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Par: SELLAOUI Raid Houssem Eddine

Thème

Commande d'un robot à base de la technologie VLC

Soutenu publiquement, le 14 /07 /2021, devant le jury composé de:

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Faculty of Science and Technology
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DISSERTATION

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Branch: Automation

Specialty: Automation and Industrial Computer Science

By: SELLAOUI Raid Houssem Eddine

Theme

Control of a robot based on VLC technology

Publicly defended, on 07/14/2021, in front of the jury composed of:

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Abstract

In this work, we realized and studied the performances of a robot car commanded by a wireless communication system based on visible light communication technology. The system consists of two Arduino cards (microcontroller), one is used as a transmitter and the other as a receiver integrated into the robot. The interface (Arduino IDE serial port window) is used to display the sent/received data. The system is set up using Bluetooth technology. The objective of this work is to provide the measurement bench with a new technology based on VLC communication. A flashlight LED is used for data transmitting and a photodiode is used to detect the VLC signal. The test results show that our proposed system can successfully transmit commands for distances up to 1.2 meters. However, with the limitation of the devices used in our application and noise due to ambient light, it is difficult to achieve long-distance data transmission. Our proposal is valid for a system operating at a medium distance.

Résumé

Dans ce travail, nous avons réalisé et étudié les performances d'une voiture robot commandée par un système de communication sans fil basé sur la technologie de communication par la lumière visible. Le système se compose de deux cartes Arduino (microcontrôleur), l'une est utilisée comme un émetteur et l'autre comme récepteur intégré dans le robot. L'interface graphique (fenêtre du port série Arduino IDE) est utilisée pour afficher les données envoyées/reçues. La mise en œuvre du système est réalisée avec la technologie Bluetooth. L'objectif de ce travail est de remettre le banc de mesure avec une nouvelle technologie basée sur la communication VLC. Une LED de lampe de poche est utilisée pour l'émission des données et une photodiode est utilisée pour détecter le signal VLC. Les résultats de test montrent que notre système proposé peut transmettre des commandes avec succès pour des distances allant jusqu'à 1.2m. Cependant, avec la limitation des dispositifs utilisés dans notre application et le bruit dû à la lumière ambiante, il est difficile d'atteindre une distance de transmission de données importante. Notre proposition est valable pour le fonctionnement du système à moyenne distance.

الملخص

في هذا العمل ، أدركنا ودرسنا أداء سيارة روبوت يقودها نظام اتصال لاسلكي يعتمد على تقنية اتصالات الضوء المرئي .يتكون النظام من وحدتي Arduino (متحكم دقيق) ، أحدهما يستخدم كجهاز إرسال والآخر كمستقبل مدمج في الروبوت .يتم استخدام الواجهة (Arduino IDE) لعرض البيانات المرسلة / المستلمة.تم إعداد النظام باستخدام تقنية . Bluetooth.الهدف من هذا العمل هو تزويد سيارة روبوت بتقنية جديدة تعتمد على اتصالات.VLC. يتم استخدام مصباح LEDلنقل البيانات ويتم استخدام Photodiode للكشف عن إشارة.VLC. تظهر نتائج الاختبار أن نظامنا المقترح يمكنه نقل الأوامر بنجاح لمسافات تصل إلى 1.2 متر .وعلى الرغم ذلك ، مع محدودية الأجهزة المستخدمة في تطبيقنا والضوضاء بسبب الإضاءة المحيطة ، من الصعب تحقيق نقل البيانات لمسافات طويلة . اقتراحنا صالح لنظام يعمل على مسافة متوسطة.

