of voltage in both directions across a motor. The IC provides a simple and efficient solution for motor driving in embedded systems, robotics, and automation projects [33].

The two full H-bridge drivers capable of driving current up to 600 mA per channel, with a peak output current of 1.2 A for short durations. It supports motor supply voltages (VCC2) ranging from 4.5V to 36V and logic voltages (VCC1) around 5V.

Each H-bridge in the IC has two inputs that control the direction of the motor and two outputs connected to the motor terminals. By adjusting the logic levels of the input pins, the direction of the motor rotation can be controlled. The device includes internal protection diodes that absorb the back EMF generated when motors are switched off, protecting the circuit from damage [33] .

Pin Configuration

The diagram below shows the pin configuration of the L293D motor driver IC, providing a reference for understanding each pin’s function in DC motor control applications [34].

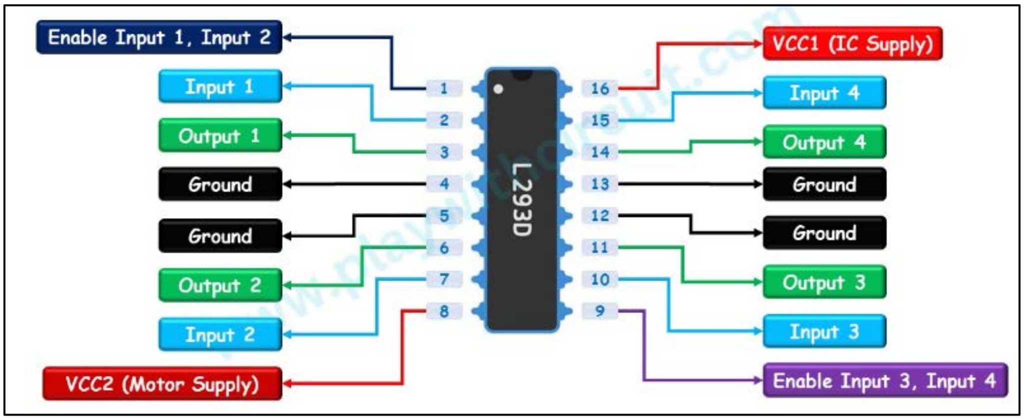


Figure II.9 L293D IC pinout [34]

The L293D features 16 pins organized as follows:

Pins 1 and 9 (Enable 1, Enable 2): Used to enable or disable the H-bridge outputs.

Pins 2, 7, 10, and 15 (Input 1–4): Control the logic to determine the motor direction.

Pins 3, 6, 11, and 14 (Output 1–4): Connected to the motor terminals.

Pins 4, 5, 12, and 13 (Ground pins): Common ground connections.

Pin 8 (VCC2): Supply voltage for the motors.

Pin 16 (VCC1): Supply voltage for the logic circuitry.

By appropriately connecting the enable and input pins, and providing the right voltage on VCC1 and VCC2, the motors can be controlled in both speed and direction [33].

Working Principle

The H-bridge inside the L293D allows current to flow in either direction through the motor, depending on the input logic:

When Input 1 is HIGH and Input 2 is LOW, the motor rotates in one direction.

When Input 1 is LOW and Input 2 is HIGH, the motor rotates in the opposite direction.

When both inputs are HIGH or both are LOW, the motor stops.

Speed control can be implemented by applying a Pulse Width Modulated (PWM) signal to the enable pins, modulating the average voltage seen by the motor [33].

The following image illustrates the pinout of the L293D Motor Driver Shield, highlighting key terminals used for controlling DC, servo, and stepper motors in Arduino-based projects. [33]

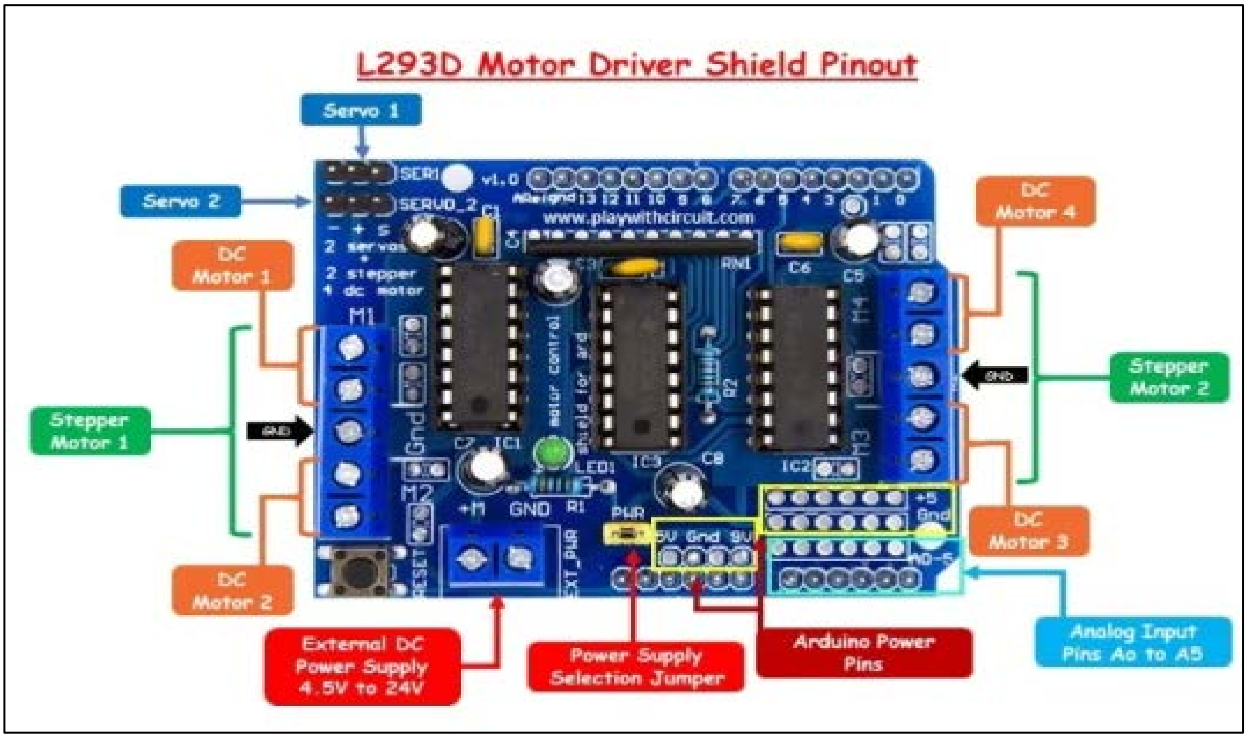


Figure II.10 Pinout of the L293D motor driver shield [33]

Working Principle

The shield simplifies the process of motor control by managing all the necessary wiring between the Arduino and the motors:

Motors connected to M1, M2, M3, and M4 terminals can be controlled in speed and direction using PWM signals and direction signals managed via the 74HC595 shift register.

Servo motors connected to Servo 1 and Servo 2 headers receive PWM signals through Arduino pins D9 and D10 respectively.

The shield can operate with a shared or separate power source for the motors and Arduino, configurable using the PWR jumper. If external power is used, the jumper must be removed to prevent damage.

Current flows from either the Arduino's Vin or an external power source to drive the motors, while logic operations remain powered through the Arduino’s 5V regulator [33].

II.2.4. Emitter

II.2.4.1. Ultraviolet LEDs

Ultraviolet (UV) lamps, particularly UV-C with wavelengths between 200–280 nm, are widely used in robotic disinfection systems due to their strong germicidal properties. Unlike traditional mercury vapor lamps, UV LEDs offer compactness, fast response (instant on/off), and precise wavelength control, which makes them ideal for robotic applications. [35], [36]

The diagram below presents the package schematic and mechanical dimensions (in mm) of the 365 nm UV LED emitter (model: LZ1-00U600), providing essential details for integration into disinfection robot designs.

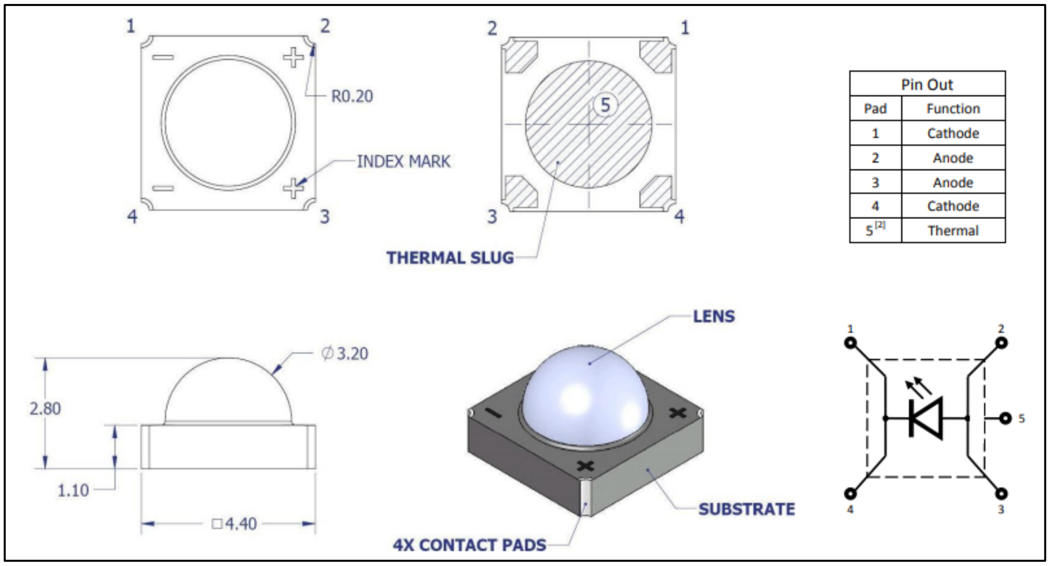


Figure II.11 Package schematic with mechanical dimensions (mm) for 365nm UV LED emitter (LZ1-00U600) [35]

Types of UV LEDs Used in Disinfection Robots

UV Lamps are traditionally mercury-based and emit a broad spectrum of UV light, typically centered around 254 nm. These lamps require a warm-up period, are generally bulkier, and pose environmental risks due to the mercury content. Despite their widespread historical use in fixed disinfection systems, they are being phased out in favor of more efficient and safer alternatives.

UV LEDs, by contrast, are semiconductor-based devices that emit light in a narrow spectral band—precisely targeted at wavelengths such as 265 nm, 365 nm, and 395 nm depending on the application. They are compact, provide instant on/off functionality, are mercury-free, and offer higher energy efficiency. Moreover, UV LEDs are more suitable for integration in mobile robotic platforms due to their size and low heat output. [35], [36], [37]

Table II.3 Comparison between UV Lamps and UV LEDs

Feature	**UV Lamps**	**UV LEDs**
Emission Spectrum	Broad	Narrow (targeted)
Warm-Up Time	Required	Instant
Size	Bulky	Compact
Power Efficiency	Lower	Higher
Environmental Safety	Contains mercury	Mercury-free, RoHS compliant
Control	Limited	Easily adjustable via current
Cost (Initial)	Lower	Higher
Lifespan	$\sim 5{,}000 - 10{,}000\ hrs$	$\sim 10{,}000 - 50{,}000\ hrs$

While UV lamps still exist in fixed industrial settings, UV LEDs are becoming the standard for robotic disinfection systems due to their efficiency, safety, and ease of integration.

Key Technical Characteristics of UV LEDs

Important characteristics include forward voltage, peak wavelength, optical power, and viewing angles. Additionally, all LEDs have specifications regarding operating temperature, ESD resistance, and reliability. [35], [36], [37]

Safety and Design Considerations

UV radiation can be hazardous. Systems should include shielding and require protective eyewear. Thermal management through MCPCBs (Metal core printed circuit boards) helps in maintaining performance. Datasheets provide reflow and mounting recommendations. [35], [36], [37]

UV LEDs are ideal for robotic disinfection due to their size, efficiency, and precision. Choosing the right LED involves evaluating power output, wavelength, and integration requirements. The field continues to advance toward higher output and longer life solutions. [35], [36], [37] *Note:* Metal Core Printed Circuit Boards (MCPCBs) use a metal base, usually aluminum, to improve heat dissipation. This makes them ideal for high-power components like UV LEDs, ensuring better performance and durability compared to standard PCBs. [36]

Here is a simple comparative table summarizing key characteristics of selected UV LEDs:

Table II.4 Characteristics of some UV LEDs [35], [36], [37]

Model	**Peak Wavelength** (nm)	**Optical Power** (mW)	**Forward Voltage** (V)	**Max Current** (mA)	**FWHM** (nm)	**Life** (hrs)
LZ1-00U600	365	260	4.1	700	-	-
504UVC2E-Q5C	395	-	3.2	20	15	-
E265SL	265	0.35	6.6	20	10	1000
E273SL	278	1.0	6.0	20	10	1000
E305SL	310	1.0	5.5	20	10	1000
E365SL	367	135	3.4	350	10	2000
E400SL	400	557	3.4	350	10	2000

II.2.5. Actuators

II.2.5.1. DC Motor

A DC motor is an electromechanical device that converts direct current electrical energy into mechanical rotational motion through the interaction of magnetic fields. In disinfection robots, DC motors play a crucial role in enabling motion control, including wheel actuation and positioning of UV-C modules. They are preferred for their simple construction, precise speed control, and compatibility with battery-powered systems [38], [39].

Types and Components

DC motors used in robotic systems typically fall into two main categories: brushed and brushless (In our case we used Brushed DC motors). Brushed DC motors are known for their cost-effectiveness and simplicity, though they require periodic maintenance due to brush wear. Brushless DC motors, by contrast, offer higher efficiency, longer life, and reduced maintenance, making them suitable for high-performance or continuous-operation environments [39].

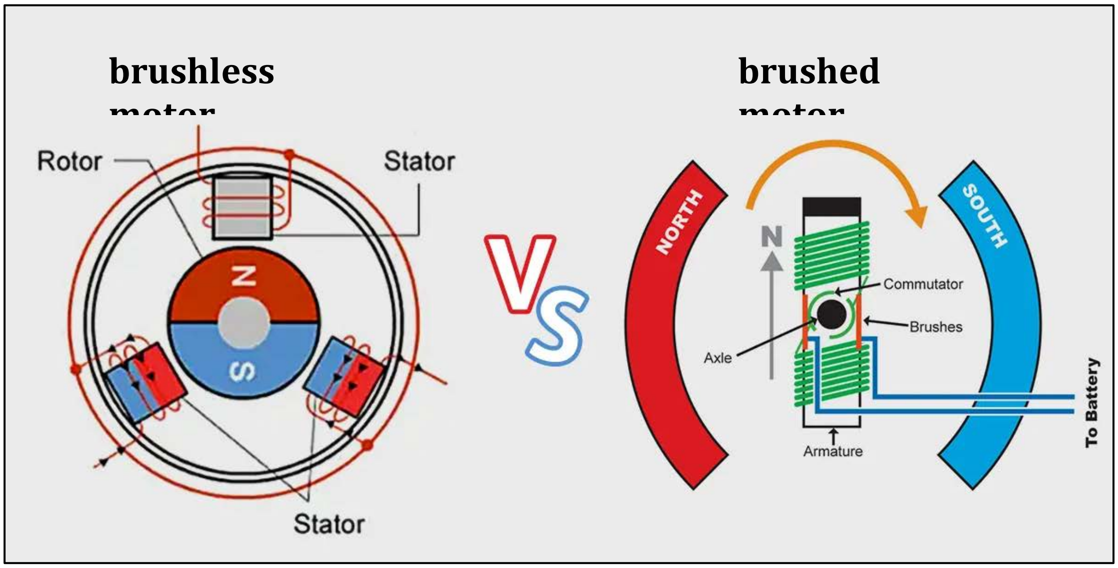


Figure II.12 Brushed motor and brushless motor [40]

When integrated with gearboxes, these motors are known as DC gear motors, which consist of the following key components:

Motor Core: Generates the initial rotational force.

Gearbox: Reduces speed and increases torque using gear mechanisms like spur or planetary gears.

Shaft and Mounting Accessories: Facilitate mechanical coupling and integration into the robotic structure.

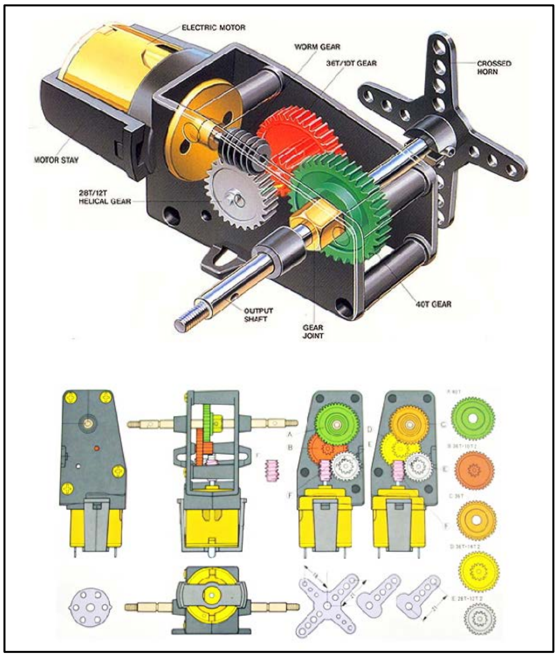


Figure II.13 Schematic diagram of a DC gear motor structure [41]

The choice of gear type affects torque output, size, and operational noise. Planetary gear motors, for example, offer compact high-torque solutions ideal for mobile platforms [38], [39].

Several technical parameters are considered when selecting a DC gear motor for disinfection robots:

Speed (RPM): The rate of rotation, which determines the velocity of the robotic platform.

Torque (T): The rotational force, which must be sufficient to drive the robot and carry its disinfection equipment.

Gear Ratio (GR): The ratio that determines how the gearbox modifies speed and torque. It is defined as:

$$Gear\ Ratio\ (GR) = \frac{N_{input}}{N_{output}} \qquad \text{(II.1)}$$

where:

N_{input} : rotational speed of the motor input shaft

N_{output} : rotational speed of the gearbox output shaft

A higher gear ratio decreases speed while increasing torque, which is ideal for precise and powerful movement in robotics [39].

For instance, a 48:1 ratio means the output turns once for every 48 motor revolutions, significantly boosting torque.

Efficiency ($\boldsymbol{\eta}$): The ratio of mechanical output power to electrical input power. It is calculated as:

$$\eta = \left(\frac{P_{out}}{P_{in}}\right) \times 100\% \qquad \text{(II.2)}$$

where:

P_{out} : mechanical power delivered to the load

P_{in} : electrical power consumed by the motor

Efficiency for DC gear motors typically ranges between 70% to 90%, depending on design and load conditions [39].

Voltage and Current: Voltage controls speed, while current influences torque. Monitoring parameters like stall current (maximum current draw at zero speed) is crucial to prevent thermal damage.

DC gear motors are fundamental actuators in robotic systems due to their excellent torque control, flexible speed regulation, and compatibility with diverse control schemes. Their integration into disinfection robots ensures precise movement, reliable operation, and adaptability to various environmental conditions. By carefully selecting motor specifications such as gear ratio, torque, and voltage ratings, designers can significantly enhance system performance and energy efficiency [38], [39].

II.2.5.2. Servo Motor

A servo motor is a rotary actuator used for precise control of position, speed, and acceleration. It combines a DC motor, gear system, feedback sensor, and control electronics to achieve accurate movement. Operating through a closed-loop system, it continuously adjusts its position based on real-time feedback to match the desired angle, making it ideal for robotics applications like disinfection robots. [42]

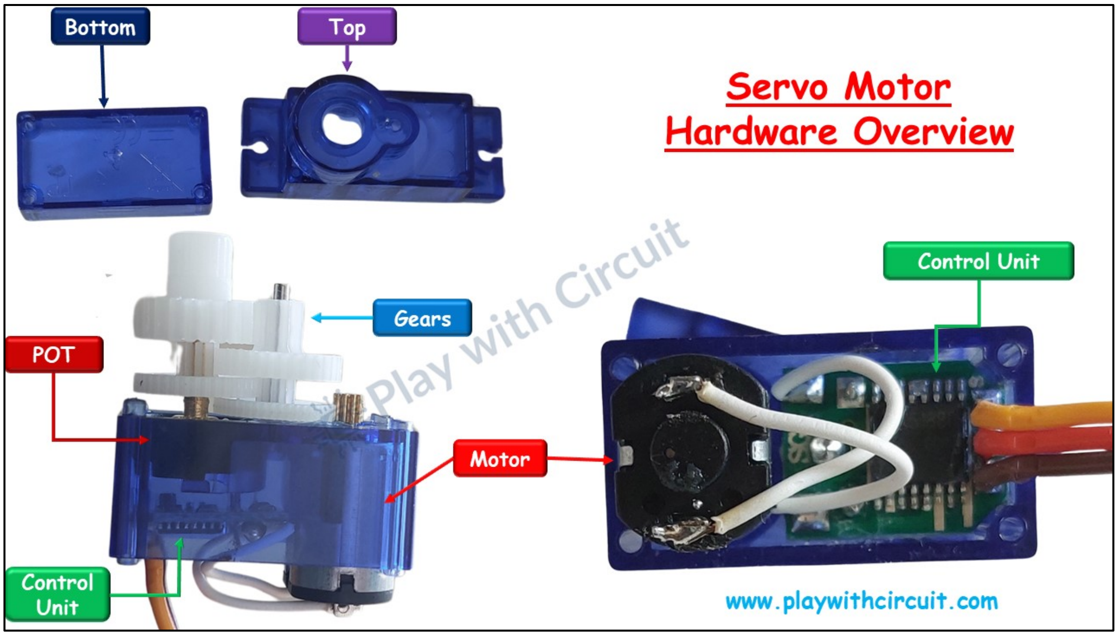


Figure II.14 Overview in servo motor [42]

Working Principle

Servo motors function using a closed-loop control system, commonly referred to as a servomechanism. This system allows the motor to continuously monitor its actual position through a built-in feedback sensor typically a potentiometer and compare it with the desired position provided by the control signal. If any deviation is detected, the motor dynamically corrects its position to match the target. This self-regulating behavior enables high-precision control, even under varying mechanical loads. [42]

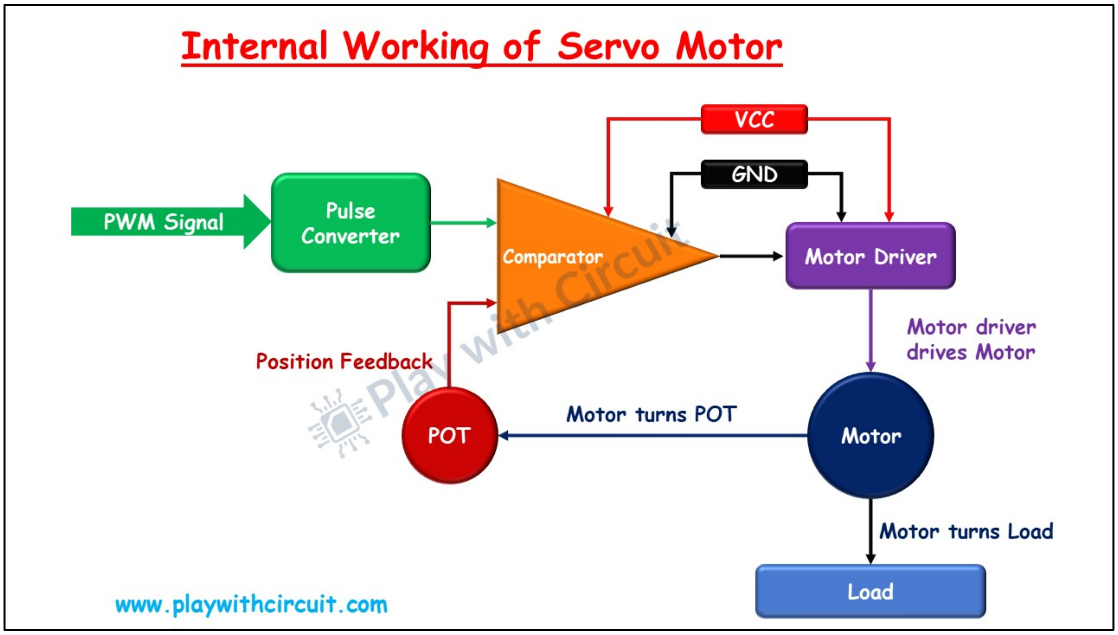


Figure II.15 Servo Motor Internal Diagram [42]

A key aspect of servo motor control is the use of Pulse Width Modulation (PWM). In this method, a microcontroller—such as an Arduino—sends a square wave signal with a variable duty cycle to the servo motor's control input. The duration of the high pulse in this waveform determines the angular position the motor should reach. [42]

For example:

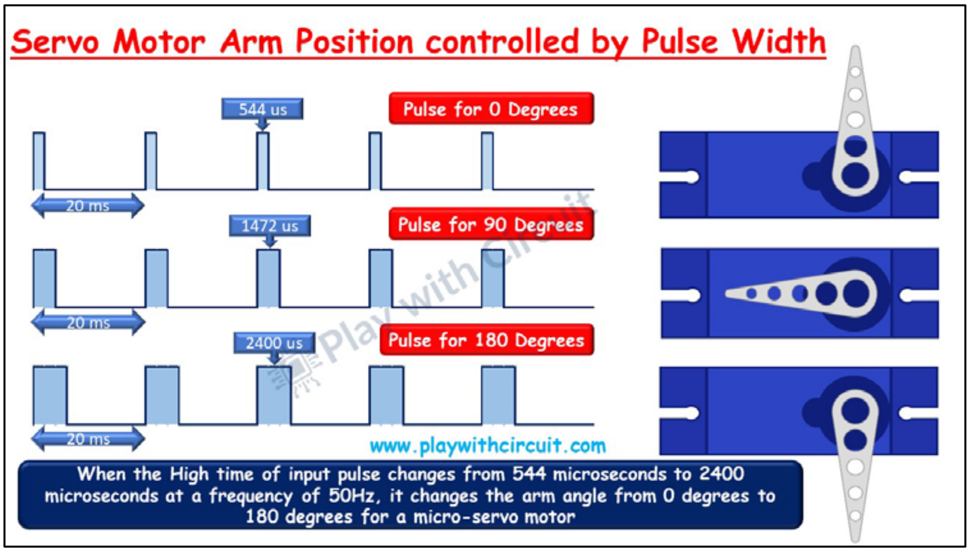


Figure II.16 The relation between pulse width and servo motor arm position [42]

A pulse width of approximately 544 microseconds (µs) positions the shaft at 0°,1472 µs corresponds to the neutral 90° position, and 2400 µs moves it to 180°. [42]

This PWM-based mechanism translates electrical input into mechanical movement with fine control, enabling servo motors to perform tasks that require exact angular placement such as adjusting sprayers or sensors in disinfection robots. [42]

II.2.5.3. Stepper Motor

Stepper motors are electromechanical actuators designed for precise motion control. Unlike conventional DC motors that rotate continuously, stepper motors move in discrete angular increments, known as "steps." This characteristic makes them ideal for systems requiring accurate positioning, such as 3D printers, robotic arms, and camera sliders. Stepper motors function as open-loop systems, which simplifies the control without the need for complex feedback mechanisms. [43]

Working Principle

The operation of a stepper motor is based on the interaction between electromagnetic coils and a toothed rotor. These motors are constructed with multiple stator windings arranged around the rotor. When these windings are energized in a specific sequence, they create a rotating magnetic field that causes the rotor to align and rotate in fixed increments. [43]

For example, a widely used stepper motor, such as the 28BYJ-48, has 64 internal steps per revolution. It is often combined with a gear reduction system (commonly around 64:1) resulting in 4096 total steps per full output shaft rotation, significantly enhancing its resolution. [44]

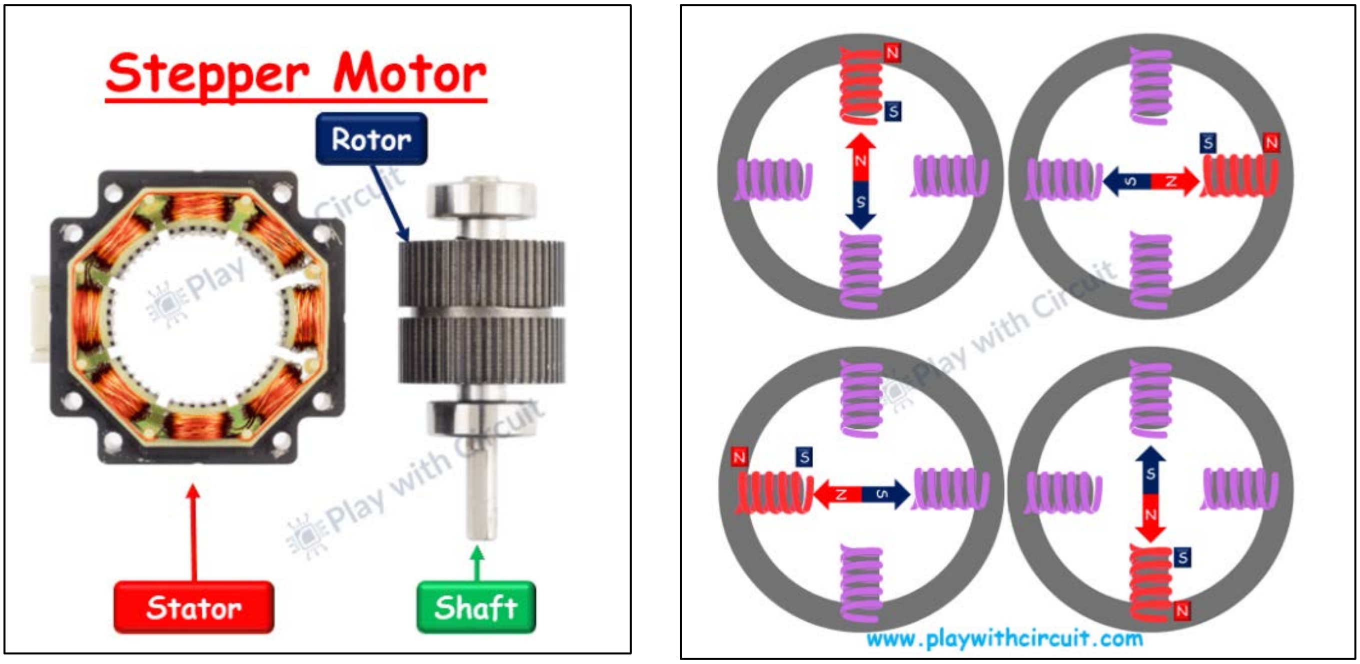


Figure II.17 (a): Basic structure of a stepper motor showing the rotor (rotating part) and stator (stationary part). **(b):** Illustration of how sequential current flow in coils generates discrete steps in rotor movement. [44]

Characteristics

Stepper motors offer predictable and consistent movement with each input pulse. Their behavior and performance can be summarized in the table below:

Table II.5 Performance Parameters and Operational Features of a Stepper Motor

Parameter	**Typical Value / Description**
Step Angle	$5.625° per\ step$ (Without gearbox)
Steps per Revolution	64 (Motor only), 4096(With gearbox)
Gear Ratio	$\sim 64:1$
Position Accuracy	High (up to 4096 steps/rev with gearbox)
Speed Control	Achieved by adjusting pulse frequency
Holding Torque	Good, holds position without continuous input
Direction Control	Easily reversible by changing stepping order
Application Scope	Robotics, automation, camera control, etc.

Stepper motors can operate in various stepping modes, including full-step, half-step, and micro-stepping, each offering a different tradeoff between resolution and torque. [44], [43], [45].

Stepper motors are reliable, cost-effective components for systems requiring accurate control of rotation and positioning. Their stepwise motion, simple interfacing, and open-loop nature make them highly suited for embedded systems and automation applications. With flexible configurations and enhanced resolution through gearing mechanisms, they continue to be a core element in precision motion control designs. [44]

II.2.5.4. DC Mini Water Pump

Definition and Overview

A DC mini water pump is a compact electromechanical device designed to move liquid, typically water, using a small direct current (DC) motor. These pumps operate at low voltages (typically 3V to 6V), making them suitable for small-scale automation and embedded systems. The pump converts electrical energy into mechanical energy through either a rotating impeller (for submersible types) or a diaphragm mechanism. Due to their portability, low power consumption, and ease of integration, these pumps are commonly used in hobby electronics, smart irrigation systems, and compact robotic applications. [46] , [47] , [48].

Working Principle

The DC Mini Water Pump functions by converting electrical energy into mechanical motion through a compact DC motor. In most submersible configurations, this motion drives a small impeller that spins rapidly, creating a pressure differential: low pressure at the inlet draws water in, while centrifugal force pushes it out through the outlet. These pumps typically operate at low voltages (often around 5V) making them suitable for microcontroller-based applications. Their operation can be managed using a transistor switch (e.g., NPN with a flyback diode) or a relay module, allowing integration into automated systems such as disinfection robots or fluid control mechanisms [46], [48].

For improved efficiency and safety, additional features like flow sensors, PWM speed control, or dry-run protection can be integrated depending on the application needs.

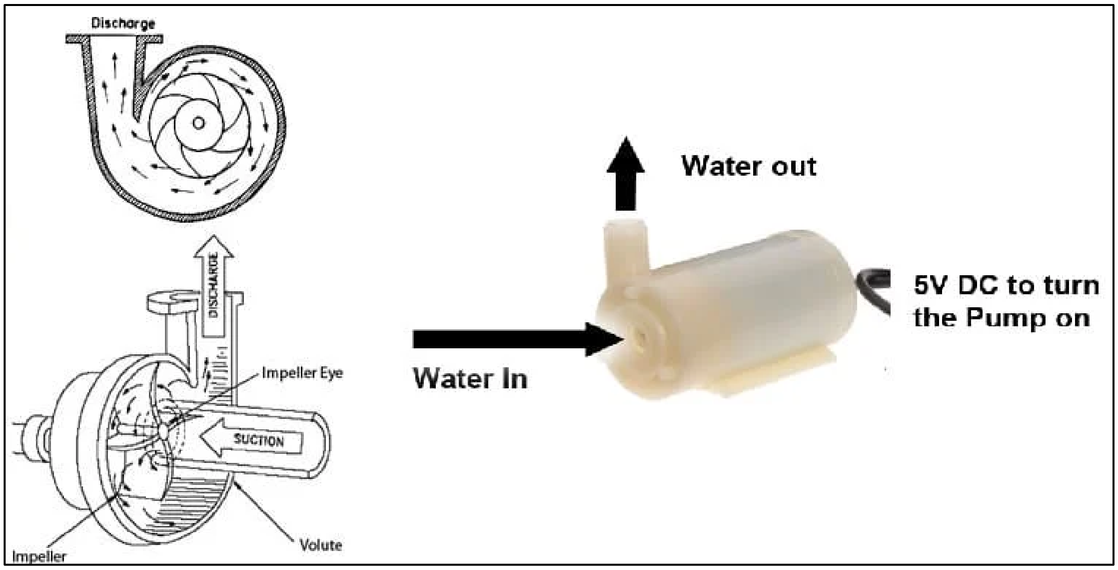


Figure II.18 Diagram of a DC mini water pump showing the internal motor, impeller chamber, inlet and outlet ports. [48]

Structure and Components

A typical 5V DC mini water pump includes the following components:

- A miniature brushed DC motor
- A sealed impeller chamber
- Plastic casing (usually waterproof)
- Two ports: inlet and outlet
- Power leads for electrical connection

Some models may also include built-in filters or anti-backflow features. [46]

Advantages and Limitations

Table II.6 Advantages and Limitations of the mini water pump

Advantages	**Limitations**
- Low power consumption - Lightweight and compact - Easy to integrate and control - Safe for low-voltage systems	- Limited flow rate and head - Not suitable for viscous or chemically aggressive fluids - Wear and tear of brushed motor over time [46], [48]

DC mini water pumps offer a practical and reliable solution for low-volume fluid transfer in embedded systems. Their ease of integration, low cost, and versatility make them a popular choice for hobbyists and engineers alike. Despite their limitations, they are ideal for compact automation applications where simplicity and efficiency are key. [46], [47], [48].

II.2.6. Sensors

II.2.6.1. Ultrasonic sensor

An ultrasonic sensor is an electronic device that measures distance by emitting ultrasonic sound waves and analyzing the reflected echoes. These sensors operate at frequencies higher than the audible range for humans, typically above 20 kHz [50].

In disinfection robots, ultrasonic sensors play a critical role in navigation and obstacle avoidance, ensuring that the robot can move safely and efficiently through environments without human intervention [51].

Working Principle

Ultrasonics sensors function based on the Doppler frequency (where the round-trip time of the ultrasound wave is read). They emit ultrasonic waves through a transmitter, which propagate through the medium (usually air). When these waves encounter an object, they are reflected back toward the sensor’s receiver [52].

The distance to the object is calculated using the formula:

$$Distance = \frac{Speed\ of\ Sound \times Time\ Delay}{2} \qquad (II.3)$$

where the speed of sound is approximately $343\ meters\ per\ second$ at $20°C$ [50].

Environmental factors like temperature and humidity can affect the speed of sound, and therefore must be considered for precise measurements [50].

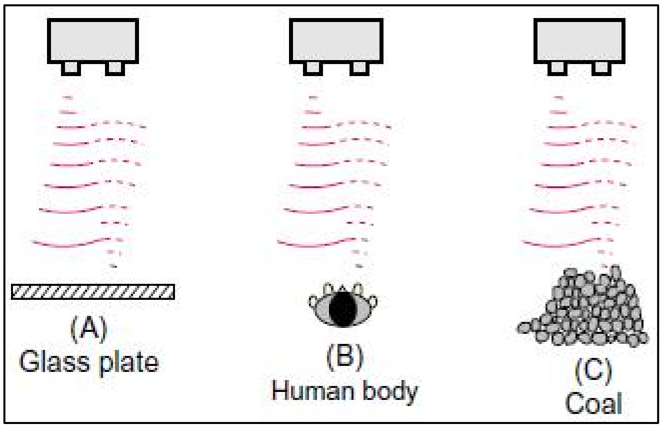


Figure II.19 Examples of different object types encountered by ultrasonic sensors [50]

(A) Flat objects such as liquids, boxes, and plastic sheets.

(B) Columnar objects including cans, bottles, and the human body.

(C) Granular objects such as ores, rocks, coal, coke, and plastic pellets.

Components

A typical ultrasonic sensor consists of three main components [52]:

- **Transmitter (Emitter or trigger):** Generates and sends ultrasonic sound waves.
- **Receiver:** Captures the reflected sound waves (echo).
- **Control Circuit:** Processes the signal to calculate the distance based on the time delay between transmission and reception.

Some ultrasonic sensors use separate transmitter and receiver units, while others integrate both functions into a single device [51].

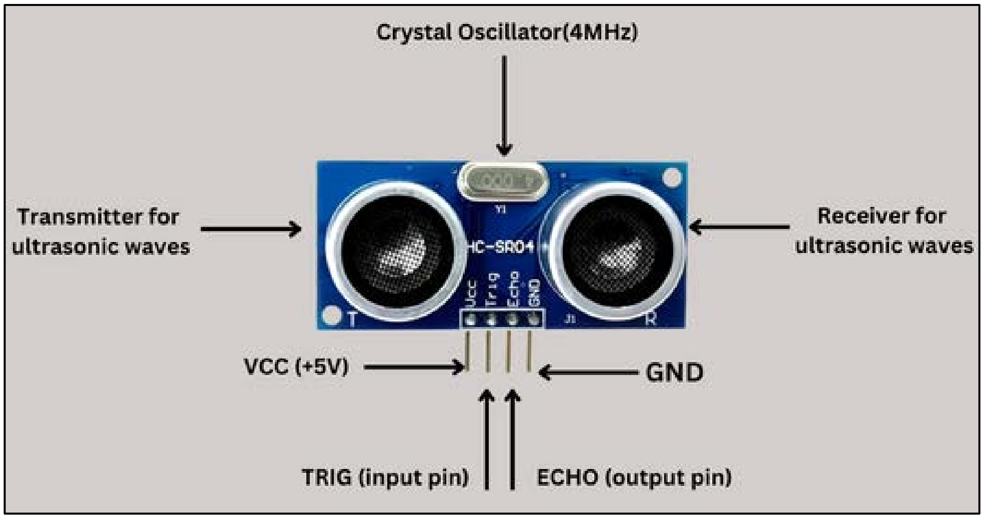


Figure II.20 Ultrasonic sensor front view with pin configuration [50]

Technical Specifications

The general technical characteristics of ultrasonic sensors include [52]:

- *Operating Voltage:* Typically, 5V DC.
- *Operating Frequency:* Most common sensors, like the HC-SR04, operate at around 40 kHz.
- *Sensing Range:* From approximately 2 cm to 400 cm.
- *Accuracy:* Measurement errors are usually within a few millimeters, depending on environmental conditions [50].
- *Beam Angle:* Effective sensing angles are typically around 15°.

Advantages and Limitations

Advantages [51], [50]

- *Non-contact Measurement:* No physical interaction with the target.
- *Performance in Various Lighting Conditions:* Operates unaffected in darkness or smoke-filled environments.
- *Low Cost and Easy Integration:* Compatible with platforms like Arduino and Raspberry Pi.

Limitations [52], [50]

- *Sensitivity to Material Type:* Soft or absorbent materials (e.g., foam) can weaken the reflected signal.
- *Environmental Influence:* Accuracy may vary with changes in temperature, humidity, or airborne particles.
- *Limited Range:* Not suitable for very long-range detection compared to radar or lidar systems.

Ultrasonic sensors are versatile and reliable components widely used in robotics for safe navigation and obstacle avoidance [51], [52].

In the context of disinfection robots, they provide an efficient solution for dynamic, autonomous movement, ensuring operational safety and efficiency even in complex environments [50].

Given their ability to function effectively regardless of lighting conditions and surface color, ultrasonic sensors remain a cornerstone technology in modern autonomous robotic systems.

II.2.6.2. HC-SR501 PIR Sensor

The HC-SR501 PIR (Passive Infrared) sensor is a widely used motion detector module that leverages infrared technology to detect motion in a specified range. It is particularly suited for battery-powered applications due to its low power consumption and reliable performance. This sensor is popular in DIY electronics, security systems, and home automation projects. [53]

Working Principle

The HC-SR501 sensor operates on the principle of detecting infrared radiation emitted by warm objects, particularly the human body. It utilizes a pyroelectric infrared sensor coupled with a control chip (BISS0001) to sense motion.

The sensor contains two sub-probes (A and B) placed at opposite ends within a rectangular window. When a human moves across the field of view (left to right or vice versa), the infrared radiation reaches the two probes at slightly different times. This time difference enables motion detection.

Conversely, movement directly towards or away from the sensor (front to back or top to bottom) doesn't cause sufficient time variation, reducing sensitivity. [53]

The output signal is digital (High = 3.3V, Low = 0V), and its behavior depends on the trigger mode set via a jumper:

L (non-repeatable): The sensor outputs high for a preset delay time when motion is detected and then goes low, even if motion continues.

H (repeatable): As long as motion continues, the output stays high; the delay timer resets with each detection.

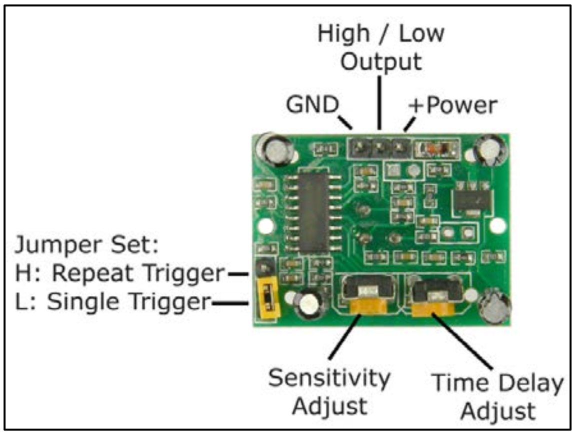


Figure II.21 The HC-SR501 sensor layout and specs

Characteristics

Here are the main technical specifications and features of the HC-SR501 PIR sensor:

Table II.7 The Specifications and Features of the HC-SR501 PIR Sensor

Parameter	**Value**
Operating Voltage	$5\,V - 20V\ DC$
Output	TTL Logic ($High$: $3.3V, Low$: $0V$)
Sensing Range	Up to 7 $meters$ within 110° cone angle
Delay Time	Adjustable: $\sim 0.3s\ to\ 5\ minutes$
Trigger Mode	Repeatable / non-repeatable
Power Consumption	$Static\ current\ <\ 50\ \mu A$
Board Dimensions	$32\ mm\ \times 24\ mm$
Lens Diameter	$23\ mm$
Block Time (inactivity)	Default 2.5 $seconds$ (adjustable)
Operating Temperature	$15℃\ to + 70℃$

Other key features include:

Micropower Consumption: Ideal for battery-powered devices.

Photosensitive Control (optional): Can prevent activation during daylight.

Temperature Compensation (optional): Improves performance in high-temperature environments.

Dual Potentiometers: One to adjust detection range, the other for delay time. [53]

II.2.7. Communication

II.2.7.1. NodeMCU ESP8266

The NodeMCU ESP8266EX is a low-cost Wi-Fi microcontroller module that plays a critical role in the communication subsystem of disinfection robots.

It is based on the ESP8266 chip developed by Espressif Systems and includes both Wi-Fi capabilities and a full microcontroller functionality.

This module provides seamless wireless communication between the robot and external devices such as smartphones or cloud servers.

Its integration simplifies the design of Internet of Things (IoT) solutions due to its built-in TCP/IP protocol stack and digital I/O pins.

Technical Specifications

The NodeMCU ESP8266EX includes the following features [54] [55]:

51Microcontroller: Tensilica L106 32-bit RISC processor, clocked at 80 MHz (up to 160 MHz)

- Flash Memory: Typically 4MB
- Operating Voltage: 3.0V–3.6V (typically 3.3V)
- I/O Voltage: 3.3V
- Digital I/O Pins: 11
- Analog Input: 1 (10-bit ADC)
- Interfaces: SPI, I2C, I2S, UART, PWM
- Wi-Fi: IEEE 802.11 b/g/n, supports WPA/WPA2 security

– USB-to-Serial interface: CH340 or CP2102 depending on the board variant

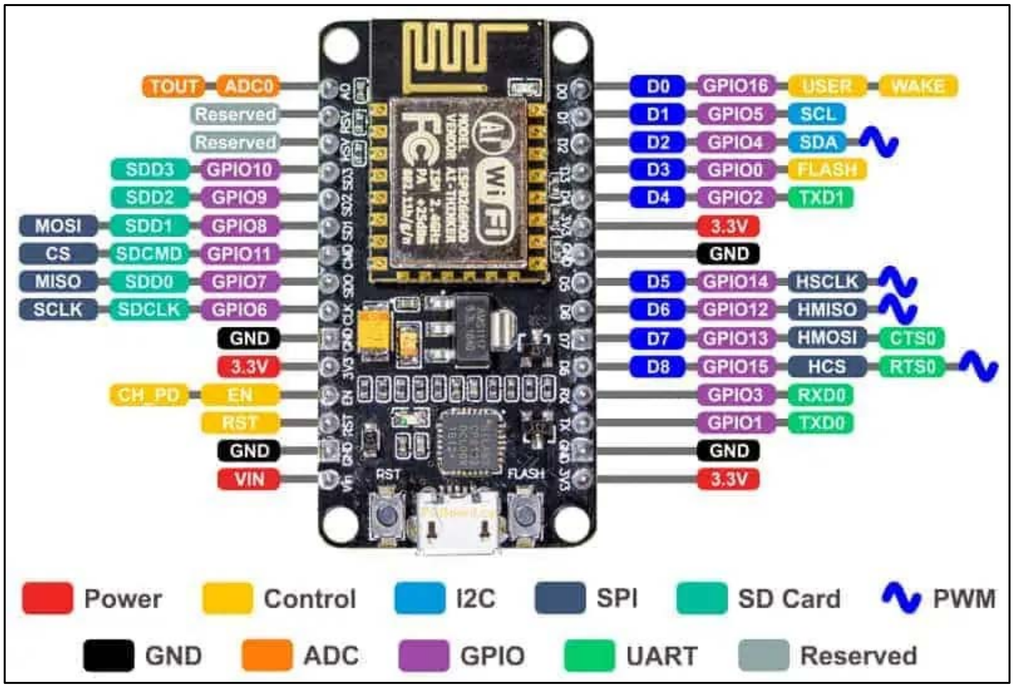


Figure II.22 Pinout diagram of NodeMCU ESP8266EX [53]

II.2.7.2. MIT App Inventor

MIT App Inventor is a visual programming platform developed by the Massachusetts Institute of Technology (MIT). It enables users, even beginners, to create Android applications quickly and easily using a block-based programming approach. This makes it a suitable choice for smart systems and embedded applications.