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LIST OF ABBREVIATIONS

RUR: Rassum's Universal Robots

IBM: International Business Machines

DJI: Da-Jiang Innovations

DARPA: Defence Advanced Research Projects Agency

EMYS: EMotive headY System

R2R: Robot-to-Robot

R2S/R2A/R2M: Robot-to-Sensor/Actuator/Machine

R2C: Robot-to-Cloud

GPS: Global Positioning System

R.A.D.A.R: Radio Detection and Ranging

FM: Frequency Modulation

5G: Fifth generation technology standard for broadband cellular networks

IoT: Internet of Things

EM: Electromagnetic

IR: Infrared

WLAN: Wireless Local Area Network

ISM: Industrial, Scientific and Medical

RFID: Radio Frequency Identification

VLC: Visible Light Communication

LED: Light-Emitting Diode

Pc-LED: Phosphor Converted LEDs

RGB: Red, Green, Blue LEDs

OLED: Organic Light-Emitting Diode

µ-LED: Micro-Light-Emitting Diodes

IM: Intensity Modulation

DD: Direct Detection systems

LOS: Line Of Sight

NLOS: Non Line Of Sight

FOV: Field Of View

FT: Full Tracked

SNR: Signal to Noise Ratio

HT: Half Tracked

NT: Not Tracked

OOK: On-off Keying

VPPM: Variable Pulse Position Modulation

PPM: Pulse Position Modulation

OFDM: Orthogonal Frequency Division Multiplexing

CSK: Color Shift Keying

Li-Fi: Light Fidelity

MRI: Magnetic Resonance Imaging

ITS: Intelligent Transport Systems

V2I: Vehicle-To-Infrastructure

V2V: Vehicle-To-Vehicle

SNR: Signal-to-Noise Ratio

ASRS: Automated Storage and Retrieval System

TOA: Time of Arrival

RSS: Received Signal Strength

General introduction

A robot is a mechanical device that can move and/or manipulate its surroundings to perform some function of work. There are many benefits to allowing robots to perform human tasks, especially ones that most would not or cannot undertake. While the current robots are not able to perform complex tasks, they can successfully complete simple ones making them useful in industrial settings.

In the 1930s, Westinghouse Electric Corporation made a humanoid robot known as Elektro, exhibited at the 1939 and 1940 World's Fairs [33]. The first electronic autonomous robots were created by William Grey Walter of the Burden Neurological Institute at Bristol, England in 1948 and 1949. They were named Elmer and Elsie [34]. These robots could sense light and contact with external objects, and use these stimuli to navigate. It wasn't until the integrated circuits were invented, and computers began to double rapidly in power, that it became possible to build robots as we imagine them. Until that time, automatons were the closest things to robots, and while they may have looked humanoid, and their movements were complex, they were not capable of the self-control and decision-making of robots today.

Wireless networks make it very easy to connect equipment that is ten meters or a few kilometres away. In addition, the installation of such networks does not require heavy improvements to existing infrastructure, as is the case with wired networks. (Digging trenches to route cables, building equipment in cabling, trunking, and connectors),

Communication with visible light (VLC) is an emerging wireless communication technology that uses visible light not only for illumination but also for data transmission. A main advantage of VLC is the use of LED lighting systems, which makes it ubiquitous and considerably reduces its implementation costs. VLC technology is developing against the background of increasing demand for wireless communications in more and more fields. In addition, frequency based radio communications are starting to show their limits. The limited range availability and the increase in the number of nodes affect the performance and reliability of the link. Under these circumstances, it is obvious that a new wireless communication technology is required. In addition to its ubiquitous nature, VLC offers a large bandwidth available for free, which allows high-speed communications.

This dissertation is made up of three chapters. The first deals with the different types of robots and wireless communication. The second chapter is devoted to Visible Light Communication (VLC). In the third chapter, we will realize and study the performance of a four wheel drive robot-car with a VLC based wireless communication system. The objective of this work is the integration of a VLC system into a simple robot.

Chapter I

INTRODUCTION TO ROBOTS AND WIRELESS COMMUNICATION

CHAPTER I: INTRODUCTION TO ROBOTS AND WIRELESS COMMUNICATION

I.1. Introduction :

In our day and age, technology is developing at an accelerated rate to the point that it is near impossible to keep up with all of its advancements. But focusing on one or two areas allows us to see and predict their development. In this research we will focus on two fields, the first is robotic engineering which is the development and improvement of autonomous devices, robots, and electro-mechanical systems. The second is Wireless Communication due to its flexibility and ease of use, making it an increasingly popular technology.

I.2. Robots :

Robot –noun- /ˈroʊbɑt/. It is a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer [1]. The first use of the word robot was by the Czech novelist Karel Capek in a 1920 play titled Rassum's Universal Robots (RUR). It originated from the Slavic word Robota, where it means labour or work. Robots can perform tasks above human physical limitations, making them future substitutes or replacements for humans, as they don't have bones to break or muscles to twist.

Robotics is the domain of application that applies the works of hardware and software, similar to embedded systems. It consists of computer science and engineering, Robotics Design, Construction, Operation, and Application of Robots. The goal of robotics is to design artificial machines that can assist human beings in their day-to-day livelihoods and works.