User Interface

The platform features a simple and intuitive interface consisting of two main sections as showing at the image:

Designer: Used to build the graphical interface by adding buttons, text fields, images, and other elements.

Blocks Editor: used to define the application's behavior using logical, interconnected programming blocks.

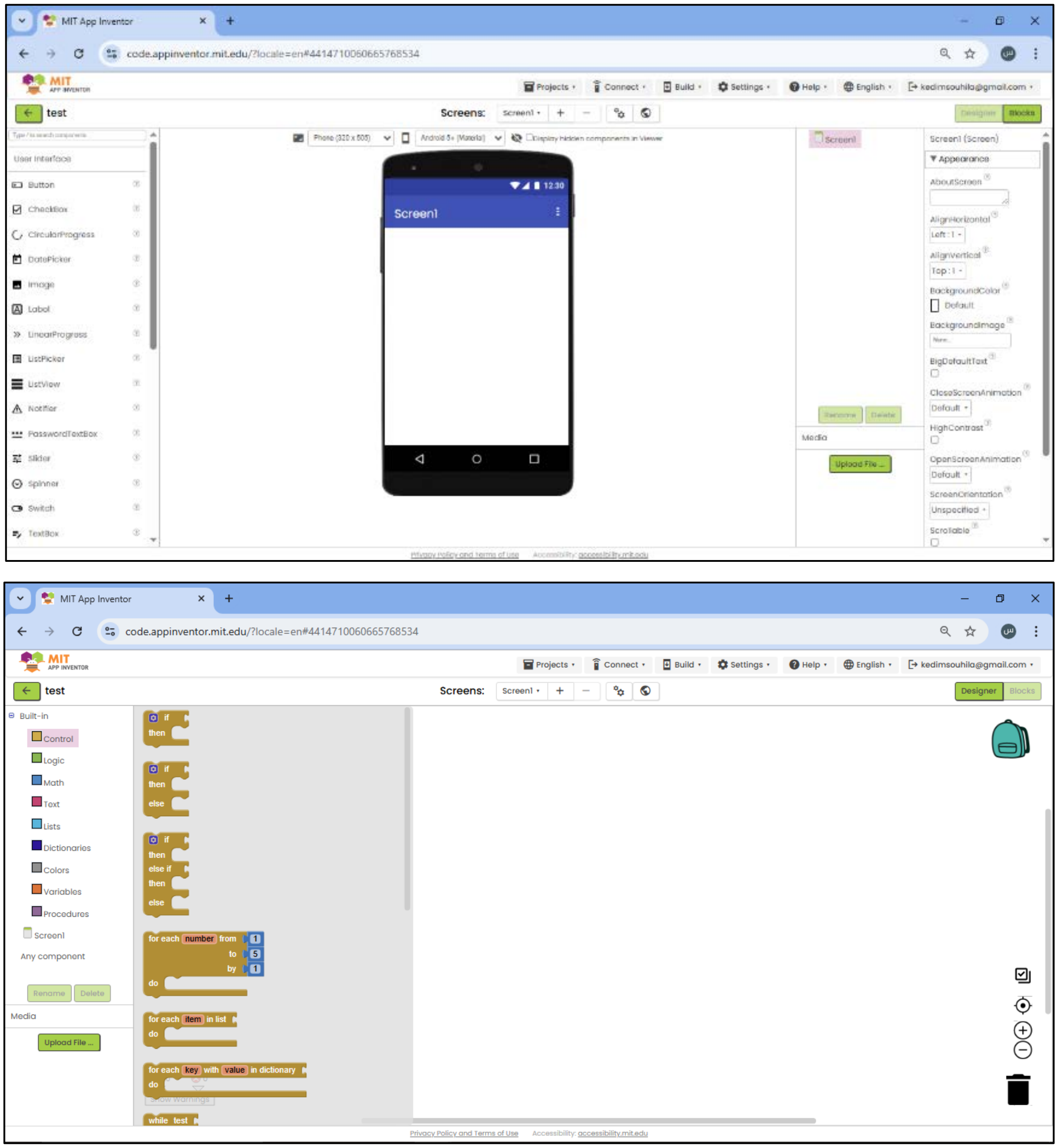


Figure II.23 Designer and Blocks editor of the platform of MIT App Inventor. (a): Designer, (b): Blocks Editor

Applications Features

Using this platform, applications can include:

- Buttons to control the robot's movement.
- Connection status indicators.
- An interactive and user-friendly interface.
- The ability to send and receive data via Wi-Fi.

Connection with ESP8266

The application connects to the NodeMCU ESP8266 board through its Wi-Fi network. Commands are sent from the app to the ESP8266 using its IP address, either through HTTP requests (using the web component) or via the $WiFiClient$ component. The ESP8266 receives the transmitted data and converts it into executable commands for the robot.

MIT App Inventor is an effective and user-friendly tool for developing remote control applications. In this project, it serves as a simple software solution to link the smartphone with the robot, enhancing the overall user interaction and control experience.

II.3. Conclusion:

This chapter detailed the architectural and component level design of the hospital disinfection robot. Starting from the power supply and control units to actuators, sensors, emitters, and communication modules, each element was analyzed in terms of its selection criteria, functionality, and integration into the overall system. This design phase lays the foundation for the implementation stage by ensuring that each subsystem is logically structured and technically feasible. The next chapter will build upon this foundation through simulation, hardware testing, and performance evaluation.

III. Chapter 3: Practical Implementation and Experimental Results

III.1. **Introduction**

This chapter presents the practical realization and experimental validation of the hospital disinfection robot, building upon the theoretical design introduced in the previous chapter. It is structured in three main parts: the simulation of subsystems including motion control, disinfection mechanisms, and communication interface; the setup and configuration of the hardware environment; and the actual testing and evaluation of key components and overall system integration. Real tests were conducted to assess sensor accuracy, actuator performance, and movement smoothness. Limitations encountered during implementation are also discussed, providing insight into the challenges and constraints of turning the conceptual model into a working prototype.

III.2. **Simulation and System Design**

Building on the theoretical groundwork, this section details the simulation processes and design choices made to develop the robot's key systems. It outlines the structure and functionality of various subsystems beginning with movement highlighting both the conceptual simulations and the corresponding circuit designs that guided the implementation phase.

III.2.1. Movement System Simulation

III.2.1.1. Circuit Design

The circuit contain the following components:

- 4 DC Motors
- Arduino Uno Board
- Arduino Driver Motor Shield (L293D)
- Ultrasonic Sensor
- Servo Motor
- 1 Battery of 9 V

The motors placed as following:

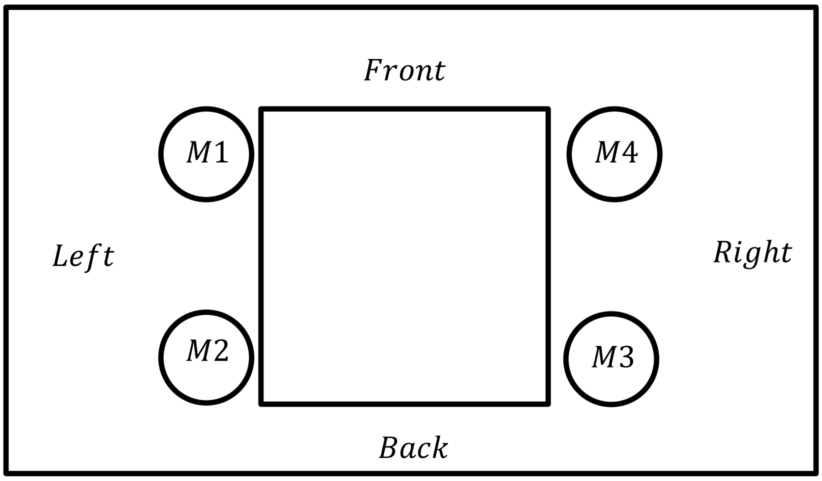


Figure III.1 Placement of each motor of the robot

These elements are connected as shown in the image below:

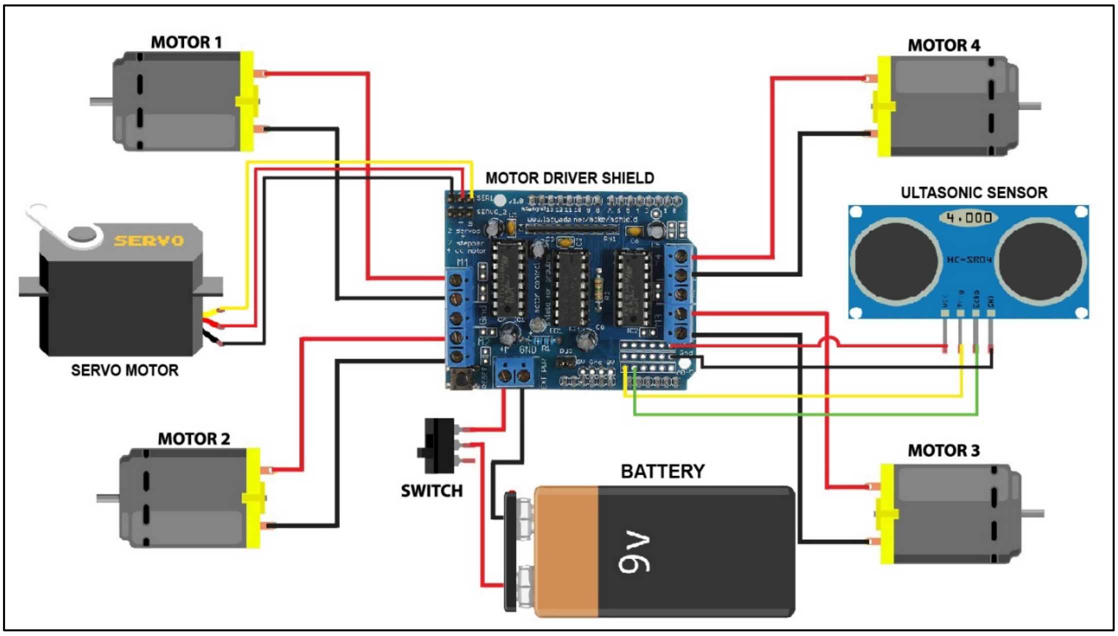


Figure III.2 Obstacle avoiding robot

III.2.1.2. Algorithmic Flow

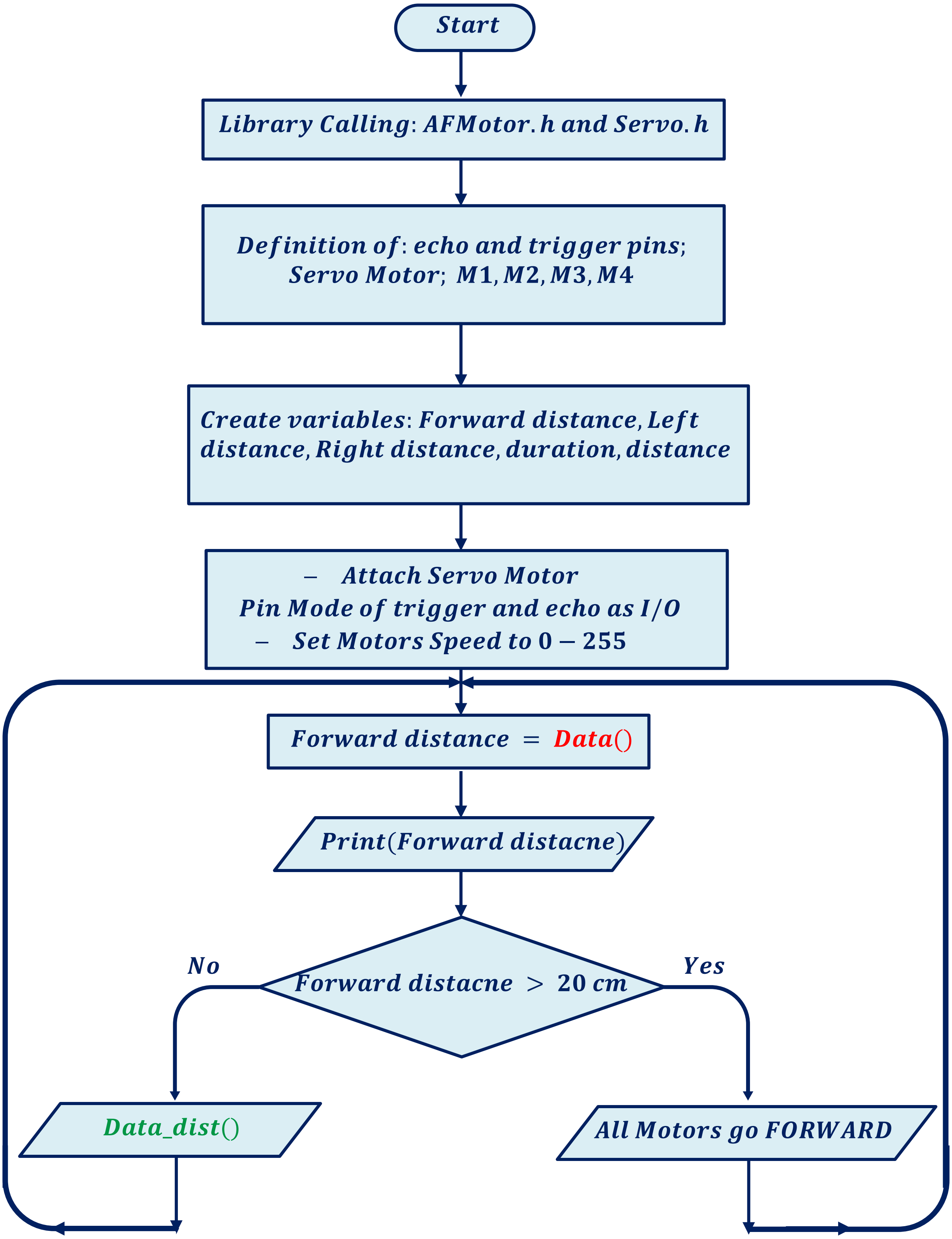
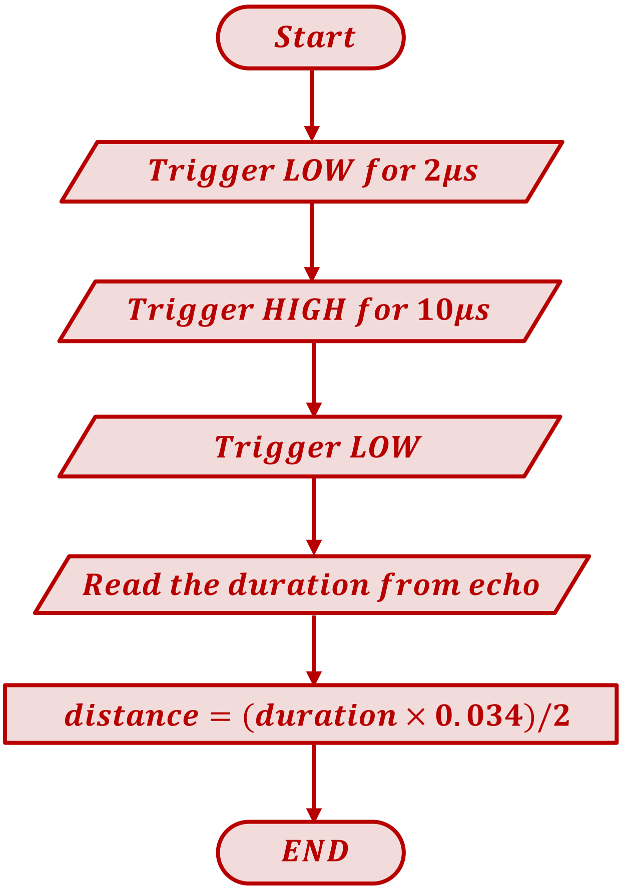
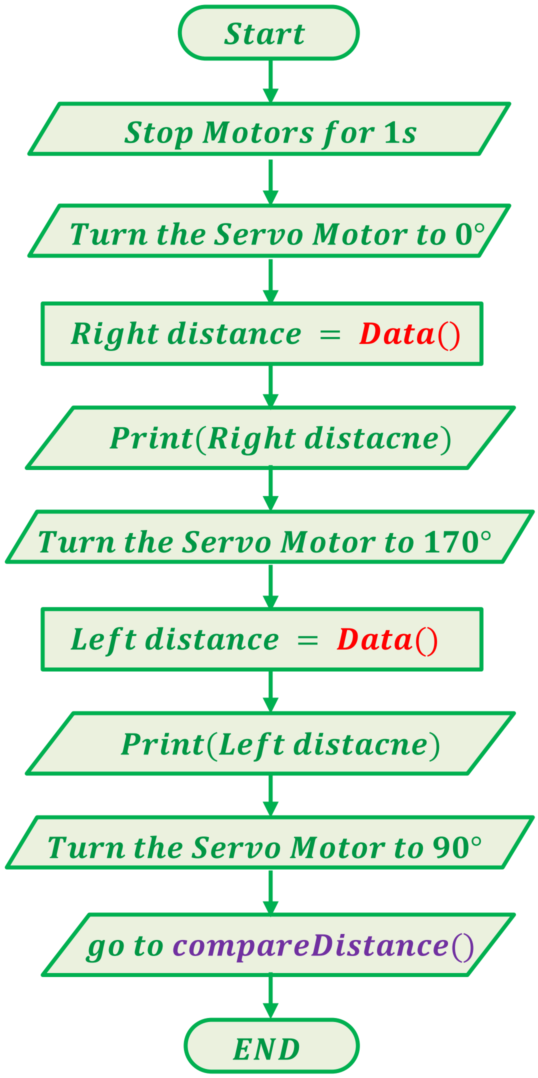


Figure III.3 Algorithmic flow for an obstacle avoiding robot

Table: The $Data()$ and $Data\_dist()$ Functions

• The $Data()$ Function:	• The $Data\_dist()$ Function:
	

- The $compareDistance()$ Function:

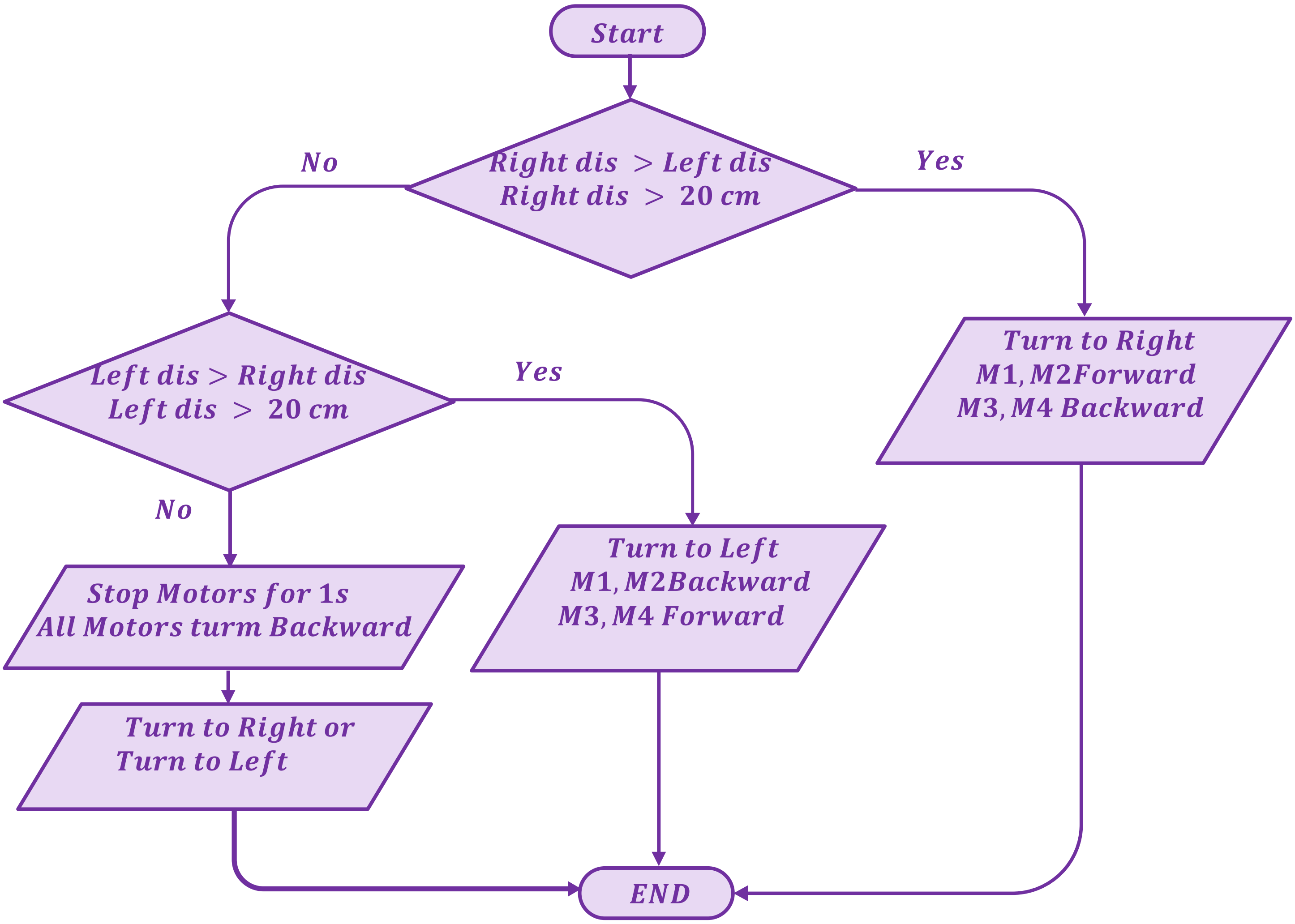


Figure III.4 Algorithmic flow for $compareDistance()$ function

III.2.1.3. Functional Description

In order for the sterilization robot to move automatically without colliding with any obstacles in its path, an ultrasonic sensor was added to measure the distance and a servo motor was added to provide a wider range of vision and to determine the direction of rotation of the robot more effectively. Thus, by measuring the distance, the robot's movement was programmed as follows:

At the start of the program, all necessary libraries ($AFMotor.h; Servo.h$) are defined and called, and the names of the echo and trigger pins, servo motor, and four motors (M1, M2, M3, M4) are specified. Variables for measuring time and distance are then created and stored for comparison.

In the next step, the position of the Servo motor (90° forward angle) and the nature of the echo and trigger pins as I/O are specified, and the speed of the motors is also specified.

After completing the definition stage and specifying the properties of each element, we move to the command setting stage where:

- First, the forward distance is measured using the $Data()$ function and the information is stored in the variable $Forward\ distance$.
- The result is compared with the minimum distance that the robot should leave between itself and the obstacle (in our case $20\ cm$).
  - If the forward distance is greater than $20\ cm$, the motors move forward and then the program is repeated.
  - If the forward distance is less than $20\ cm$, we move to the $Data\_dist()$ function. After exiting the function, the program is repeated.

In the $Data()$ function: Trigger pin is set to $0\ (LOW)$ for $2\ \mu s$ to ensure no ultrasonic transmission, then set to 1 $(HIGH)$ for 10 μs, i.e., 10 μs of ultrasonic wave transmission, then set to 0 again, then wait for the return wave to be received via echo pin, the time taken between transmission and reception is stored in duration variable. The distance is calculated using the mathematical equation:

$$distance = \frac{(duration \times 0.034)}{2} \qquad \text{(III.1)}$$

Where: $the\ speed\ of\ sound \approx 0.034\ cm/\mu s$; and divide by 2 because the measured time consists of the sending time and the receiving time.

From this, the value given by the $Data()$ function becomes the $distance$ variable. If you go to the $Data\_dist()$ function, the following will happen automatically:

- Stop all motors for a second.
- Servo motor moves to angle 0° (i.e., right of the robot).
- Calculate the distance using the $Data()$ function and store it in the $Right\ distance$ variable.
- Servo motor moves to angle 170° (i.e., Left of the robot).

- Calculate the distance using the $Data()$ function and store it in the $Left\ distance$ variable.
- Return the Servo motor to angle 90° (i.e., forward).
- Go to the $compareDistance()$ function.

In the $compareDistance()$ function, the values stored in both $Right\ distance$ and $Left\ distance$ are compared where:

- If $Right\ distance$ is greater than $Left\ distance$ and also greater than $20\ cm$ (the minimum distance between the robot and the obstacle), the robot rotates to the right.
- If one of the conditions is not met, it is compared whether $Left\ distance$ is greater than $Right\ distance$ and also greater than $20\ cm$:
  - If yes, the robot rotates to the left.
  - If no, the robot reversed and rotates to the left.

III.2.2. Disinfection System Simulation

III.2.2.1. Ultraviolet LEDs System

III.2.2.1.1. **Circuit Design**

The circuit contain the following components:

- Arduino Uno Board
- 2 Resistors ($1k\Omega, 220\Omega$)
- UV_LED
- PIR Sensor
- JBT Transistor ($2N2222$)
- White LED

These elements are connected as shown in the image below:

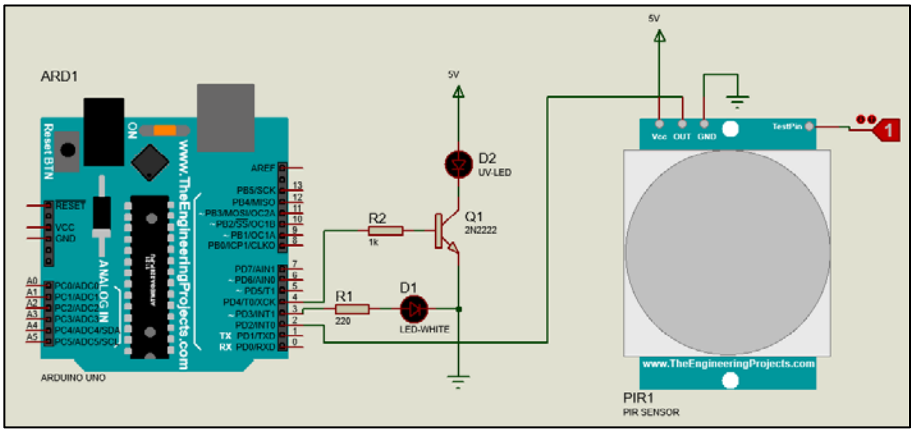


Figure III.5 A Simulation in proteus for the UV LED system

III.2.2.1.2. **Algorithmic Flow**

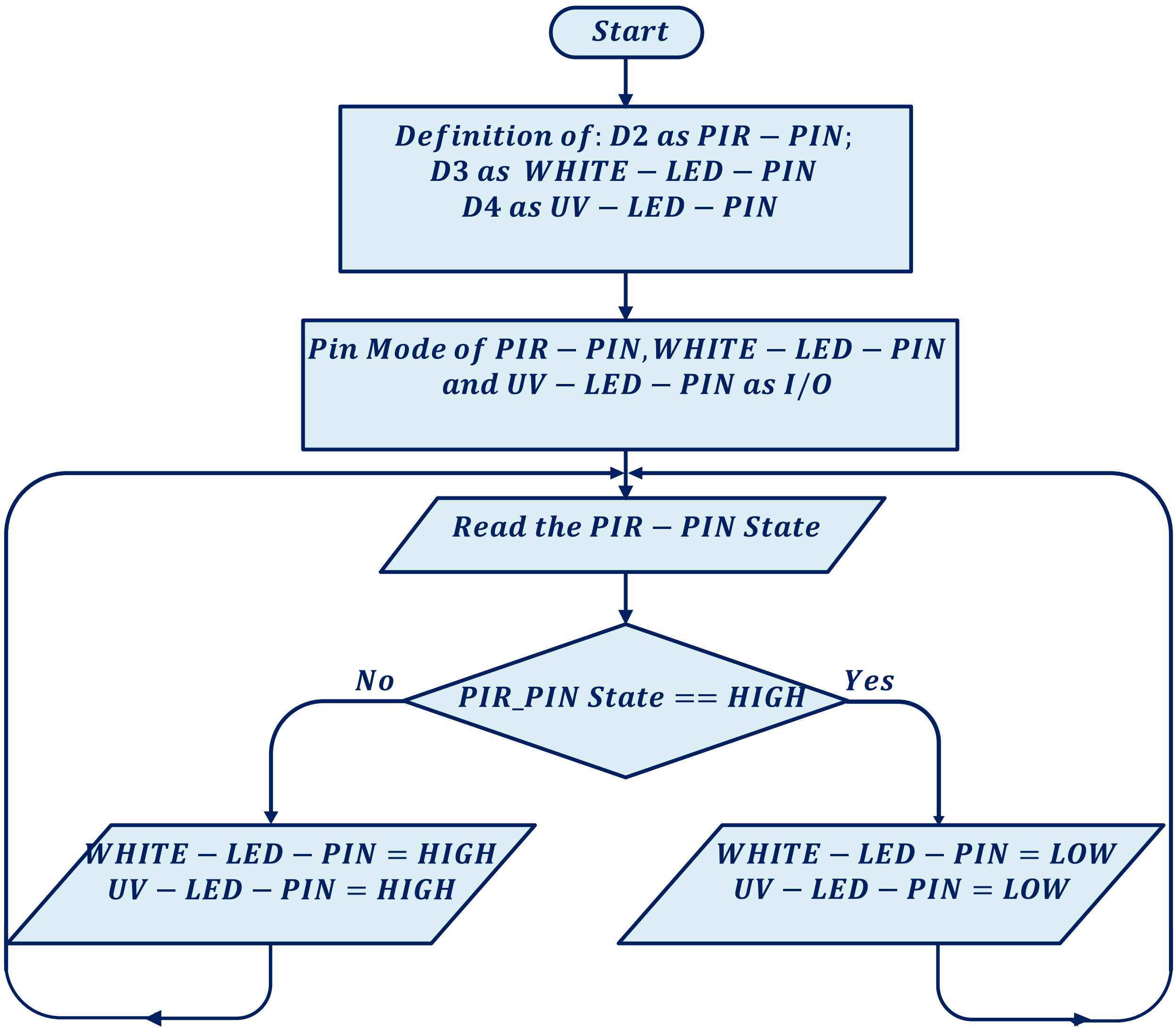


Figure III.6 Algorithmic flow for UV LED system

III.2.2.1.3. **Functional Description**

The UV_LED disinfection system operates on a simple principle: ultraviolet light is directed onto the surface to be disinfected for a specific duration. This system utilizes UV-C radiation, which is less harmful to human compared to other types (A and B), and has a wavelength that directly targets the DNA and RNA of bacteria and viruses, inhibiting their ability to reproduce.

To enhance the safety and efficiency of the system, a PIR sensor was added. This sensor detects thermal motion (such as human presence) and serves as a safety alert. When motion is detected, it triggers an alert and automatically turns off the UV_LED to avoid human exposure.

Additionally, a white LED is included to verify the effectiveness of the UV_LED, as one of the drawbacks of UV disinfection is its reduced performance in shaded areas.

Regarding the circuit connection, the UV_LED anode (+) is connected to an external 5V power source, and the cathode (-) is connected to the collector of an NPN transistor (2N2222). The UV_LED is not connected directly to an Arduino pin, despite the Arduino also outputting 5V, because UV_LEDs typically require a current much higher than $40\ mA$, which exceeds what an Arduino pin can safely provide. Therefore, to avoid damage to components, the UV_LED is driven using the 2N2222 transistor.

The system is programmed as follows:

- At the beginning of the code, the Arduino pins are defined:
  - $D2 : PIR - PIN$
  - $D3 : WHITE - LED - PIN$
  - $D4: UV - LED - PIN$
- Pin modes are set as input/ output accordingly.
- In the $loop()$ function, the system continuously reads the state of the PIR sensor:
  - If PIR_PIN reads HIGH (1), indicating human presence, all LEDs are turned off.
  - If PIR_PIN reads LOW (0), indicating no presence, the LEDs are turned on.
- The loop then restarts, continually monitoring the environment.

III.2.2.2.Liquid Disinfection System

III.2.2.2.1. **Circuit Design**

The circuit contain the following components:

- Arduino Uno Board
- Arduino Driver Motor Shield (L293D)
- Water Pump
- Stepper Motor

These elements are connected as shown in the image below:

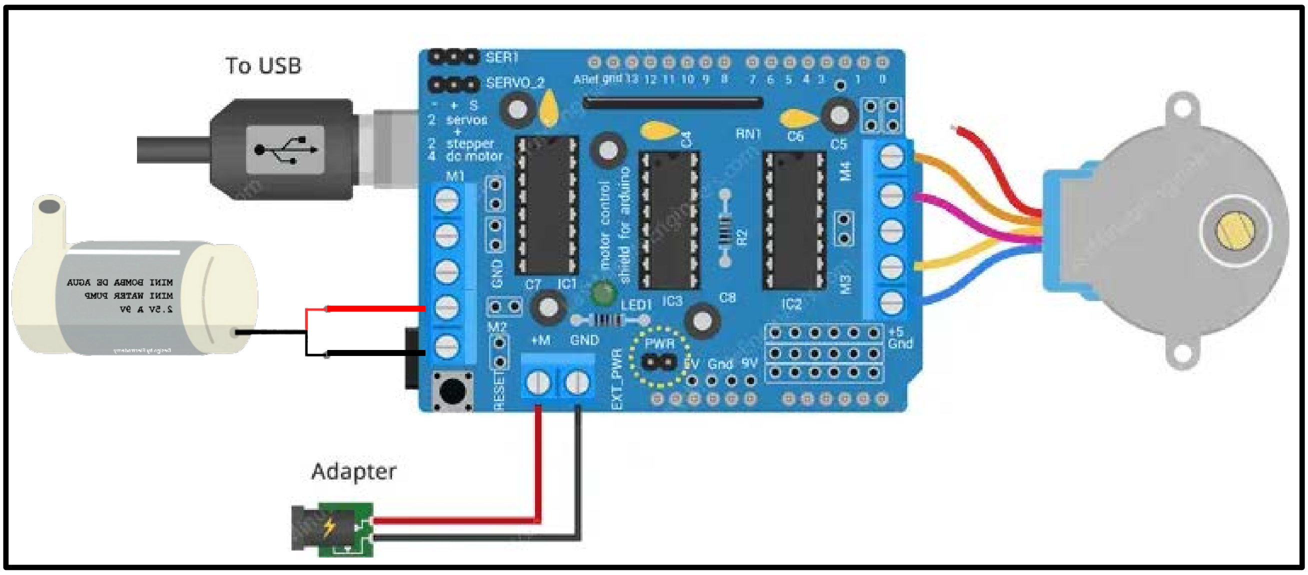


Figure III.7 Circuit diagram of the liquid disinfection system

III.2.2.2.2. Algorithmic Flow

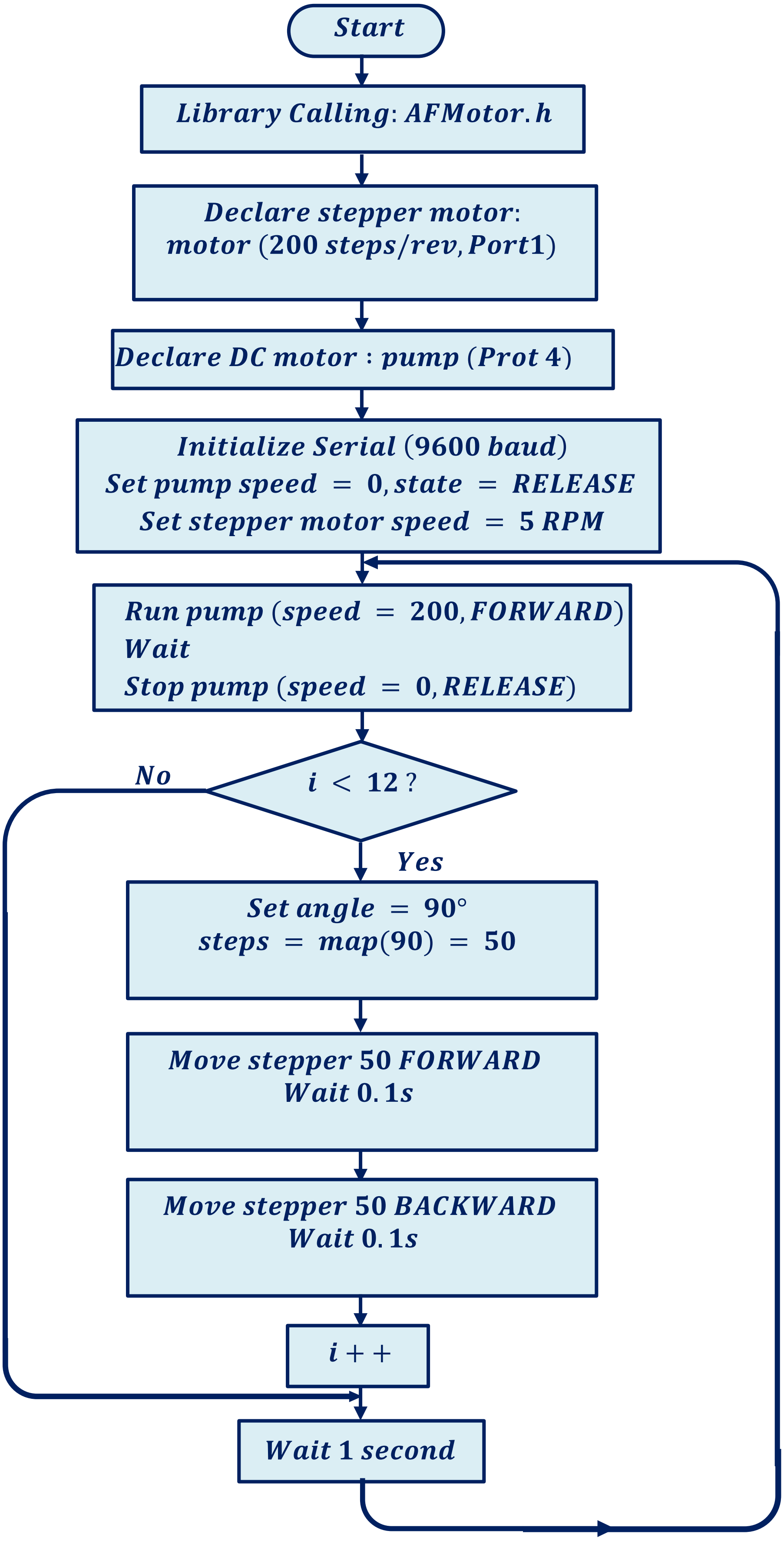


Figure III.8 Algorithmic flow for liquid disinfection system

III.2.2.2.3. **Functional Description**

This system performs a combined sterilization and drying process autonomously. The DC pump sprays the disinfectant in a controlled pulse, while the stepper-driven wiper arm makes alternating sweeps to dry the surface. The looped motion simulates a windshield wiper cleaning a flat surface. So, this system was programmed as follows:

At the beginning of the program, the required library $AFMotor.h$ is included. This library provides the necessary control functions for interfacing the Arduino with the L293D motor driver shield.

Initialization Phase:

- The stepper motor is declared with 200 steps per revolution and connected to Port 1.
- The DC motor (pump) is declared on Port 4.
- Serial communication is initialized at 9600 baud rate for debugging or monitoring.
- The pump speed is set to 0 and its state is set to RELEASE, indicating that it is idle at start.
- The stepper motor speed is set to 5 RPM to ensure smooth and slow movement of the wiper.

Sterilization Phase:

- The pump is activated at speed 200 in FORWARD direction, causing the sterilizer fluid to spray.
- A brief delay allows enough time for spraying.
- The pump is stopped by setting the speed to 0 and the state to RELEASE.

Drying Cycle:

- A loop is initiated to repeat the drying process 12 times, representing 12 wiper passes.
- Within each loop iteration:
  - The angle of movement is set to 90 $degrees$.
  - Using the $map()$ function, this angle is translated to 50 steps.

- The stepper motor moves 50 steps forward simulating the wiper moving in one direction.
- A delay of 0.1 seconds is introduced to stabilize the motion.
- The stepper motor then moves 50 steps backward to return to the original position.
- Another 0.1 second delay ensures complete motion before the next cycle.
- The loop counter is incremented.

End Phase:

- After completing all 12 repetitions, the system waits for 1 second before stopping entirely.
- The program ends, having completed both sterilization and drying functions.

III.2.3. Communication System Simulation

This section presents the communication architecture allowing the smartphone application to control the robot through the ESP8266 NodeMCU. The system ensures that movement and disinfection tasks are handled in parallel through two Arduino boards.

III.2.3.1. Circuit Design

The system is based on a bidirectional communication model:

- The NodeMCU receives commands from the smartphone via Wi-Fi.
- It forwards commands to:
  - Arduino Uno A (movement control)
  - Arduino Uno B (disinfection system)

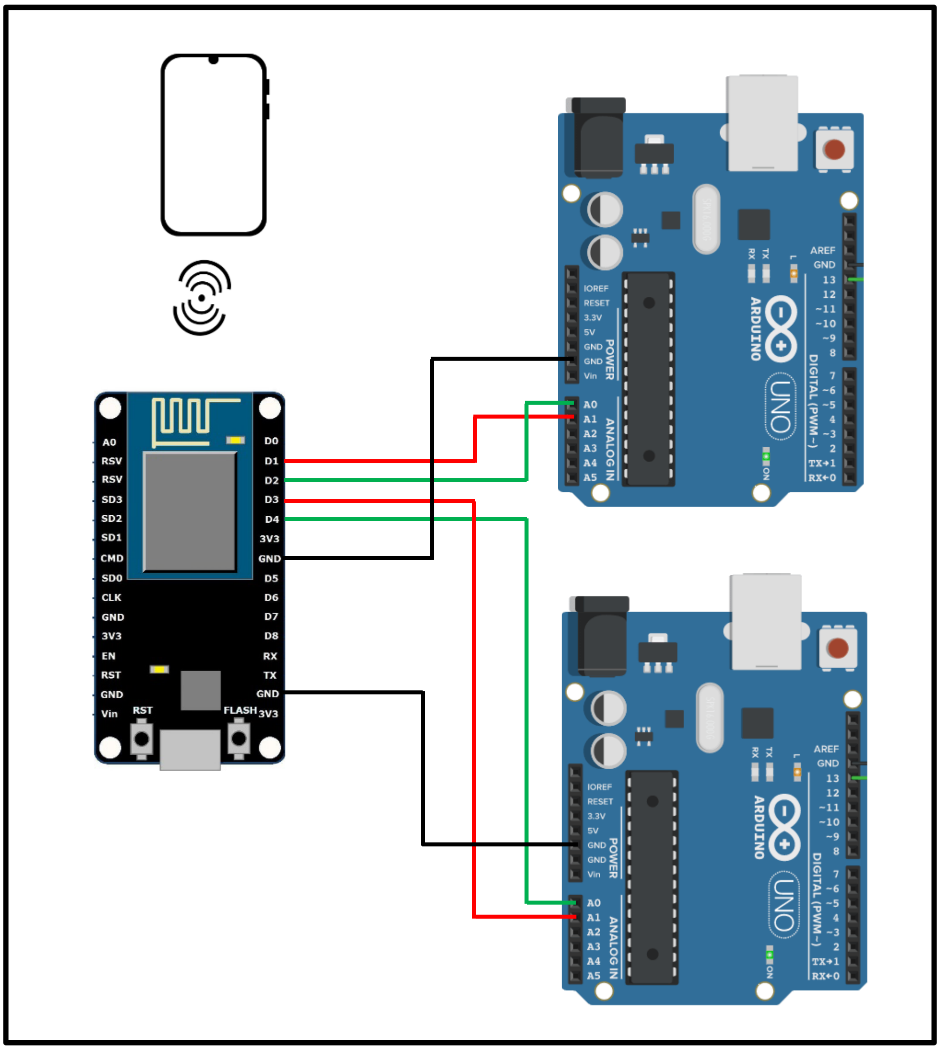


Figure III.9 Circuit diagram of the communication part (Black wire is GND, Red wire (from RX of ESP8266 to TX of Arduino Uno), Green wire (from TX of ESP8266 to RX of Arduino Uno))

III.2.3.2. Application Interface

The Android application contains six interfaces:

1. Home Screen or Main Screen: Choose between robot motion control, spray and drying mode, and UV sterilization node.

2. Motor control mode: buttons for automatic and manual mode (and also a button to return to the main screen).

3. auto mode: Contains buttons to start and stop the motion system with another button to return to the previous screen.

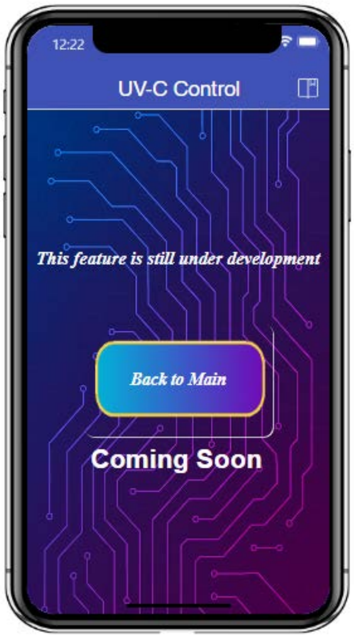
4. Manual mode: Movement buttons and another button to return to the previous screen.

5. Pump and Drying Control: The upper section is for turning the pump on and off, with a slide controller to change the flow rate of the sterile solution. The lower section is for drying mode, with on and off buttons. The last section is for returning to the previous screen.

6. UV Control: Since the circuit components were not available, this part of the app was not developed, and the focus was on other parts of the app. Therefore, there is only an explanatory massage with a button to return to the main screen.

Table III.1 User Interface Screenshots of the Mobile Application

Screen 1	Screen 2	Screen 3
		

Screen 4	Screen 5	Screen 6
		

To illustrate the interaction flow and connectivity between the application's interfaces, a navigation diagram is provided below.