I.2.1. Robot categorizes :

It's not easy to categorize robots. Each one has its unique features, and as a whole, robots vary hugely in size, shape, and capabilities. However, many robots can be grouped based on their movements. And doing so, we recognize three major categories:

- **Stationary (Manipulator) Robots:** A stationary robot is a robot that works without changing its position. The word stationery is in relation to the base of the robot as opposed to the entire machine. Stationery robots manipulate their environment through position and orientation control of an end factor. These end factors can be for welding, drilling or gripping devices.

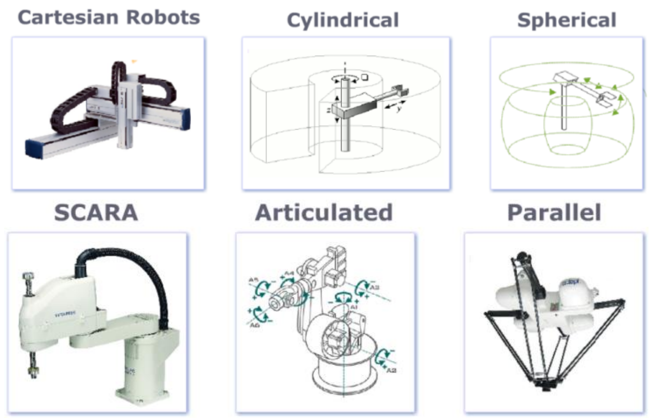

Figure I.1: Examples of Stationary (Manipulator) robots [2].

- **Wheeled robots:** Wheeled robots are robots that move on the ground with the use of their wheels. This is a frequently used design because it is the simplest in design, production, and programming. Another advantage of wheeled robots is their being easy to control than other robot types.

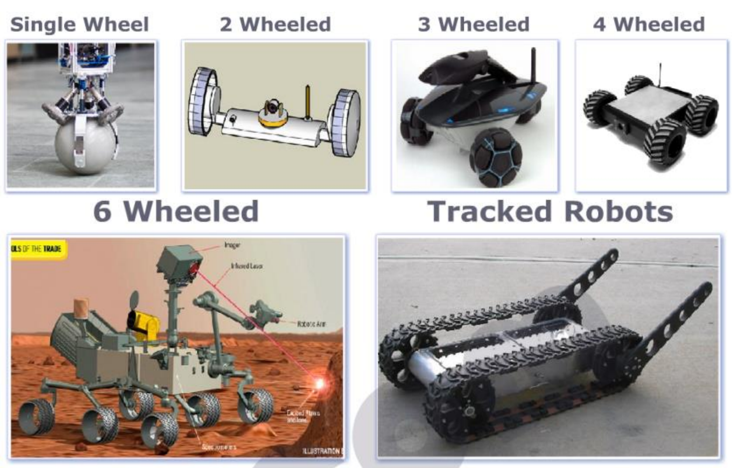

Figure I.2: Examples of wheeled robots [2].

- **Legged Robots:** Legged robots are mobile robots, but their movement method is more sophisticated and complicated compared to their wheeled counterparts. As their name suggests, they use their legs to control their locomotion, and they perform much better than wheeled robots on uneven terrain. Despite the high cost and production complexity of these robots, their advantages on uneven terrain make them indispensable for most applications.