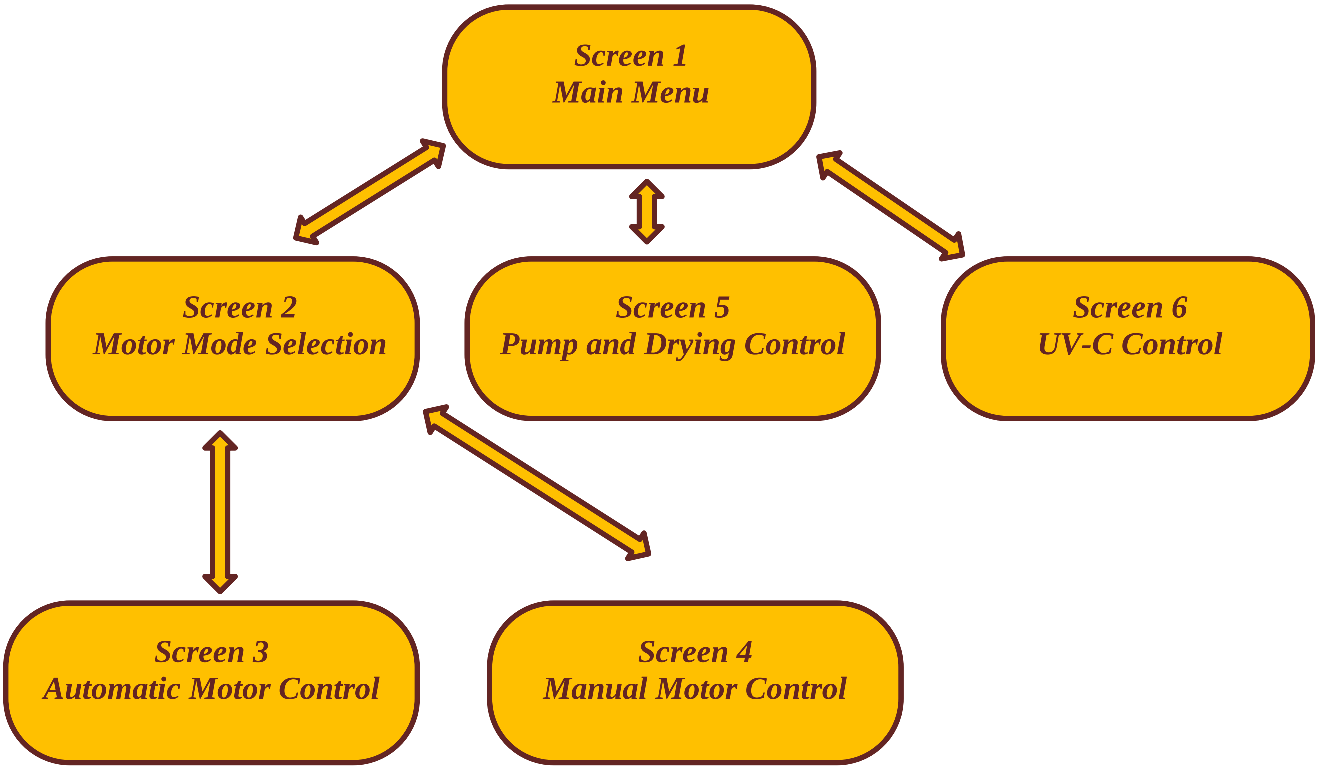


Figure III.10 Navigation diagram of the mobile application interface

III.2.3.3. Algorithmic Flow

The following flowchart describes the logical steps involved in the communication process between the mobile application, the ESP8266 (NodeMCU), and the two Arduino Uno boards responsible for motor control and disinfection functions.

It outlines how the system reacts to user input, interprets commands, and distributes them accordingly.

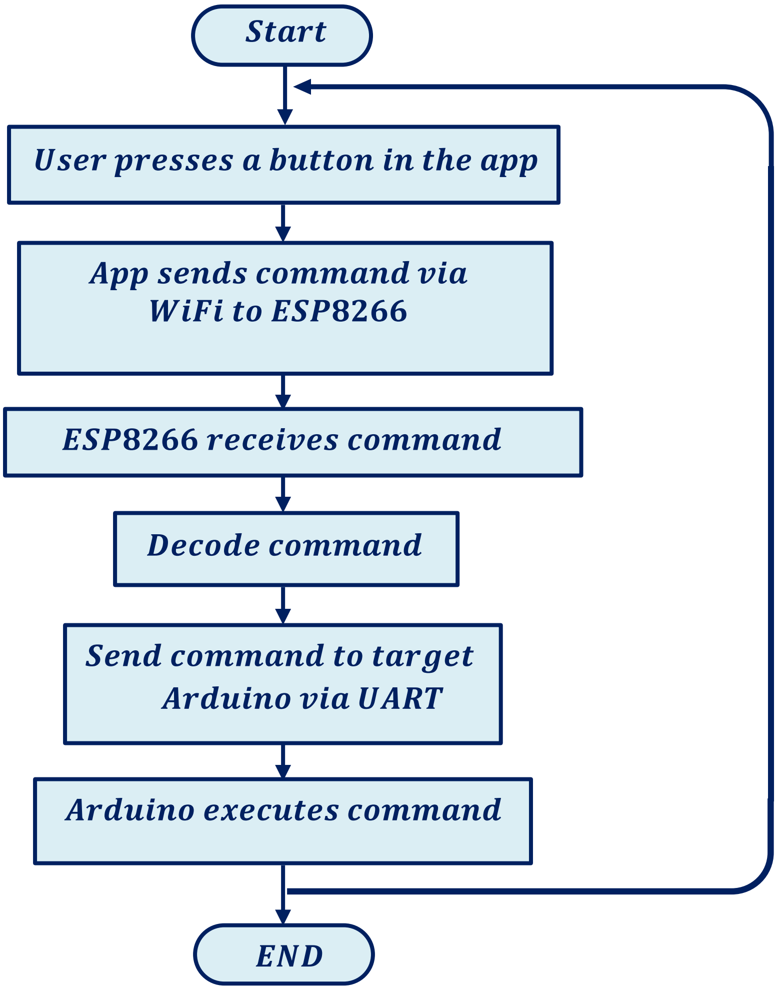


Figure III.11 Algorithmic flow of the communication between mobile app, ESP8266, and Arduino uno boards.

The communication system in this project ensures seamless interaction between the mobile application and the physical hardware components via Wi-Fi. This functionality is achieved using the ESP8266 module, which serves as a communication bridge between the user interface (the mobile app) and the Arduino microcontroller that controls the actuators.

When the user interacts with the app, such as selecting the motor mode or accessing other system controls, a corresponding command is transmitted via Wi-Fi to the ESP8266. The ESP8266 is configured to act as a server that listens for incoming HTTP requests from the mobile application, developed using MIT App Inventor.

Upon receiving the command, the ESP8266 forwards it to the Arduino Uno board via a serial UART (Universal Asynchronous Receiver/ Transmitter) connection. The Arduino then interprets the received command string and activates the appropriate output. For instance:

- If the user selects Automatic Mode, the Arduino activates the ultrasonic sensor and controls the motors to move accordingly, avoiding obstacles.
- In Manual Mode, the Arduino directly controls motor movement based on the direction buttons pressed in the app.
- When the Pump and Drying System interface is used, the Arduino activates the connected pump to spray the disinfectant solution and the stepper motor to operate the mechanical drying system. Both components are controlled through the L293D driver shield.
- For the UV Control screen, the application currently displays a “Under Development” message, as this module has not been implemented in the physical circuit due to lack of components.

This structure creates a closed-loop system that links user input to real-time hardware responses. The system is designed to be expandable for future features, such as feedback from sensors or confirmation messages from the hardware to the app.

III.3. Experimental Setup

This section presents the experimental setup prepared to test and validate the proposed disinfection and obstacle-avoiding robot. The setup includes the hardware components used, the testing environment, and the adopted protocol for running and evaluating the experiments.

III.3.1. Hardware Components

The main components used in the system are listed below:

- Arduino Uno: Used as the main controller to manage motor control, ultrasonic readings, and general logic.
- ESP8266 NodeMCU: Handles Wi-Fi communication between the robot and the mobile application for remote control.
- HC-SR04 Ultrasonic Sensor: Mounted on a servo motor and used for obstacle detection in front of the robot.
- Servo Motor: Rotates the ultrasonic sensor to scan the environment in multiple directions.
- 4 × DC Motors: Provide movement for the robot's four wheels.
- L293D Motor Driver Module: Used to drive the DC motors in both directions with proper current.
- Power Supply: Lithium-ion batteries pack was used to power the motors and the Arduino.
- UV LED (for simulation): Used in simulation to represent the disinfection process triggered by PIR sensor detection.
- PIR Motion Sensor: Used in the simulation to detect human presence and disable UV LEDs accordingly.

III.3.2. Testing Environment

The robot was tested in an indoor room with flat tile flooring and moderate ambient light. The room included simulated obstacles such as boxes and furniture to replicate a realistic navigation environment. The dimensions of the testing area were approximately 3m × 2.5m.

All tests were performed under controlled conditions to reduce variability, and care was taken to avoid external Wi-Fi interference during remote control testing via ESP8266.

III.3.3. Test Protocol and Methodology

Each functionality of the robot was tested separately before proceeding to full system integration:

- Motor and direction control was tested through manual commands via serial communication and later via the mobile application.
- Obstacle detection was evaluated by placing various objects at different distances and angles from the robot.
- Servo motor sweep was used to scan the surroundings by rotating the ultrasonic sensor from left to right.
- PIR sensor logic was tested in simulation mode, using Proteus, where the UV LED would activate only in the absence of motion.

Each test was repeated multiple times (minimum of 3 iterations per scenario) to ensure consistency. All behaviors were recorded and compared to expected results to assess the system's reliability and response time.

III.4. **Testing of Individual Components**

III.4.1. Accuracy of the Ultrasonic Sensor

Objective

The main objective of this test is to evaluate the precision and accuracy of the ultrasonic sensor (HC-SR04) by comparing its measured distances to actual, known distances.

Experimental Setup

The sensor was mounted on a fixed stand and directed perpendicularly toward a flat surface. Known distances ranging from 10 cm to 100 cm were marked and used as reference points.

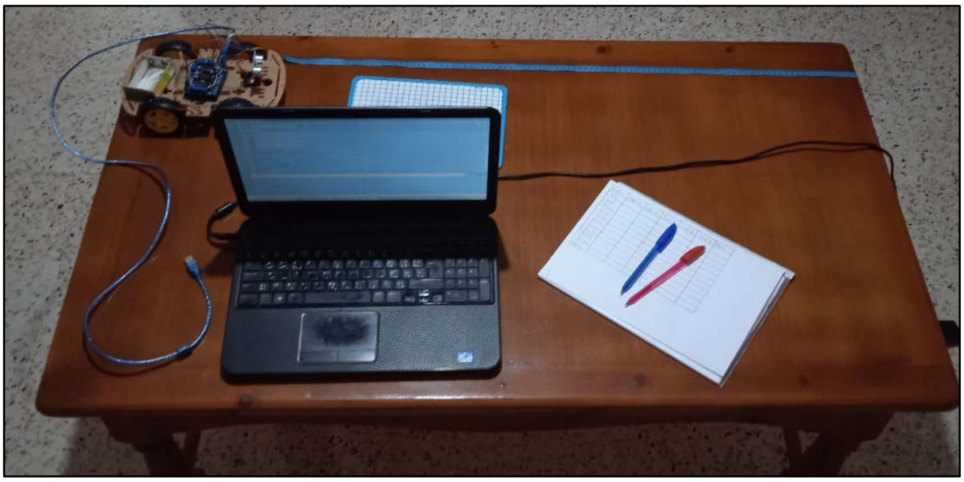


Figure III.12 The test place of the precision and accuracy of the ultrasonic sensor (HC-SR04)

Methodology

For each distance, the sensor was triggered multiple times (5 readings per distance), and the average measured value was recorded. The actual distance was then compared to the measured value to calculate the error.

Tools and Materials

- Ultrasonic sensor HC-SR04
- Arduino Uno
- Measuring tape
- Serial monitor (for data logging)
- MATLAB plotting software for graphs

Results: Measured vs Actual Distance for Ultrasonic Sensor

The table below presents a comparison between actual and the measured distances using the ultrasonic sensor. To quantify the sensor's accuracy, two types of error were calculated:

- **Absolute Error (in cm):**

$$Absolute\ Error = |D_{actual} - D_{measured}| \qquad \text{(III.2)}$$

- **Relative Error (percentage):**

$$Relative\ Error = \left|\frac{D_{actual} - D_{measured}}{D_{measured}}\right| \times 100 \qquad \text{(III.3)}$$

These formulas were used to compute the values shown in the following table:

Table III.2 Table of Results of Measured Distance Absolute Error and Relative Error

Actual Distance (cm)	**Measured Distance** (cm)	**Error** (cm)	**Error** (%)
5	4.4	0.6	12
10	9.8	0.2	2
20	19.8	0.2	1
30	29.2	0.8	2.66
40	38.6	1.4	3.5
50	48.4	1.6	3.2
60	57.6	2.4	4
70	68	2	2.85
80	77.4	2.6	3.25
90	81.6	8.4	9.33
100	82	18	18

1. Measured Distance vs Actual Distance

Figure III.12 illustrates the relationship between the actual distances and those measured by the ultrasonic sensor. Ideally, if the sensor were perfectly accurate, all data points would lie on the line y = x. Any deviation from this line represents a measurement error.

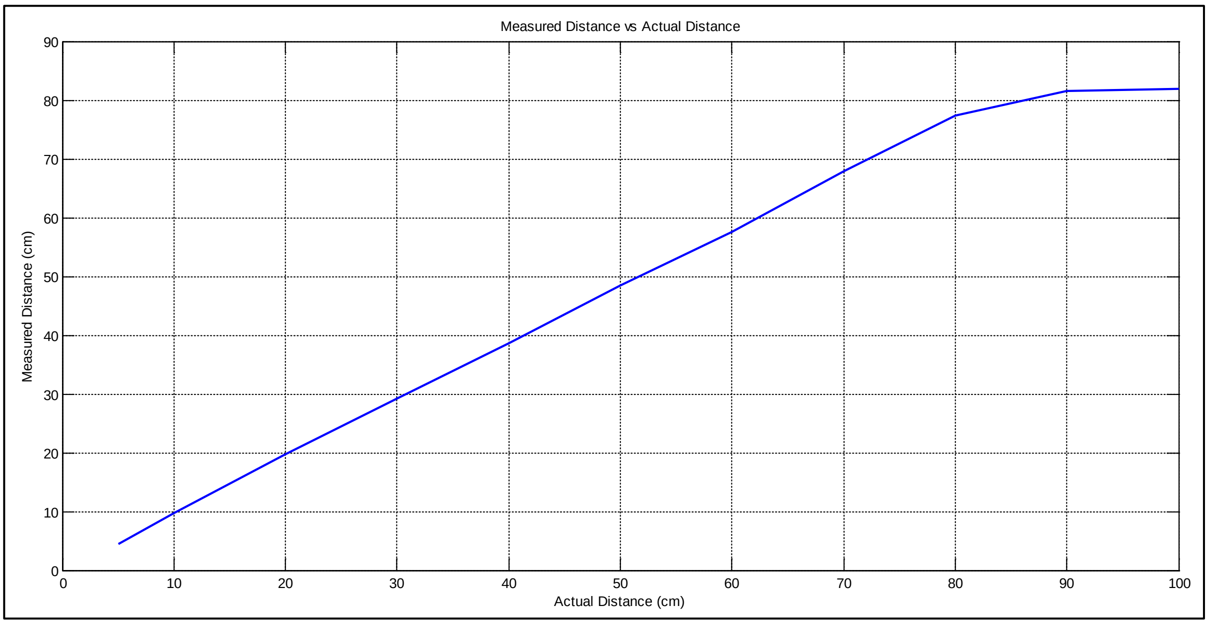


Figure III.13 Graph of measured distance versus actual distance using MATLAB

Observation:

The curve follows the ideal line closely up to around 80 cm. However, beyond this range, particularly at 90 cm and 100 cm, the sensor significantly underestimates the distance, with errors reaching up to 18 cm at 100 cm. This suggests that the sensor's accuracy degrades at longer distances.

2. Relative and Absolute Error vs Actual Distance

Figure III.13 illustrates how both the absolute error (in cm) and the relative error (in %) vary with increasing actual distance. The absolute error provides a direct measure of the deviation between the sensor's readings and the true values, while the relative error assesses the proportional accuracy across different distances. Together, these metrics offer a comprehensive evaluation of the sensor’s performance over its operating range.

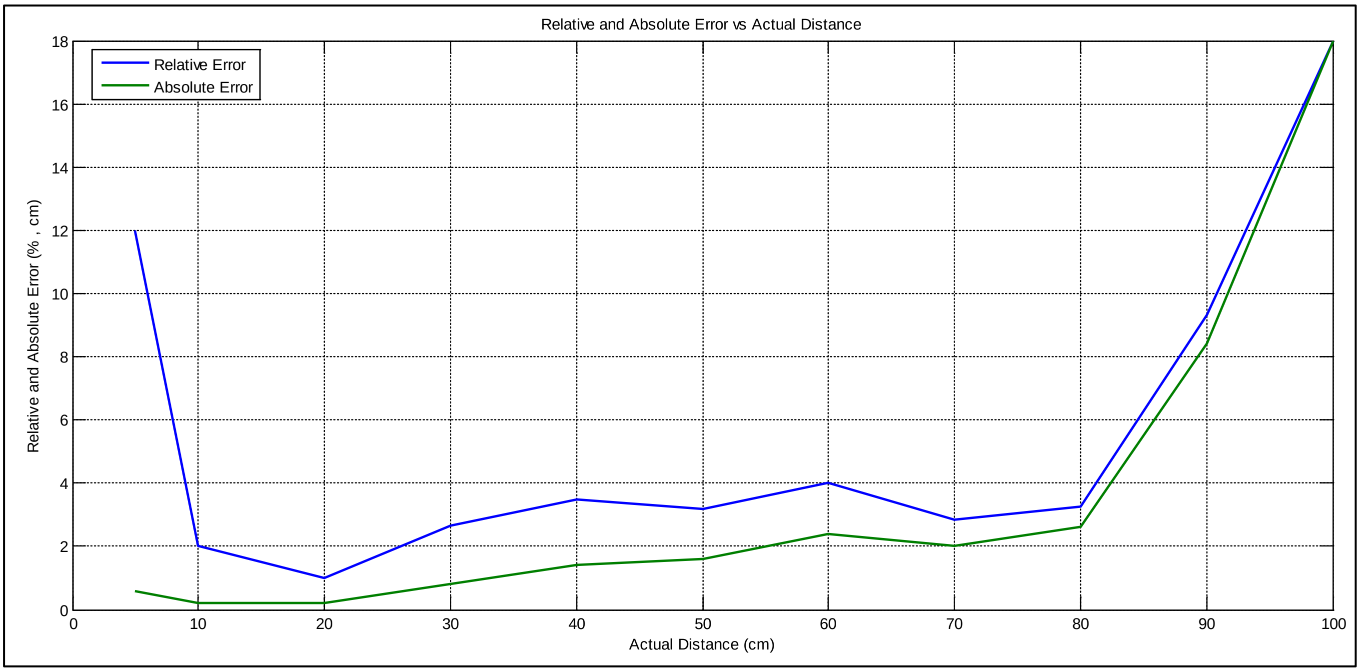


Figure III.14 Graph of relative and absolute error versus actual distance using MATLAB

Observation & Interpretation:

The graph presents both absolute error (in cm) and relative error (in %) as a function of actual measured distance. For distances up to 80 cm, the absolute error remains low and stable (≤ 2.6 cm), and the relative error stays below 5%, reflecting good sensor accuracy in this range. However, beyond 80 cm, both error metrics increase sharply: the absolute error jumps to 8.4 cm at 90 cm and 18 cm at 100 cm, while the relative error climbs to 9.33% and 18%, respectively. These values highlight the performance degradation of the ultrasonic sensor at longer distances, suggesting a practical operating range limited to 80 cm for reliable measurements.

Analysis

The experimental results reveal that the ultrasonic sensor performs with acceptable precision across short to medium distances. From 10 cm to 80 cm, both absolute and relative errors remain relatively low typically below 2.6 cm and 5%, respectively. This indicates stable and reliable sensor behavior within this range. However, a significant deviation is observed at longer distances, particularly at 90 cm and 100 cm, where the absolute error sharply increases to 8.4 cm and 18 cm, respectively. Consequently, the relative error also spikes to 9.33% and 18%.

This sudden degradation in accuracy suggests that the sensor's effective measurement range is limited to approximately 80 cm. Beyond this threshold, the sensor tends to underestimate the actual distance, which may lead to critical errors in robotic applications, such as obstacle avoidance or distance-based decision making.

The results also show slightly higher relative errors at very short distances (e.g., 12% at 5 cm), which is expected due to the sensitivity of percentage error at small denominators. Therefore, the sensor is best used in the 10–80 cm range for more reliable and consistent measurements.

III.4.2. Servo Motor Angle Accuracy

Objective

To assess how accurately the servo reaches the commanded angles.

Experimental Setup

An Arduino Uno controls the servo to rotate to set angles. A protractor is positioned behind the servo arm to measure the actual angle reached after movement.

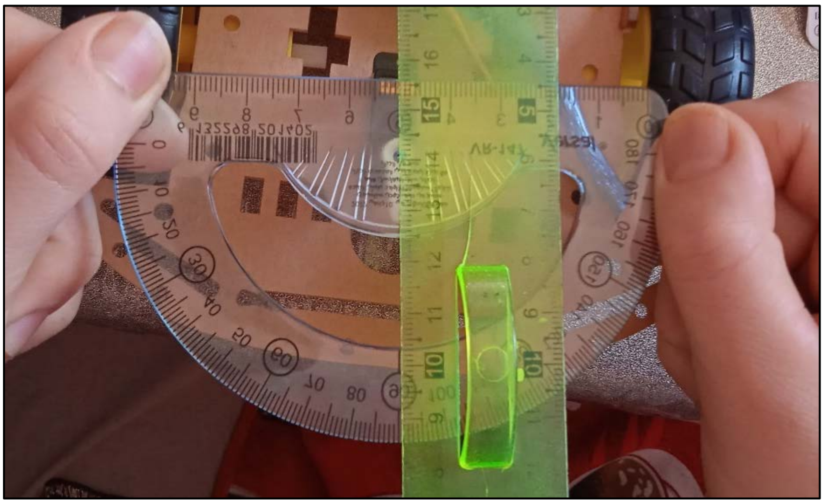


Figure III.15 Test of servo motor angle accuracy

Methodology

The servo was programmed to move to predefined angles. For each angle, the final position was observed using a protractor after the servo settled. Three readings were taken per angle, and the average was recorded. The error was calculated as the difference between the commanded and measured angles

Tools and Materials

- Arduino Uno
- Servo motor
- Protractor
- Pointer (attached to servo arm)

Results

The measured angles for each commanded position were recorded and averaged to evaluate the servo's static accuracy. The table below summarizes the commanded angles, the average measured angle, and the resulting absolute error:

Table III.3 Commanded vs Measured Angles

Commanded Angle (°)	**Average Measured Angle** (°)	**Error** (°)
0°	0°	0°
30°	30°	0°
45°	45°	0°
60°	60°	0°
90°	90°	0°
120°	115°	5°
135°	126°	10°
150°	147.33°	2.67°
170°	161.33°	8.67°
180°	170.33°	9.67°

Graph 1: Commanded Angle vs Measured Angle

The graph below shows the relationship between the commanded angle and the measured angle. The ideal line (y = x) represents perfect accuracy. The measured data line shows how closely the servo follows the intended positions.

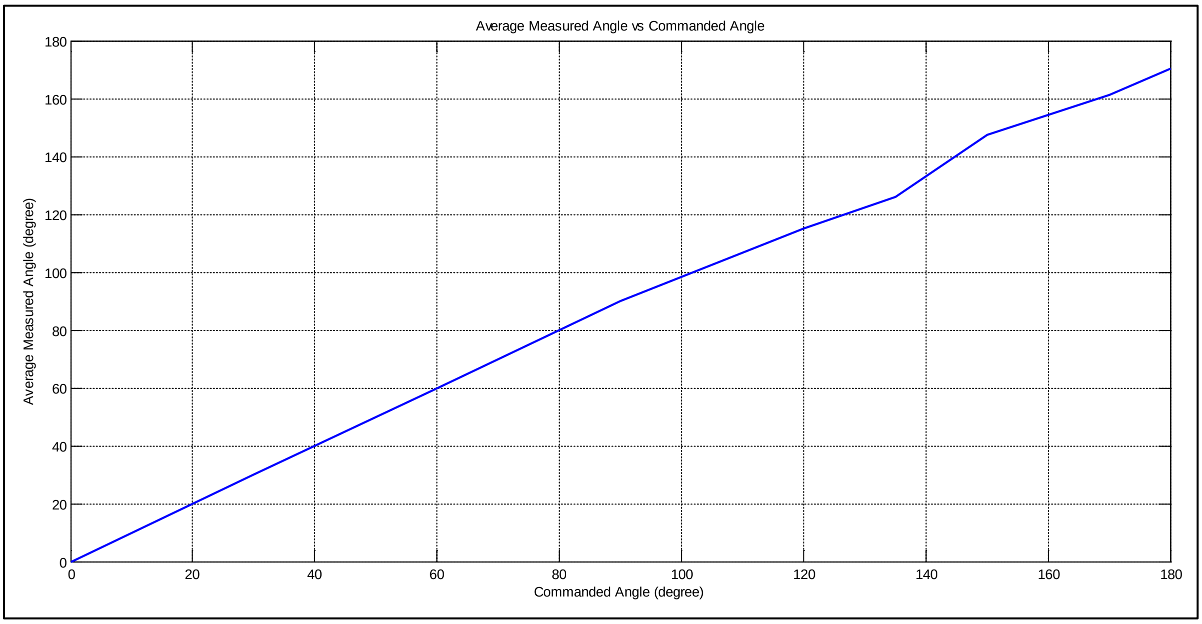


Figure III.16 Graph of average measured angle versus commanded angle

Graph 2: Error vs Commanded Angle

This graph displays the error magnitude at each commanded angle. It highlights the trend of increasing error at higher angles, indicating performance limitations in the servo's accuracy range.

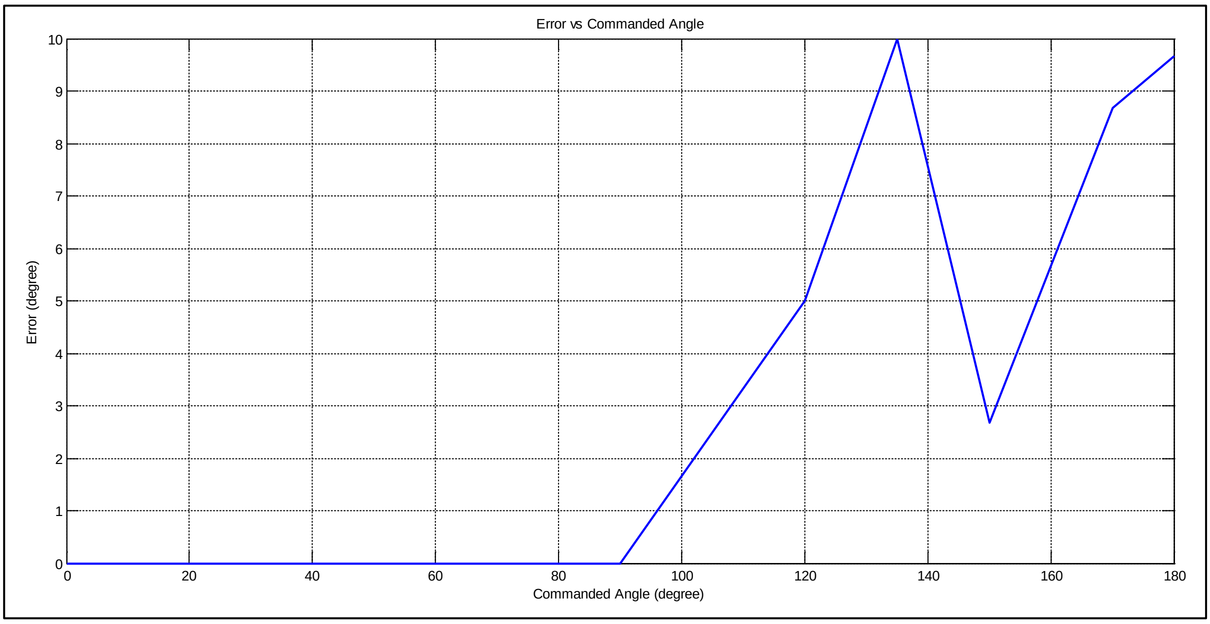


Figure III.17 Graph of error versus commanded angle

Analysis

The servo motor demonstrated high accuracy for lower and mid-range angles (0° to 90°), where the measured angles matched the commanded values with 0° error. However, as the commanded angle increased beyond 90°, the error began to appear and gradually increased, reaching a maximum of ~10° at 180°.

This suggests that the servo performs well at small to moderate angles but tends to underreach at higher angles, possibly due to mechanical limits, power supply constraints, or internal calibration offsets.

III.5. **Movement System Evaluation**

This section includes two mobility tests. The first evaluates the robot's ability to detect and avoid obstacles, which is essential for safe navigation. Once confirmed, the second test analyzes the smoothness of movement at different speeds to optimize performance. This order ensures the robot's basic functionality is validated before refining its motion behavior.

III.5.1. Smoothness of Movement and Rotation Speed

This experiment aimed to evaluate the robot's responsiveness and rotation smoothness during 90° turns at different motor speed settings, using a four-wheel DC motor setup controlled via the $AFMotor$ library and an Arduino Uno. Motor speeds were varied using the $motor.setSpeed(x)$ function, with values of 50, 100, 150, 200, and 255. For each speed, the robot was instructed to rotate 90° to both the right and left, and the time taken was measured using the $delay()$ function. Observations were made on whether the robot successfully completed the turn and how smoothly it moved, noting any failures or hesitations. The setup included an L293D motor driver, flat testing surface, and delay-based timing to ensure consistency.

The results showed the impact of speed on rotational performance, helping to identify the minimum effective motor speed for reliable and precise movement.

Table III.4 Robot Rotation Behavior at Various Motor Speeds for 90° Turn

Trial. No	**Speed**	**Rotation Direction**	**Time (ms)**	**Observation**
1	50	$Right$	$-$	$Don't\ move$
2	50	$Left$	$-$	$Don't\ move$
3	100	$Right$	$-$	$Slow\ response\ from\ M3; M4$
4	100	$Left$	$-$	$M3; M4\ do\ not\ rotate\ backward$
5	150	$Right$	770	$Acceptable$
6	150	$Left$	900	$Acceptable$
7	200	$Right$	500	$Smooth$
8	200	$Left$	600	$Smooth$
9	255	$Right$	550	$Smooth$
10	255	$Left$	550	$Smooth$

This table presents the results of 10 trials where the robot was commanded to perform a 90-degree rotation at different speed settings. Observations include whether the robot responded correctly, the time taken for rotation, and any anomalies during execution.

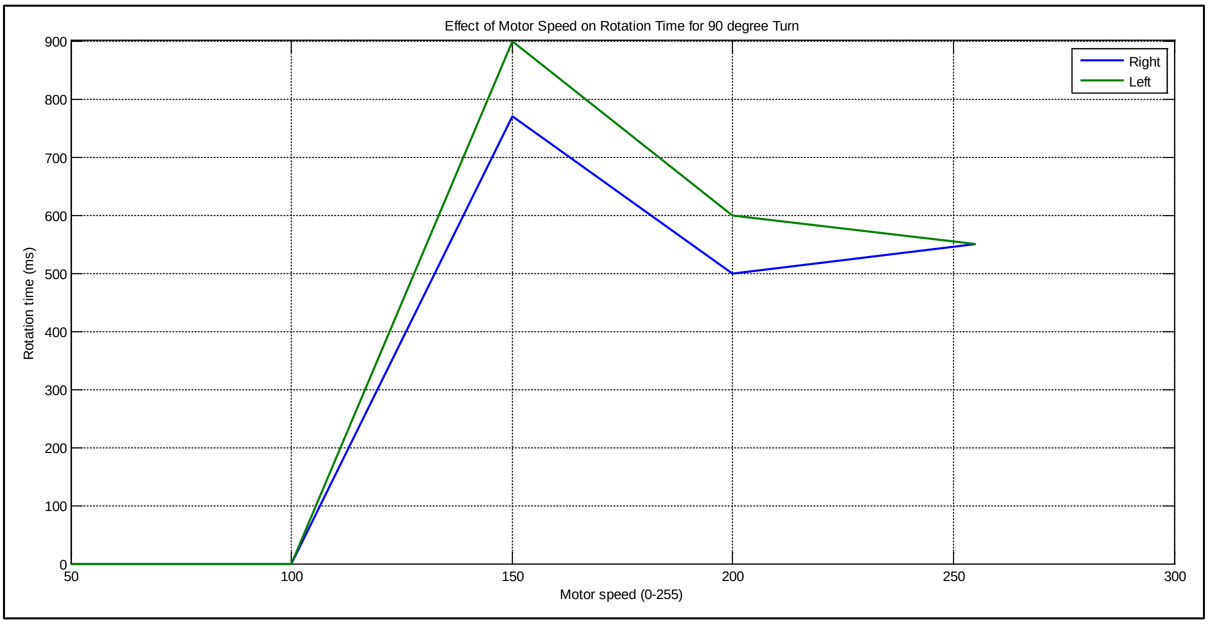


Figure III.18 Effect of motor speed on rotation time for 90° turn

This graph shows how the robot's rotation time decreases as motor speed increases. It highlights those speeds below 150 fail to trigger movement, while speeds between 200 and 255 achieve optimal response and smooth rotation.

Analysis

From the collected data and plotted graph, several insights can be drawn:

Minimum effective speed: The robot was unable to rotate at speeds below 150. This suggests that the motor torque at low PWM values is insufficient to overcome static friction and load.

Improved performance with increased speed: As motor speed increases from 150 to 200, rotation time decreases significantly, indicating a more responsive and powerful movement.

Optimal smoothness and balance: At speeds 200–255, both right and left turns are completed in approximately the same amount of time, showing good mechanical symmetry and consistent motor behavior.

Motor behavior: Observations such as "M3/M4 do not rotate" suggest possible issues in wiring, load imbalance, or the need for higher base PWM to initiate reverse motion.

III.6. Disinfection System Evaluation

III.6.1. UV-C LED Disinfection System

III.6.1.1. Limitations of Implementation and Simulation-Based Validation

During the practical implementation phase, we encountered a major challenge in sourcing the UV-C disinfection system components, particularly UV LEDs, due to their unavailability in the Algerian market. Given the limited time and work pressure ordering them from abroad was not feasible.

Consequently, no real-life testing was performed for this system. However, a simplified simulation was conducted using Proteus, integrating a PIR motion sensor and a UV LED. The simulation confirmed the logical behavior of the proposed disinfection system, thus supporting its conceptual validity.

Simulation Setup and Components

To validate the system conceptually, a Proteus simulation was created using the following components:

- Arduino Uno Board
- PIR Motion Sensor
- UV-C LED (simulated)
- White LED (for visual representation)
- JBT Transistor ($2N2222$)
- Two resistors: $1\ k\Omega$ and $220\ \Omega$

A wiring diagram of the simulated system is presented in Figure **III.18**, showing the configuration in the inactive state (no motion detected, LED off).

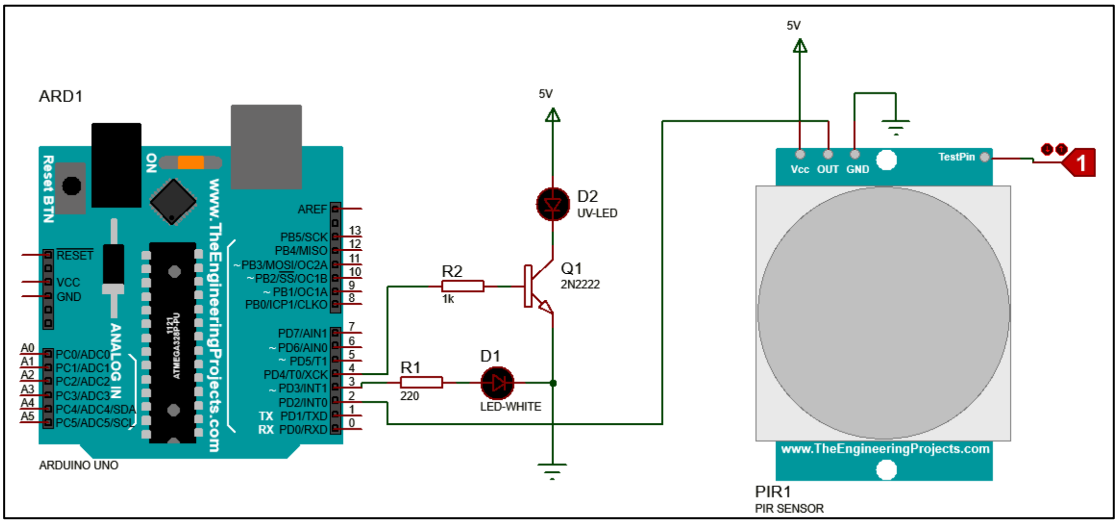


Figure III.19 Diagram of the simulated system in the inactive state

System Logic and Operation

The logic implemented in the simulation is based on a basic safety principle:

No human presence detected → the UV-C LED turns ON to disinfect the area.

Human motion detected → the LED turns OFF to avoid UV-C exposure.

This behavior was verified in the simulation as illustrated in the following figures:

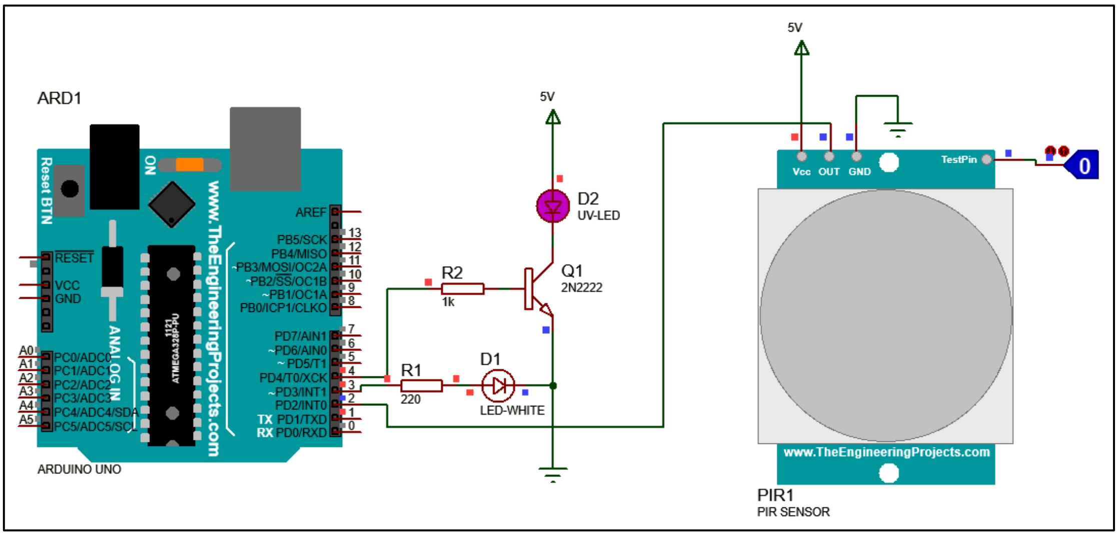


Figure III.20 System in the active disinfection state (no motion detected).

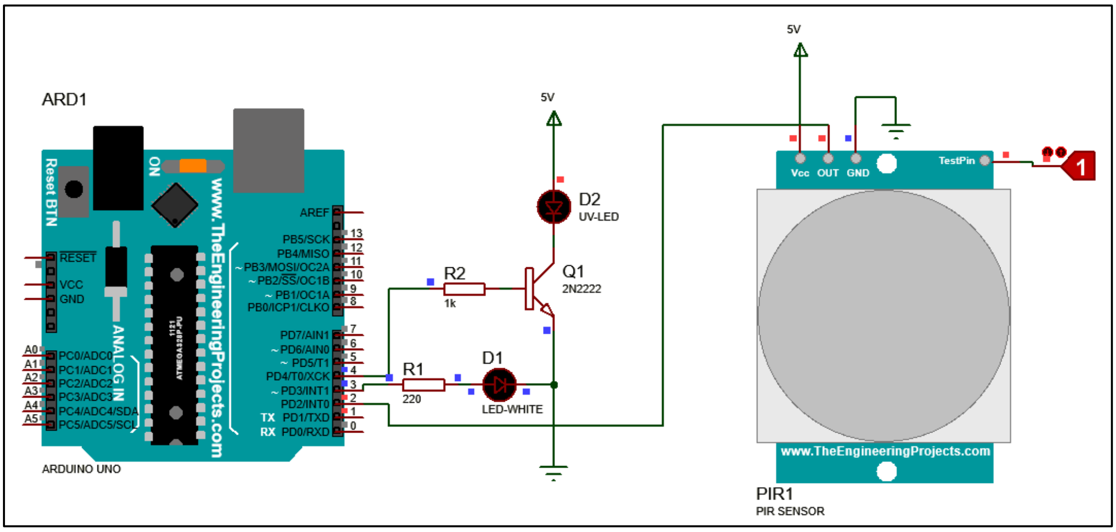


Figure III.21 System in the standby state (motion detected, LED off).

The simulation results validated the proposed logic and behavior of the disinfection system, confirming its conceptual soundness. Once the necessary components become available, the system can be physically implemented based on this design.

III.7. Full System Integration Test

The purpose of the full system integration test is to evaluate the performance of the robot when all subsystems (movement, disinfection, and communication) are combined and operated simultaneously. This test aims to simulate real-world operating conditions and highlight potential conflicts, inefficiencies, or system failures during integration.

III.7.1. Test Procedure

The robot was tested in an indoor environment, on a flat surface. Each subsystem had previously been tested independently. In this phase, the full system was powered on, and an attempt was made to run the robot through different operational modes, including:

- Autonomous obstacle avoidance.
- Manual control (conceptually).
- Switching between spraying and drying modes.

The mobile application was not tested in real-time but had been developed to allow switching between control and disinfection modes.

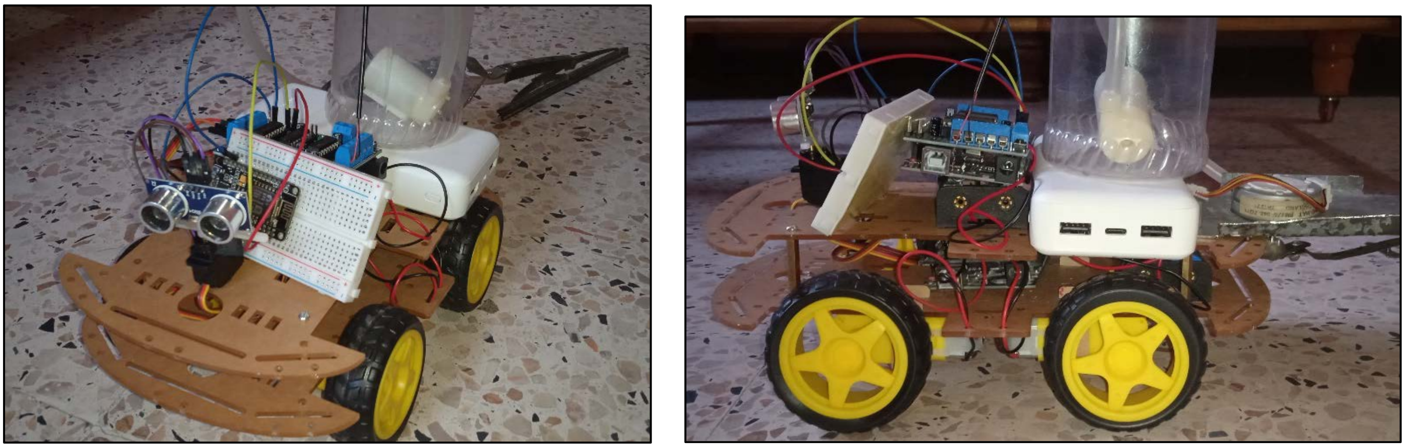


Figure III.22 Prototype of the disinfection robot during integration test

Figure III.23 Overhead view for prototype of the disinfection robot during integration test

III.7.2.Results

Movement System

The obstacle avoidance feature failed during testing. The robot could not detect or bypass obstacles on its own. The movement was erratic, and manual intervention was needed. The ultrasonic sensor showed poor accuracy, likely due to its limited range or incorrect angle of detection.

Disinfection System (Spray and Dry)

The spraying system worked, but it could not run in parallel with the drying system. The drying phase only stared after the spray had stopped. Moreover, the stepper motor intended to rotate the drying module did not function at all when the robot was placed on the ground. This is likely due to insufficient torque and the mechanical load not being properly supported.

Communication System (Mobile App)

Although not tested live, the app’s design conceptually supports manual navigation and switching to disinfection functions. Since these features are fully independent in the code, it is theoretically possible to move the robot manually, activate spraying, and then return to manual control. However, the expected performance would likely remain poor without real-time validation.

III.7.3.Analysis

The integration test revealed several limitations:

- Sensor limitations significantly affected autonomous behavior.
- Inadequate mechanical design, especially in relation to the stepper motor, reduced the effectiveness of the drying system.
- Lack of parallel execution between spraying and drying exposed weaknesses in the system’s software architecture.
- Communication features remain unvalidated due to time or hardware constraints.

These results underscore the importance of robust subsystem testing, careful mechanical design, and real-world validation of software features.

Although the full system did not perform as expected, the integration test was a valuable step in identifying test was a valuable step in identifying key flaws and limitations. The insights gained will help guide future improvements in design, control logic, and mechanical optimization. This phase if testing emphasizes that successful integration requires both accurate hardware implementation and efficient software coordination.

III.8. Discussion and Analysis

This section aims to analyze the experimental results obtained from testing the robot's subsystems, including the motion system, disinfection modules, and communication interface. It also compares the robot's performance in simulation versus real-world implementation, evaluates the achievement of project objectives, highlights strengths and limitations, and suggests areas for future improvement.

Motion System Analysis

Rotation tests revealed that the robot requires a minimum PWM of 150 to initiate movement due to insufficient torque at low values. The best performance was observed at speeds between 200 and 255, where turns were smooth and symmetrical, indicating stable mechanical balance.

Sensor Accuracy

The HC-SR04 ultrasonic sensor provided accurate readings up to $80\ cm$. Beyond this, error increased significantly, reaching $18\ cm$ at $100\ cm$. This limits its effectiveness for long-range detection. The servo motor demonstrated high accuracy up to $90°$, with minor deviations at higher angles.

Disinfection System Evaluation

The UV-C system could not be physically tested due to hardware unavailability. However, simulation confirmed its logical correctness. The spray and dry system faced two main issues: the stepper motor failed to operate under real mechanical load, and parallel execution of spraying and drying was not achieved, exposing a limitation in the software structure.

Full system integration

Full system integration revealed several issues, particularly the failure of autonomous navigation, which led to erratic movement requiring manual intervention. The spray and dry processes could not run simultaneously. Although the mobile app was fully designed, it was not tested in real conditions due to time constraints.

Simulation vs. Real Implementation

While simulations showed ideal performance across all systems, real-world testing exposed significant simulated conditions but showed variability in actual environments due to lighting and surface factors. Motor strength in simulation did not account for surface resistance or real torque requirements.

Alignment with Project Objectives

Despite the challenges, the project partially fulfilled its objectives. A robot capable of autonomous movement and disinfection was developed, and communication through a mobile app was established. However, full system integration and real-time testing were not completely achieved, leaving room for future improvements.

Recommendations and improvements

- Improve motor balance and consider a higher-torque stepper motor for drying.
- Implement multi-threaded programming to enable simultaneous actions.
- Use longer-range and more accurate sensors.
- Enhance the mobile app to include real-time hardware feedback.
- Conduct extensive field testing to validate stability and performance.

III.9. **Challenges and Limitations**

Technical Challenges

The project faced several technical difficulties, notably the inability of some components to perform as expected in real-world conditions. For example, the stepper motor responsible for drying failed to operate on the ground due to insufficient torque. Additionally, the system could not run the spray and dry functions in parallel, revealing structural limitations in the software.

Hardware Availability

A major limitation was the unavailability of critical components, such as UV-C LEDs, in the local market. This prevented complete real-world testing of the UV disinfection system and led to reliance on simulation to validate the system’s logic and functionality.

Software and System Architecture Constraints

The software structure did not allow parallel execution of spraying and drying tasks. Furthermore, all subsystems were not integrated within a synchronized, unified platform, which impacted the effectiveness of system coordination.