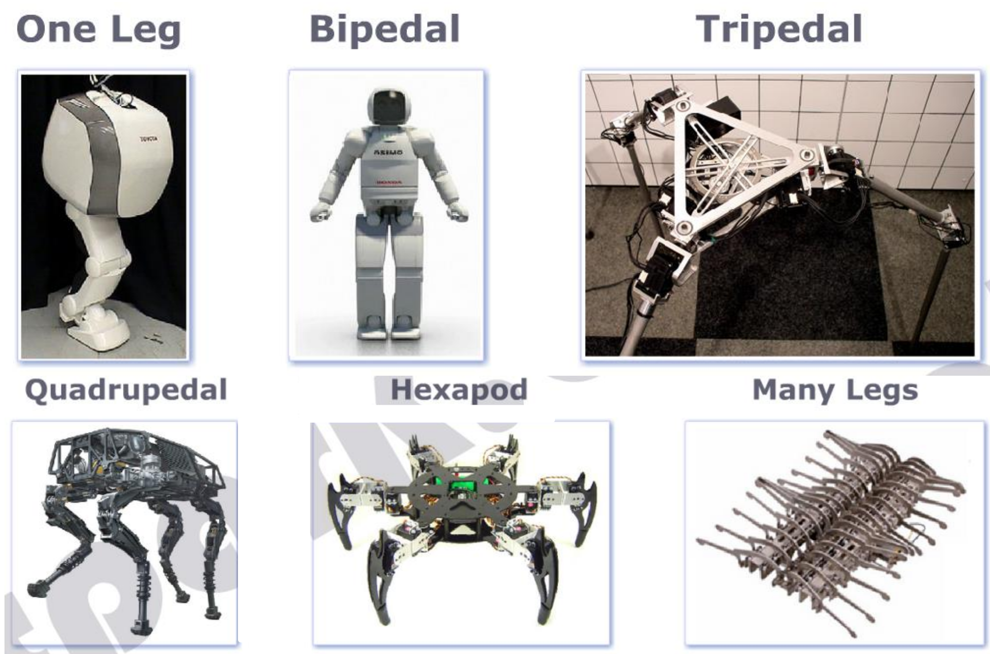

Figure I.3: Examples of legged robots [2].

There are other minor categories such as:

- **Flying Robots:** Flying robots float and manoeuvre on air using their plane-like or bird/insect-like wings, propellers, or balloons.
- **Swarm Robots:** Swarm robots are systems that consist of multiple small robots. They structurally do not create a single united robot, but operate as their robot modules operate cooperatively.
- **Modular Robots:** Similar to swarm robots, modular robotic systems have multiple robots in their configurations. The power of modular robotics comes from its versatility in its configurations.

- **Micro Robots:** We use the term Micro robots to define both robots that have dimensions on the micrometre scale and robots that can operate on micrometre resolution.
- **Nano Robots:** The term nano robot defines both very small robots which have nano meter scaled dimensions and robots that can manipulate their environment with a nano meter scale resolution regardless of their actual sizes.
- **Soft/Elastic Robots:** Soft/elastic robots are new introductions to robotics. These robots are generally bio-inspired.

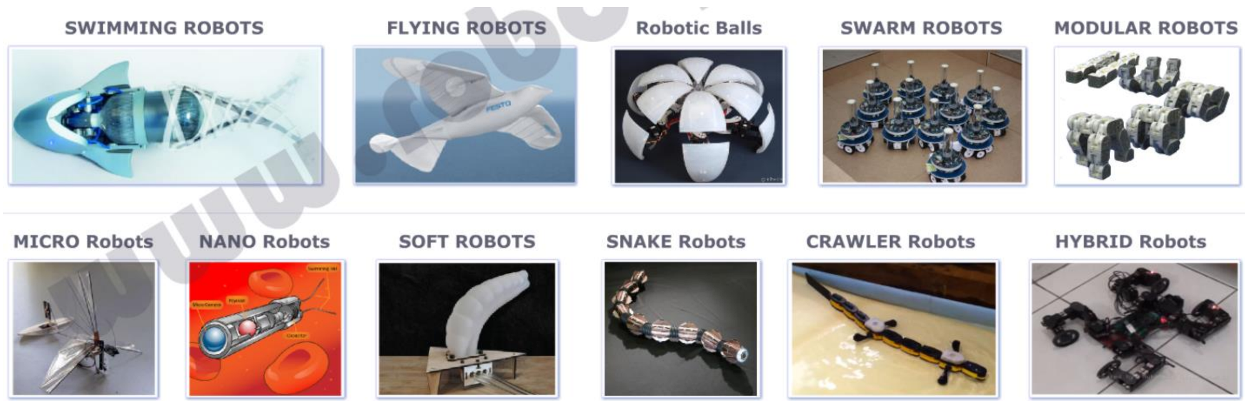

Figure I.4: Examples of other less known robots [2].

I.2.2. Fields of use :

Due to the versatility and variety of robots, they are being used in many fields and areas.

- **Industrial:** An industrial robot is a robot system used for manufacturing. Industrial robots are automated, programmable and capable of movement on three or more axes [2]. An example is the Unimate, the grandfather of all factory robots. This category includes also systems like Amazon's warehouse robots and collaborative factory robots that can operate alongside human workers.

Figure I.5: Unimateand and Amazon's warehouse robots.