Mechanical Constraints

Testing revealed that certain components, like the stepper motor, are highly sensitive to weight and surface friction, indicating a need for redesign or use of more robust mechanical components in future iterations.

III.10. **Conclusion**

This chapter presented the practical implementation and testing of the disinfection robot based on the previously defined theoretical design. The work began with the simulation of the robot's core systems—movement, disinfection, and communication—through detailed circuit design, algorithmic flow, and functional descriptions.

Following this, the experimental setup was constructed, and real hardware configured. Several individual tests were carried out, such as evaluating the ultrasonic sensor’s accuracy, servo motor’s angular precision, and DC motors’ rotation smoothness. The results were collected, analyzed, and represented graphically to assess performance.

Despite limitations like insufficient torque and power constraints that prevented full robot mobility and mobile app testing, the project successfully validated key components in real conditions. The findings confirm the feasibility of the proposed system and highlight areas requiring improvement for a complete functional deployment in real-world settings.

BUSINESS MODEL CANVA (BMC)

1) Value proposition: القيمة المقترحة

a) What problems do we solve for our customers?

ما هي المشاكل التي نحلها لعملائنا؟

تعاني العديد من المؤسسات الصحية والمختبرات والأماكن المغلقة من تحديات كبيرة في ضمان تعقيم الهواء بشكل فعال ومستمر. ومن أبرز هذه المشاكل:

- ارتفاع معدلات العدوى داخل المستشفيات (Infections)، والتي تعد من الأسباب الرئيسية لزيادة مدة إقامة المرضى وتكاليف العلاج.
- الاعتماد الكبير على طرق التعقيم اليدوية، والتي تفتقر غالبًا إلى الدقة والاستمرارية، وتعتمد على العنصر البشري الذي قد يتعرض للإجهاد أو الخطأ.
- الاستخدام المفرط والمستمر للمواد الكيميائية، مما يؤدي إلى أضرار بيئية وصحية على المدى الطويل.
- عدم توفر وسائل ذكية وآلية يمكنها مراقبة جودة الهواء وإجراء التعقيم بشكل تلقائي ومستقل.

من خلال EcoSan-Bot، نقدم حلاً فعالاً ومتكاملاً لهذه المشكلات من خلال روبوت ذكي قادر على تحسين جودة الهواء والتقليل من خطر العدوى بشكل تلقائي ومستدام، مما يعزز سلامة المرضى والطواقم الطبية في نفس الوقت.

b) What customer needs do our products or services satisfy?

ما هي الاحتياجات التي تلبيها منتجاتنا أو خدماتنا لعملائنا؟

لا يقدم روبوت التعقيم EcoSan-Bot فقط أداة تكنولوجية، بل يلبي مجموعة من الاحتياجات الجوهرية والعاجلة لدى فئات متعددة من المستخدمين، أبرزها:

- الاحتياج إلى أمان صحي أعلى داخل المستشفيات وغرف العمليات والعزل.
- التحكم في جودة الهواء باستمرار.
- تسريع عمليات تجهيز الغرف بين كل مريض وآخر، مما يرفع كفاءة العمل ويقلل أوقات الانتظار.
- تقليل تكاليف التشغيل على المدى الطويل، من خلال تقليل الاعتماد على مواد التعقيم الكيميائية وتقليل العدوى.
- إدارة ذكية ومتصلة عبر تطبيق جوال يمكن الفرق الطبية من تتبع أداء الروبوت وضبط مهامه.
- الحفاظ على البيئة من خلال اعتماد تقنيات غير مضرة لجسم الانسان (UV).

c) How is our offer different from that of our competitors?

في ماذا تختلف عروضنا عن تلك التي يقدمها منافسونا؟

ما يميز EcoSan-Bot هو الجمع بين التعقيم الذكي، الحركة المستقلة، والاتصال الرقمي في منصة واحدة. فيما يلي بعض أوجه التميز عن الحلول الأخرى:

- تصميم قابل للتطوير والاستخدام في عدة بيئات (مستشفيات، مختبرات، منازل ذكية)، مما يزيد من مرونته التسويقية.
- إمكانية تخصيص الوظائف حسب احتياجات المؤسسة (إضافة مستشعرات، تعديل بروتوكولات التعقيم، التحكم عبر الهاتف).
- عرض خدمات ما بعد البيع يشمل الصيانة، إعادة المعايرة، وتحديثات برمجية دورية لضمان الاستدامة التقنية.
- كفاءة في استهلاك الطاقة واستخدام مواد صديقة للبيئة تقلل الانبعاثات وتُراعي شروط السلامة البيئية.

d) What is our unique value proposition?

ما الذي يميز عرضنا عن غيره ويجعله ذا قيمة فريدة؟

الذي يجعل عرضنا فريدًا هو أننا لا نقدم مجرد "جهاز تعقيم"، بل نقترح نظامًا ذكيًا متكاملاً قادرًا على إحداث تحول فعلي في طريقة التعامل مع تعقيم الهواء داخل الأماكن الحساسة. القيمة الفريدة تتمثل في:

- التحول من العمليات اليدوية إلى الأتمتة الذكية في مجال الصحة العامة، ما يضمن دقة وأداء أعلى دون تدخل بشري مستمر.
- واجهة استخدام ذكية وسهلة عبر الهاتف، تتيح للمستخدمين من غير المختصين تشغيل الروبوت بكفاءة.
- دعم طويل الأمد للمنتج عبر عقود صيانة وخدمة عملاء مخصصة.
- التوافق مع توجهات العصر في الصحة الرقمية، المدن الذكية، والمباني المستدامة.

2) Customer segment: **أنواع العملاء**

a) Who are our main customers?

من هم العملاء أو الزبائن الرئيسيون؟

العملاء الرئيسيون الذين يستفيدون بشكل مباشر من روبوت التعقيم EcoSan-Bot هم:

- المستشفيات والمراكز الصحية (العمومية والخاصة)، بما في ذلك غرف العمليات، غرف المرضى، وقاعات الانتظار.
- العيادات الطبية المتخصصة (مثل عيادات طب الأسنان، الجلدية، الأطفال...).

- المختبرات العلمية والبحثية، خصوصًا تلك التي تتعامل مع مواد بيولوجية أو كيميائية حساسة.
- مراكز العزل الصحي والمناطق الوبائية.
- مراكز التجميل والعيادات شبه الطبية.
- الأسر الذكية والمستخدمون المهتمون بجودة الهواء في المنازل، خاصة في المدن الكبرى.
- المدارس، الجامعات، ودور الرعاية.

يمثل هؤلاء شرائح عملاء حيوية تسعى إلى تعزيز النظافة الهوائية والوقاية الصحية باستخدام حلول تقنية مبتكرة.

b) What are the different customer segments we are targeting?

ما هي الفئات المختلفة من العملاء التي نستهدفها؟

يمكن تقسيم الشرائح المستهدفة إلى أربع فئات رئيسية:

- **القطاع الصحي المؤسسي**
  - مثل المستشفيات، العيادات، مراكز الاستشفاء والعزل الطبي.
- **القطاع العلمي والبحثي**
  - مثل مختبرات الجامعات، مراكز البحث، غرف التحاليل، ومرافق التصنيع الدقيق.
- **القطاع السكني الذكي**
  - ويشمل المستخدمين الفرديين في المنازل الذكية، المهتمين بجودة الهواء وسلامة أفراد العائلة (أطفال، مرضى ربو...).
- **القطاع التجاري والخدماتي**
  - مثل مراكز التجميل، صالات الرياضة، المدارس الخاصة، والمكاتب المغلقة التي تهتم براحة موظفيها.

c) What are the specific needs of each customer segment?

ما هي الاحتياجات الخاصة بكل فئة من العملاء؟

لكل فئة من العملاء احتياجات محددة تختلف حسب بيئة الاستخدام:

الفئة	الاحتياجات الخاصة
المستشفيات	تقليل العدوى الداخلية، تسريع تعقيم الغرف، ضمان الامتثال للمعايير الصحية، توفير الوقت والموارد البشرية.
المختبرات	الحفاظ على بيئة خالية من التلوث، تقليل التداخلات التجريبية، تأمين شروط جودة دقيقة.
الأسر الذكية	تحسين جودة الهواء الداخلي، الحماية من الفيروسات والغبار، توفير حل ذكي وسهل الاستخدام.
القطاع الخدماتي	تحسين صورة المؤسسة، ضمان بيئة نظيفة وآمنة للزبائن، احترام البروتوكولات الصحية.

d) How can we categorize customers into distinct groups?

كيف يمكننا تصنيف العملاء إلى مجموعات متميزة؟

يمكن تصنيف العملاء إلى مجموعات متميزة حسب سلوك الاستخدام والاحتياج الأساسي كالتالي:

- **عملاء يبحثون عن الحماية والوقاية الصحية**
  - مثل المستشفيات والمنازل الذكية (التركيز على مكافحة العدوى).
- **عملاء يبحثون عن الدقة والنقاء البيئي**
  - مثل المختبرات ومراكز البحث (التركيز على جودة الهواء).
- **عملاء يهتمون بالراحة والرفاهية**
  - مثل صالونات التجميل، المدارس، المكاتب المغلقة (التركيز على تجربة المستخدم).
- **عملاء حكوميون أو مؤسساتيون**
  - يشترون بكميات كبيرة وفق صفقات أو مناقصات، يهتمون بالكفاءة والتكلفة.

هذا التصنيف يساعد على تخصيص العروض التسويقية والخدمات لكل فئة بشكل أدق ويُسهّل تطوير استراتيجيات تسويق فعالة ومبنية على احتياجات واقعية.

3) Customer relationship: العلاقة مع العملاء

a) What type of relationship does each customer segment expect from us?

ما نوع العلاقة التي يتوقعها كل شريحة من العملاء منا؟

كل شريحة من العملاء لديها توقعات مختلفة حول نوع العلاقة التي ترغب في إقامتها معنا، والتي تتناسب مع طبيعة احتياجاتها وظروف استخدامها للروبوت:

- **المستشفيات والمؤسسات الصحية**
  - تتوقع علاقة مهنية قائمة على الدعم الفني المستمر، الجاهزية عند الأعطال، وتحديثات دورية للنظام، بالإضافة إلى عقود صيانة واضحة ومضمونة.
- **المختبرات ومراكز البحث**
  - تتطلب علاقة مبنية على الاعتمادية والدقة، مع توفير توثيق تقني، دعم لمعايرة المستشعرات، وتفاعل مباشر مع فرق التطوير لتحسين الأداء حسب بيئتهم البحثية.
- **المستخدمون المنزليون**
  - يتوقعون علاقة مبسطة، تتميز بـ سهولة الاستخدام، دعم عبر تطبيق جوّال، وإرشادات واضحة باللغة المحلية، بالإضافة إلى خدمة ما بعد البيع تراعي خصوصيتهم واحتياجاتهم اليومية.
- **القطاع التجاري (مثل صالونات التجميل والمدارس)**
  - يرغب في علاقة تعتمد على الاستجابة السريعة والمهنية، حلول مرنة حسب عدد المستخدمين، وتفاعل سهل عبر الإنترنت.

b) How do we currently maintain our relationships with our customers?

كيف نحافظ حاليًا على علاقاتنا مع عملائنا؟

رغم كون المشروع في مراحله الأولية، إلا أن نموذج الحفاظ على العلاقة مع العملاء تم تصميمه على أسس متينة تشمل:

- خدمة ما بعد البيع تشمل إصلاح الأعطال، تقديم قطع الغيار، وبرمجيات الصيانة الدورية.
- تواصل مباشر مع العملاء من خلال البريد الإلكتروني أو الهاتف، خصوصًا للعملاء المؤسسيين.
- توفير تحديثات برمجية دورية عبر الإنترنت للحفاظ على أداء الروبوت وكفاءته.
- دليل استخدام شامل يرافق المنتج، مع محتوى مرئي (فيديوهات) يوضح خطوات التشغيل.
- ردود فعل العملاء يمكن أن تُجمع عبر استبيانات وملاحظات يتم تحليلها لتحسين الأداء المستقبلي.

c) How can we improve or personalize our interactions with our customers?

كيف يمكننا تحسين أو تخصيص تفاعلاتنا مع عملائنا؟

هناك عدة طرق استراتيجية يمكن من خلالها تحسين العلاقة مع العملاء وجعلها أكثر تخصيصًا وفعالية:

- **إطلاق تطبيق ذكي مخصص للروبوت، يتيح للعملاء:**
  - مراقبة حالة الجهاز.
  - طلب خدمات صيانة.
  - تلقي تنبيهات أوتوماتيكية عند الحاجة إلى تعقيم أو صيانة.
  - تقديم ملاحظاتهم بشكل فوري.
- **نظام دعم متعدد القنوات يشمل:**
  - حسابات رسمية على شبكات التواصل الاجتماعي للإجابة عن الأسئلة الشائعة.
  - قاعدة بيانات إلكترونية متاحة للمستخدمين.
- **تخصيص المحتوى حسب نوع العميل:**
  - إرسال إشعارات للعملاء المؤسسيين تتضمن التحديثات والابتكارات.
  - تقديم خصومات أو عروض خاصة بناءً على سلوك الشراء السابق أو عدد الأجهزة المستخدمة.
- **برنامج ولاء أو اشتراك:**
  - إطلاق برنامج ولاء للمستخدمين المتكررين.
  - توفير حزم اشتراك سنوية تشمل التحديثات، الصيانة المجانية، وإمكانية تجربة إضافات جديدة.
- **الزيارات الميدانية:**
  - إرسال فرق تقنية عند التثبيت الأولي لتعزيز الثقة والتفاعل الإيجابي.

4) Distribution channels: قنوات التوزيع

a) By which channels do our customers prefer to be contacted?

من خلال أي قنوات يفضل عملاؤنا أن يتم التواصل معهم؟

يفضل عملاؤنا أن يتم التواصل معهم عبر قنوات متعددة تعتمد على طبيعة كل فئة:

- **المستشفيات والمؤسسات الصحية**
  - يفضلون التواصل الرسمي والمباشر عبر:
    - البريد الإلكتروني المهني.
    - الاجتماعات المباشرة.
    - زيارات ميدانية للتعريف بالمنتج أو تقديم عروض مخصصة.
- **المختبرات والمراكز البحثية**
  - يفضلون القنوات التقنية الرسمية مثل:
    - البريد الإلكتروني العلمي/المهني.
    - المعارض والمؤتمرات العلمية.
    - التواصل عبر الجامعات والمؤسسات الأكاديمية.
- **المستخدمون المنزليون والمكاتب**
  - يفضلون التواصل السهل والمرن عبر:
    - مواقع التواصل الاجتماعي (Facebook، Instagram).
    - تطبيق الهاتف المحمول.
    - موقع إلكتروني بسيط وسلس.
- **المؤسسات التجارية والتعليمية**
  - يفضلون:
    - منصات B2B مثل LinkedIn.
    - البريد الإلكتروني.
    - التواصل عبر وسطاء أو موزعين محليين.

b) Which channels are the most effective to reach each customer segment?

ما هي القنوات الأكثر فعالية للوصول إلى كل شريحة من العملاء؟

يمكن تحديد القنوات الأكثر فعالية كما يلي:

شريحة العملاء	القنوات الفعالة
المستشفيات والمؤسسات الصحية	العروض المباشرة – زيارات ميدانية – اتفاقيات شراء جماعي – مناقصات حكومية.
المختبرات والمراكز العلمية	المشاركة في المعارض الأكاديمية – التواصل عبر الجامعات – مجلات علمية وتقنية.
المستخدمون المنزليون	التسويق عبر وسائل التواصل – إعلانات موجهة عبر الإنترنت – المتاجر الإلكترونية.
المدارس والمراكز التجارية	الحملات الرقمية – الوسطاء التجاريون – الشراكات مع مؤسسات تعليمية.

c) How can we integrate the different channels to improve the customer experience?

كيف يمكننا دمج القنوات المختلفة لتحسين تجربة العملاء؟

لتحقيق تجربة متكاملة ومتميزة للعملاء، يمكن دمج القنوات المختلفة وفق استراتيجية متعددة المستويات:

- **إنشاء منصة إلكترونية مركزية**
  - موقع إلكتروني رسمي يحتوي على:
    - معلومات تفصيلية عن المنتج.
    - طلبات الشراء.
    - مركز دعم فني.
    - حساب خاص لكل نوع عميل (مؤسسة، فرد، موزع).
- **تطبيق للهاتف المحمول**
  - يمكن من خلاله:
    - مراقبة حالة الجهاز.
    - طلب قطع غيار أو خدمات.

- التفاعل مع الدعم الفني.
- تلقي تنبيهات أوتوماتيكية.

- **تنسيق بين التسويق الرقمي والميداني**
  - بدء الاتصال عبر الإعلان الرقمي.
  - ثم المتابعة عبر مكالمات مخصصة أو زيارات ميدانية.
  - توفير نماذج تجريبية للمؤسسات لتجربة المنتج قبل الشراء.
- **إدارة علاقات العملاء (CRM)** Customer Relationship Management
  - استخدام نظام لمتابعة كل عميل حسب القناة التي يتفاعل من خلالها، مع تسجيل ملاحظاته وتخصيص العروض له بناءً على احتياجاته.
- **تكامل منصات التواصل الاجتماعي مع خدمة العملاء**
  - الرد الفوري على الاستفسارات عبر فيسبوك أو إنستغرام.
  - استخدام الرسائل الآلية الذكية (Chatbots) لتوفير المعلومات الأولية.

5) Key Partners: الشركاء الرئيسيون

a) Who are our key partners?

من هم شركاؤنا الرئيسيون؟

يمثل شركاؤنا الرئيسيون الجهات التي ساهمت في تطوير المشروع أو التي نحتاج إلى التعاون معها لضمان استمرارية النمو والإنتاج، ومنهم:

- **جامعة أبي بكر بلقايد – تلمسان**
  - قدمت الدعم الأكاديمي، التقني، والمخابر اللازمة لتطوير النماذج الأولية.
  - ساهمت في توفير بعض المكونات الإلكترونية.
- **الأساتذة والمشرفون الأكاديميون**
  - دعم في التصميم، اختيار التكنولوجيا المناسبة، والتحليل العلمي للأداء.
- **الموردون المحليون للمكونات الإلكترونية**
  - يوفرون قطع الغيار مثل المستشعرات، المحركات، والمتحكمات بأسعار تنافسية.
- **شركاء محتملون في المستقبل:**
  - شركات البرمجيات: لتطوير منصة التطبيق الذكي ونظام التحكم عن بُعد.
  - شركات تصنيع محلية: لإنتاج الروبوت بكميات تجارية.

- o مراكز طبية أو مخابر تجريبية: لاختبار المنتج ميدانياً واعتماده.
- o مستثمرون أو حاضنات أعمال جامعية: لدعم التصنيع والتسويق التجاري.

b) Which partnerships help us reduce costs, access new resources, or improve our value proposition?

ما هي الشراكات التي تساعدنا على تقليل التكاليف، والوصول إلى موارد جديدة، أو تحسين عرض القيمة الذي نقدمه؟

بعض الشراكات لها تأثير مباشر وفعّال على النموذج الاقتصادي وعرض القيمة:

- **الجامعة:** توفر مخابر مجانية، مكونات بأسعار مدعّمة، وتُسهل إجراء التجارب دون تكلفة إضافية.
- **الموردون المحليون:** عقد اتفاقيات معهم يمكن أن يقلل من كلفة شراء القطع بشكل كبير، خاصة عند الطلب بكميات كبيرة.
- **شركات البرمجيات أو طلاب تكنولوجيا المعلومات:** يمكن التعاون معهم في إطار مشاريع مشتركة لتقليل كلفة تطوير التطبيق الذكي وتحسين نظام التشغيل.
- **الشراكة مع مراكز صحية لاختبار المنتج:** تمنحنا بيانات حقيقية من أرض الواقع، مما يُحسّن من جودة المنتج ويُكسبنا ثقة السوق.
- **مؤسسات التمويل وحاضنات الأعمال:** يمكن أن توفر التمويل والبنية التحتية، وتفتح لنا أبواب الشراكات المستقبلية أو الصفقات العمومية.

c) How can we align our interests with those of our partners?

كيف يمكننا مزامنة مصالحنا مع مصالح شركائنا؟

لضمان شراكات فعّالة ومستدامة، يجب أن تكون العلاقة مبنية على مبدأ "رابح-رابح" (Win-Win)، وذلك من خلال:

- **تقديم قيمة متبادلة**
  - o للموردين: ضمان شراء كميات دورية.
  - o للجامعة: الاستفادة من نجاح المشروع كقصة نجاح أكاديمية.
  - o للمستثمرين: منح نسب من الأرباح مقابل التمويل أو التسويق.
- **تحديد الأدوار بوضوح**
  - o توثيق الاتفاقيات وتحديد من المسؤول عن ماذا (التطوير، التصنيع، التوزيع...).
- **فتح آفاق الابتكار المشترك**

- o التعاون في تطوير نماذج جديدة أو تحسين المنتج حسب التغذية الراجعة من الشركاء.
- **مشاركة الأرباح أو النتائج البحثية**
- o مثلاً نشر نتائج الأداء بالمشاركة مع الشركاء الأكاديميين، أو تقديم حوافز للموزعين عند تحقيق أهداف بيعية.
- **إشراك الشركاء في رؤية المشروع على المدى البعيد**
- o بناء علاقة طويلة الأمد لا تقتصر فقط على منتج واحد بل على نظام بيئي متكامل (روبوت – صيانة – تطبيق – دعم...).

6) Key Activities: الأنشطة الرئيسية

a) What essential tasks must we carry out to deliver our value proposition?

ما الأنشطة الضرورية التي ينبغي القيام بها لتحقيق عرض القيمة الخاص بنا؟

لتحقيق عرض القيمة الفريد الذي يقدمه روبوت EcoSan-Bot والمتمثل في توفير حل ذكي، صديق للبيئة، لتعقيم الهواء في الفضاءات المغلقة يجب تنفيذ مجموعة من الأنشطة الأساسية تشمل:

- **تطوير تكنولوجيا فعالة للتعقيم الذكي**
- o برمجة خوارزميات التحكم في الحركة والتهوية.
- o دمج المستشعرات (كالكشف عن الجسيمات، الرطوبة، وجود الأشخاص).
- o تحسين الأداء البيئي عبر تقنيات UV.
- **تصميم وبرمجة النظام الإلكتروني والميكانيكي**
- o تركيب الدوائر الإلكترونية، وربط المتحكمات والمشغلات.
- o تطوير لوحات التحكم وتكاملها مع تطبيق الهاتف الذكي.
- **اختبارات الجودة والسلامة**
- o التأكد من فاعلية التعقيم، وسلامة الجهاز للاستخدام في المستشفيات.
- o التحقق من مطابقة المعايير البيئية والصحية.
- **تحليل احتياجات السوق وتكييف المنتج معها**
- o دراسة بيئات العمل المختلفة (مستشفيات، مختبرات، منازل).
- o تخصيص تصميم الجهاز بما يتناسب مع كل فئة مستهدفة.

b) What are the essential operations that keep our business running smoothly?

ما الأنشطة الضرورية لضمان نجاح أعمالنا؟

حتى نحافظ على استمرارية مشروعنا ونموه، يجب الحفاظ على مجموعة من العمليات الإدارية والتجارية:

- **إدارة سلسلة التوريد**
  - التواصل المستمر مع الموردين لضمان توفر المكونات.
  - تقليل التكاليف عبر اتفاقيات توريد طويلة الأمد.
- **التسويق والترويج للمنتج**
  - إعداد محتوى ترويجي يبرز نقاط القوة (الأمان، الاستقلالية، الصداقة للبيئة).
  - المشاركة في المعارض الصحية والتقنية لعرض الابتكار.
- **خدمة العملاء والدعم الفني**
  - توفير دعم تقني ما بعد البيع.
  - التفاعل السريع مع الأعطال أو الأسئلة من المستخدمين.
- **تطوير مستمر وتحسين المنتج**
  - جمع تغذية راجعة من العملاء والمؤسسات الصحية.
  - تحديث البرمجيات وإدخال تحسينات تكنولوجية دورية.
- **إدارة العلاقة مع الشركاء**
  - التواصل مع الجامعات والمستثمرين والموزعين.
  - تطوير نماذج تعاون تضمن النمو المشترك.

c) Which actions deliver the greatest benefit to our customers?

ما هي الأنشطة التي تخلق أكبر قدر من القيمة لعملائنا؟

الأنشطة التالية تُعد الأكثر تأثيرًا في تحسين تجربة العميل وخلق قيمة مضافة حقيقية:

- **التعقيم الفعال والمستقل دون تدخل بشري**
  - العميل يستفيد من تقليل العدوى وتحسين جودة الهواء بشكل أوتوماتيكي وآمن.
- **السهولة في التشغيل والمتابعة عبر تطبيق ذكي**
  - تمكن العملاء من مراقبة الروبوت، برمجة أوقات العمل، وتلقي التنبيهات.

- **ضمان الصيانة الدورية والتحديثات البرمجية**
  - يطمئن العميل إلى استمرار عمل الروبوت بكفاءة عالية دون تعطل.
- **التصميم المدمج والذكي**
  - الروبوت لا يسبب إزعاجًا بصريًا أو صوتيًا، ويتكيف مع مختلف البيئات.
- **الاستجابة السريعة لاحتياجات كل فئة عميل**
  - تقديم نماذج مخصصة (حجم، نمط تشغيل، تقنيات تعقيم مختلفة) حسب القطاع (صحي، منزلي، تعليمي...).

7) Key Resources: الموارد الرئيسية

a) What is our essential tangible, intangible, and human assets?

ما هي أصولنا المادية وغير المادية والبشرية الأساسية؟

لتحقيق أهداف مشروع EcoSan-Bot وضمان تقديم عرض قيمة عالي الجودة، نعتمد على مجموعة من الموارد الرئيسية المصنفة كالتالي:

1. **الأصول المادية (Tangible Assets):**
   - المعدات الإلكترونية: متحكمات دقيقة (Microcontrollers)، مستشعرات، محركات كهربائية، بطاريات قابلة للشحن.
   - أدوات مخبرية: أجهزة قياس، معدات لحام وتجميع، منصات اختبار الأداء.
   - الهيكل الفيزيائي للروبوت: مكونات ميكانيكية مطبوعة بتقنية D3 أو من مواد خفيفة قابلة للتعقيم.
2. **الأصول غير المادية (Intangible Assets):**
   - البرمجيات الخاصة بالروبوت: نظام التحكم الذكي، خوارزميات الملاحة الذاتية، وواجهة التحكم عبر الهاتف المحمول.
   - المعرفة التقنية: الخبرة المكتسبة في مجال الاستشعار والتحكم والاتصالات.
   - الملكية الفكرية المحتملة: إمكانات الحصول على براءة اختراع للتقنية أو التصميم.
   - سمعة المشروع: كونه مشروع جامعي مبتكر له بُعد صحي وبيئي يعزز من مصداقيته في السوق.
3. **الموارد البشرية (Human Assets):**
   - الفريق المطور: طلبة الهندسة المتخصصون في الآليات والأنظمة الذكية.
   - الإشراف الأكاديمي: أساتذة وخبراء يوجهون مراحل التطوير العلمي والهندسي.
   - الشركاء المحتملون في البرمجة، التصميم الصناعي، أو التسويق.

b) What tools, technologies, or partnerships do we need to succeed?

ما هي الأدوات والتقنيات أو الشراكات التي نحتاجها للنجاح؟

الأدوات والتقنيات:

- برمجيات التصميم (مثل SolidWorks أو Fusion 360) لتطوير الهيكل.
- منصات التطوير المدمج (مثل Arduino، ESP32) لتطوير الأنظمة الذكية.
- بيئات تطوير البرمجيات (مثل Python، C++) لتصميم خوارزميات الملاحة والتعقيم.
- تقنيات الاتصالات (مثل Wi-Fi، Bluetooth) لربط التطبيق بالروبوت.

الشراكات:

- الجامعة: لتوفير البيئة البحثية والدعم الفني والمالي الأولي.
- موردو المكونات الإلكترونية: لتأمين قطع الغيار عالية الجودة بأسعار تنافسية.
- مراكز صحية ومخابر: لاختبار المنتج وتقديم تغذية راجعة عملية.
- حاضنات أعمال أو مؤسسات تمويل: لدعم الانتقال من النموذج الأولي إلى السوق.

c) What are the main competitive advantages of our resources?

ما هي المزايا التنافسية الرئيسية لمواردنا؟

- **تكامل التخصصات:** الجمع بين الهندسة الإلكترونية، البرمجة، وتصميم الأنظمة الذكية يمنحنا قدرة شاملة على الابتكار في منتج متكامل وفعال.
- **المرونة والابتكار الذاتي:** معظم التطوير تم بموارد محدودة مما يعكس قدرة الفريق على الإنجاز بكفاءة، وهو ما يُعد ميزة تنافسية عند دخول السوق.
- **دعم أكاديمي قوي:** توفير الجامعة للخبرة والمخابر والتوجيه يرفع من جودة المنتج ويمنحه مصداقية بحثية.
- **التكلفة التنافسية:** اعتماد مكونات متوفرة محلياً بأسعار منخفضة يُمكّننا من تقديم منتج بجودة عالية وسعر مناسب مقارنة بالمنافسين الدوليين.
- **التركيز على الاستدامة والبيئة:** استخدام تقنيات صديقة للبيئة (مثل UV بدلاً من المواد الكيميائية) يجعل المشروع متماشياً مع المعايير البيئية الحديثة.
- **سهولة التخصيص والتطوير المستقبلي:** تصميم مفتوح المصدر جزئياً يُتيح لنا التوسع لاحقاً بوظائف جديدة أو أسواق جديدة (كالمدارس أو الفنادق...).

8) Expenses and Costs: التكاليف والمصاريف

a) What are the fixed and variable costs associated with our business model?

ما هي التكاليف الثابتة والمتغيرة المرتبطة بنموذجنا الاقتصادي؟

التكاليف الثابتة (Fixed Costs):

وهي التكاليف التي تبقى ثابتة نسبياً بغض النظر عن حجم الإنتاج أو عدد الوحدات المنتجة:

- تكلفة تطوير البرمجيات والأنظمة الذكية: تشمل تصميم خوارزميات التحكم، التكامل مع التطبيق المحمول، وتحديثات النظام.
- البحث والتطوير (D&R): ويشمل اختبارات الأداء، التجريب، وتحسينات التصميم.
- تكاليف المعدات الأساسية:

تكلفة مكونات النموذج الواحد

- **البطاريات (Batteries):** 4 × 300 = 1200
- **مستشعر بالموجات فوق الصوتية (Ultrasonic sensor):** 1 × 400 = 400
- **مضخة (Pump):** 1 × 550 = 550
- **أردوينو أونو (Arduino UNO):** 2 × 1500 = 3000
- **مشغل (L293 driver) L293:** 1 × 850 = 850
- **ESP8288:** 1 × 900 = 900
- **سيارة روبوت (Robot Car):** 1 × 4000 = 4000
- **أسلاك (Wires):** 2 × 400 = 800
- **باور بانك (Power bank):** 1 × 5500 = 5500
- **محرك تيار مستمر (Dc motor):** 1 × 800 = 800
- **محرك سيرفو (Servo motor):** 1 × 700 = 700
- **محرك خطوي (Stepper motor):** 1 × 1450 = 1450
- **HC-SR501:** 1 × 800 = 800
- **دائرة حماية البطارية (Battery protection circuit):** 1 × 500 = 500

الإجمالي للمكونات الأساسية: 21450 دينار جزائري

مكونات يمكن إضافتها:

- **مصباح بالأشعة فوق البنفسجية (Ultra violet lamp):** 1 × 5000 = 5000
- **خزان التطهير (Disinfection tank):** 1 × 3000 = 3000
- **بخاخ (Sprayer):** 1 × 7000 = 7000
- **ذراع روبوت (Robotic arm):** 1 × 15000 = 15000
- **شاشة (LCD screen) LCD:** 1 × 3000 = 3000
- **ألواح شمسية (Solar panels):** 1 × 16900 = 16900

الإجمالي للمكونات الإضافية: 49900 دينار جزائري

التكلفة الإجمالية للنموذج الواحد (بما في ذلك المكونات الإضافية):

21450 (أساسي) + 49900 (إضافي) = 71350دينار جزائري مع اضافة تكاليف شحن المكونات و الهيكل الخارجي يمكن أن تصل التكلفة الإجمالية للنموذج الواحد=80000 دينار جزائري

- الاستضافة والتراخيص الرقمية: مثل خدمات تخزين البيانات، السيرفرات السحابية، أو تراخيص البرمجيات المستخدمة.

التكاليف المتغيرة (Variable Costs):

تختلف حسب عدد الوحدات المنتجة أو المبيعات:

- تكلفة المكونات الإلكترونية لكل وحدة: مثل المستشعرات، المحركات، البطاريات، لوحات التحكم.
- تكلفة التغليف والشحن.

  - تتأثر تكلفة التغليف والشحن بالكميات والوجهات، ويتراوح متوسط التكلفة الشهرية للتعبئة والشحن المحلي بين 5,000 و15,000 دينار جزائري، اعتمادًا على حجم الشحنات. أما التكاليف التسويقية المتغيرة، التي تشمل الإعلانات الرقمية والحملات الترويجية، فيمكن أن تبدأ من 30,000 دينار جزائري شهريًا، مع إمكانية الزيادة بناءً على نطاق الحملات التسويقية.

- صيانة وتبديل القطع الاستهلاكية.

- تكلفة العمالة:

الشرح	الراتب الشهري (دج)	العدد	الوظيفة
تركيب وصيانة القطع الإلكترونية	40,000 - 50,000	3	فني تركيب قطع (تقني ميداني)
تطوير وصيانة البرمجيات	60,000 - 80,000	2	مبرمج/مهندس برمجيات
صيانة المعدات والآلات	35,000 - 45,000	2	عامل صيانة
متابعة الحسابات، المداخيل، النفقات	50,000 - 65,000	1	محاسب
متابعة توفر القطع وشرائها قبل النفاذ	40,000 - 50,000	1	مسؤول مخزون (قطع إلكترونية)
إدارة التواصل مع الزبائن ووسائل الإعلام	45,000 - 60,000	1	ممثل تسويق وتواصل
تنسيق بين المؤسسة والعملاء، المؤتمرات	45,000 - 55,000	1	مسؤول تنسيق علاقات العملاء
490,000		الاجمالي الشهري	

في المرحلة الأولية من المشروع، سأتولى و صديقتي دور مشرفة مشروع ، حيث نساهم في التنسيق العام، المتابعة الفنية، والإشراف على مختلف مراحل التطوير. وبعد انطلاق المشروع ودخوله في مرحلة التشغيل، سيتم تخصيص راتب شهري لنا بصفة مهندسين مسؤولين عن التطوير والمراقبة التقنية .

يمكن اعتماد راتب **60,000** دج كبداية بعد فترة الإشراف المجاني .

b) What are the most important costs for our company?

ما هي التكاليف الأكثر أهمية لشركتنا؟

- تكلفة تطوير وتحديث البرمجيات: باعتبار أن الروبوت يعتمد بشكل كبير على الذكاء والتحكم الذاتي، فإن الاستثمار في البرمجيات (التحكم، التطبيق، الاتصال) يعتبر حاسماً.
- شراء المكونات الإلكترونية عالية الجودة: لضمان الأداء والموثوقية، خاصة في البيئات الحساسة كالقطاع الصحي.
- البحث والتطوير المستمر: لتحديث التقنية، دمج خوارزميات جديدة، وتحسين الأداء.

- الدعم الفني وخدمة ما بعد البيع: لتقديم تجربة موثوقة ومستدامة للعملاء، خصوصاً في المؤسسات الطبية.
- التسويق وبناء العلامة التجارية: للترويج للروبوت كمنتج ذكي وبيئي يمكن الوثوق به في المؤسسات.

c) How can we reduce costs or improve the efficiency of our operations?

كيف يمكننا تقليل التكاليف أو تحسين كفاءة عملياتنا؟

- **إبرام شراكات استراتيجية مع الموردين**
  - توقيع اتفاقيات طويلة المدى مع موردين محليين أو دوليين لتخفيض تكلفة المكونات.
- **الاعتماد على الإنتاج المحلي وتكنولوجيات منخفضة التكلفة**
  - تصنيع الأجزاء غير الحساسة باستخدام الطباعة ثلاثية الأبعاد أو تقنيات CNC البسيطة.
- **الاستفادة من دعم الجامعات والحاضنات**
  - استخدام الموارد المتاحة في الجامعة (مخابر، دعم تقني، إنترنت، أدوات) لتقليل التكاليف التشغيلية خلال مراحل التطوير.
- **إعادة استخدام الموارد وتدوير النفايات التقنية**
  - الاستفادة من بقايا مكونات المشاريع السابقة أو أجزاء قابلة لإعادة الاستخدام لتقليل الهدر.
- **تبني مبدأ "التطوير المستمر" بدلاً من "الإطلاق الكامل"**
  - تطوير إصدار أولي MVP لاختبار السوق بأقل التكاليف، ثم التوسع حسب الطلب الفعلي.
- **أتمتة بعض عمليات الصيانة والاختبار**
  - برمجة النظام ليقوم بفحص دوري تلقائي للمكونات، مما يقلل من تدخل البشر ويزيد من كفاءة الصيانة.

9) Revenues: الإيرادات

a) What products or services are our customers willing to pay for?

ما هي المنتجات أو الخدمات التي يكون عملاؤنا مستعدين للدفع مقابلها؟

عملاؤنا، خاصة من القطاع الصحي والمؤسسات الحساسة بيئياً، مستعدون للدفع مقابل:

- **الروبوت نفسه كوحدة تعقيم ذكية**
  - روبوت محمول، ذاتي الحركة، مزود بمستشعرات وتقنيات التعقيم بالهواء.
- **خدمات ما بعد البيع**
  - عقود صيانة دورية (recalibration، استبدال المستشعرات).
  - تحديثات برمجية ذكية للتكيف مع التغيرات في معايير السلامة.

- **التكامل مع التطبيقات الذكية**
  - تطبيق للهاتف المحمول يتيح التحكم، جدولة التعقيم، وتقديم تقارير جودة الهواء.
- **التخصيص حسب الطلب**
  - تكييف تصميم الروبوت أو خصائصه وفقًا لاحتياجات كل مؤسسة (مثلاً: وضع صامت لغرف النوم، أنظمة تنقل مختلفة للممرات الضيقة...).
- **برمجيات إدارة متعددة الروبوتات**
  - أنظمة تحكم مركزي تسمح للمستشفيات أو المختبرات بإدارة أسطول كامل من روبوتات EcoSan-Bot.

b) What are the different ways we can generate revenue?

ما هي الطرق المختلفة التي يمكننا من خلالها توليد الإيرادات؟

- **البيع المباشر**
  - بيع وحدة EcoSan-Bot بشكل فردي أو بكميات كبيرة للمؤسسات.
- **نموذج الاشتراك (Subscription)**
  - اشتراك شهري أو سنوي يشمل الصيانة والتحديثات الذكية.
- **الخدمات المخصصة (Customization)**
  - رسوم إضافية مقابل تعديلات معينة في التصميم أو البرمجيات.
- **الدخول في المناقصات الحكومية والمستشفيات الكبرى**
  - تقديم عروض تنافسية للحصول على عقود تزويد طويلة الأمد.
- **إيرادات من التطبيق الذكي**
  - ترقيات مدفوعة لميزات متقدمة في التطبيق، مثل تقارير دقيقة أو إدارة عن بُعد.
- **الترخيص (Licensing)**
  - ترخيص التقنية أو النظام لمصنعين أو موزعين محليين في دول أخرى.

c) What is our pricing model?

ما هو نموذج التسعير الخاص بنا؟

يعتمد نموذج التسعير على مبدأ القيمة مقابل الجودة والاستدامة، ويأخذ بعين الاعتبار طبيعة السوق المستهدف (قطاع صحي، مختبرات، مؤسسات رسمية):

نموذج التسعير المقترح:

- **تسعير قائم على القيمة (Value-Based Pricing)**
  - تحديد السعر بناءً على الفائدة التي يجنيها العميل من تقليل العدوى وتحسين جودة الهواء.
- **نموذج البيع + الاشتراك**
  - بيع الوحدة الأساسية بسعر محدد، مع إمكانية الاشتراك في باقات الخدمة والصيانة.
- **تسعير تفضيلي للمؤسسات الحكومية**
  - تخفيضات خاصة في حالة الشراء الجماعي أو التعاقد طويل الأمد.
- **تسعير مرن:** القدرة على تقديم باقات متعددة:
  - Basic: الروبوت بدون تطبيق أو صيانة.
  - Professional: يشمل التطبيق والصيانة السنوية.
  - Enterprise: يشمل كل شيء بالإضافة إلى تخصيص شامل حسب بيئة العمل.

General Conclusion

General Conclusion

In light of the growing demand for autonomous and contactless technologies in healthcare and public safety, this project focused on the design and implementation of a hospital disinfection robot that combines mobility, dual sterilization systems, and wireless communication.

The work began with Chapter I, which offered a comprehensive overview of robotics, particularly in the medical field, highlighting the role of disinfection robots and comparing UV-C, hydrogen peroxide vapor, and electrostatic spraying methods. This theoretical foundation provided the necessary background to understand the motivations and technological possibilities for robotic disinfection.

In Chapter II, the architecture and components of the proposed robot were examined in detail. Each subsystem—including the power supply, control unit, actuators, sensors, UV-C LEDs, liquid pump, and communication modules—was presented and justified. This chapter served as a blueprint for the robot's functionalities and component integration.

Chapter III addressed the practical side, covering simulation work, testing of individual components, and partial real-world implementation. The ultrasonic sensor's accuracy, the servo motor's angular precision, and the smoothness of DC motor rotation were all tested experimentally. However, due to hardware limitations—such as low torque and power constraints—the robot's full integration, movement performance, and mobile application control could not be tested in real conditions. The pump system was only briefly verified for functionality without detailed experimentation.

Despite these challenges, the project successfully demonstrates the feasibility of a low-cost, autonomous disinfection robot with hybrid sterilization methods, laying the foundation for future enhancements.

Perspectives

Looking ahead, several improvements and future developments are recommended to optimize the system's functionality and usability:

System Integration: Finalizing the communication between ESP8266 and Arduino Uno for reliable mobile app control.

Mechanical Optimization: Reducing chassis weight and enhancing motor torque for better movement capability.

Safety Automation: Implementing motion detection to automatically disable UV-C in the presence of humans.

Energy Management: Enhancing power supply through improved batteries or renewable sources like solar panels.

Pump System Control: Developing a more precise and automated liquid disinfection mechanism.

Prototype Miniaturization: Creating a more compact and lightweight version for confined spaces.

Field Validation: Collaborating with healthcare institutions to test the system under real operating conditions.

These perspectives provide a roadmap for transforming the current prototype into a fully functional, safe, and scalable robotic solution suitable for medical and public health environments.

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Abstract

The ongoing global concern over infection control has led to the growing demand for autonomous and contactless disinfection systems. In response, this thesis presents the design and implementation of a smart hospital disinfection robot that combines mobility, dual sterilization techniques (UV-C and liquid spraying), and wireless communication.

The work begins with a theoretical overview of robotics and disinfection technologies, followed by a detailed system design that includes power supply, Arduino Uno microcontroller, L293D driver, various actuators (DC, servo, stepper motors), sensors (ultrasonic, PIR), and a mobile interface via ESP8266 and MIT App Inventor.

Simulation and experimental tests were conducted to validate the robot's performance. Real tests confirmed the accuracy of the ultrasonic sensor, the angular precision of the servo motor, and the smoothness of DC motor movement. Despite power limitations that prevented full movement and mobile control testing, key components were successfully validated in real conditions.

This work lays the groundwork for a low-cost, hybrid disinfection robot suitable for hospitals and public facilities, with future improvements expected in integration, mobility, and real-world deployment.

Keywords: Disinfection Robot, UV-C Sterilization, Arduino Uno, ESP8266, Smart Healthcare, Wireless Control, Hospital Automation, Mobile Robot, Sensor Accuracy, Liquid Spraying.

الملخص

أدى القلق المتزايد عالميًا حول مكافحة العدوى إلى تصاعد الحاجة إلى أنظمة تعقيم ذاتية وغير تلامسية. واستجابةً لذلك، تقدم هذه المذكرة تصميم وتنفيذ روبوت ذكي لتعقيم المستشفيات، يجمع بين القدرة على الحركة، وتقنيتي تعقيم مزدوجتين) الأشعة فوق البنفسجية UV-C والرش بالسائل(، إضافةً إلى الاتصال اللاسلكي.

بدأ العمل بعرض نظري حول الروبوتات وتقنيات التعقيم، تلاه تصميم مفصل لنظام الروبوت، يشمل: مصدر الطاقة، لوحة التحكمArduino Uno ، سائق المحركاتL293D ، مجموعة من المشغلات (محركات تيار مستمر، محركات خطوة، ومحركات سيرفو)، حساسات) فوق صوتية وحركة(PIR ، ونظام اتصال عبر ESP8266وتطبيق مبرمج باستخدام.MIT App Inventor

تم إجراء محاكاة واختبارات حقيقية للتحقق من أداء النظام. أظهرت النتائج دقة مستشعر الموجات فوق الصوتية، ودقة الزوايا في محرك السيرفو، وسلاسة حركة المحركات. وعلى الرغم من محدودية الطاقة التي حالت دون اختبار الحركة الكاملة والاتصال بالتطبيق، فقد تم التحقق من فعالية المكونات الأساسية في بيئة واقعية.

يمثل هذا العمل خطوة أولى نحو تطوير روبوت تعقيم ذكي منخفض التكلفة، قابل للتطوير مستقبلاً فيما يخص التكامل، الحركة، والتطبيق الميداني في البيئات الصحية والعامة.

الكلمات المفتاحية :روبوت التعقيم، الأشعة فوق البنفسجيةUV-C ، Arduino Uno، ESP8266، التحكم اللاسلكي، الرعاية الصحية الذكية، الحركة الذاتية، دقة الحساسات، الرش بالسائل.

Résumé

La préoccupation croissante à l'échelle mondiale concernant la lutte contre les infections a renforcé le besoin de systèmes de désinfection autonomes et sans contact. Dans ce contexte, ce mémoire présente la conception et la réalisation d'un robot intelligent de désinfection hospitalière, combinant mobilité, double technique de stérilisation (rayonnement UV-C et pulvérisation liquide), ainsi qu'une communication sans fil.

Le travail a débuté par une étude théorique sur la robotique et les technologies de désinfection, suivie d'un design détaillé du système proposé. Celui-ci intègre une alimentation électrique, une carte Arduino Uno, un pilote de moteur L293D, plusieurs actionneurs (moteurs à courant continu, moteurs pas-à-pas, moteurs servo), des capteurs (ultrasoniques et infrarouges PIR), ainsi qu'un module de communication basé sur ESP8266 et une application développée via MIT App Inventor.

Des simulations et des tests expérimentaux ont été réalisés pour valider les performances du système. Les résultats ont confirmé la précision du capteur ultrasonique, l'exactitude angulaire du moteur servo, et la fluidité du mouvement des moteurs DC. Malgré certaines limitations liées à l'alimentation, qui ont empêché les tests complets de déplacement et de contrôle via l'application mobile, les composants essentiels ont été validés dans des conditions réelles.

Ce projet constitue une première étape vers le développement d'un robot de désinfection hybride, intelligent et à faible coût, avec des perspectives d'amélioration en termes d'intégration, de mobilité et d'applicabilité sur le terrain.

Mots-clés : Robot de désinfection, UV-C, Arduino Uno, ESP8266, contrôle sans fil, soins de santé intelligents, robot mobile, précision des capteurs, pulvérisation liquide.