- **Consumer:** Consumer robots are robots you can buy to help you with tasks and house chores or use just for fun. Examples are the Roomba vacuum, AI-powered robot assistants, robot dog Aibo, and a variety of robotic toys and kits.

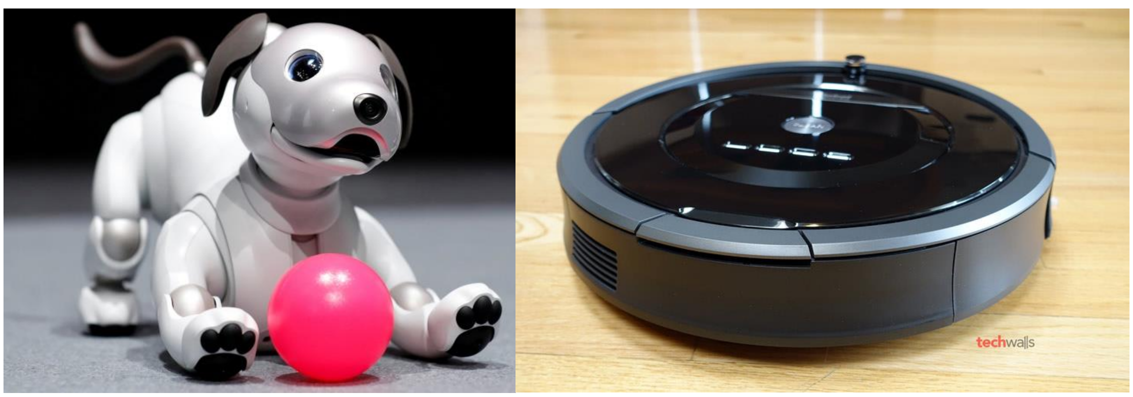

Figure I.6: Robot dog Aibo and a Roomba vacuum.

- **Medical:** health-care robots include bionic prostheses stationary robots such as the da Vinci surgical robot. A system that fits in this category but is not a robot is Watson, the IBM question-answering supercomputer, which has been used in healthcare applications.

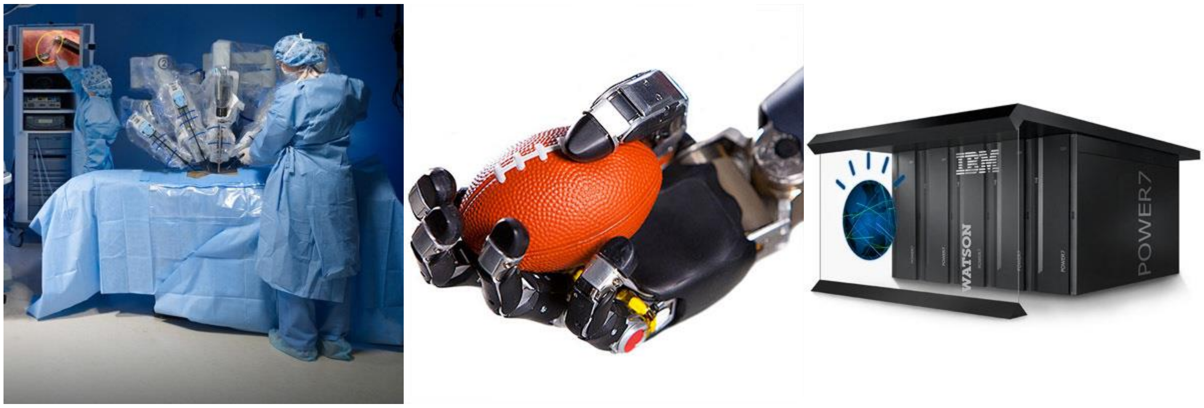

Figure I.7: Da Vinci surgical robot, bionic prostheses and IBM's Watson.

- **Exoskeletons:** Robotic exoskeletons can be used for physical rehabilitation and for enabling a paralysed patient to walk again. Some have industrial or military applications, by giving the wearer added mobility, endurance, or capacity to carry heavy loads.

Figure I.8: Exoskeletons used by paralysed patients.

- **Disaster Response:** These robots perform dangerous jobs like searching for survivors in the aftermath of an emergency. For example, after an earthquake and tsunami struck Japan in 2011, Pack bots were used to inspect damage at the Fukushima Daiichi nuclear power station.

Figure I.9: Photos of disaster response robots.

- **Drones:** drones come in different sizes and have different levels of autonomy. Examples include DJI's Phantom series and Parrot's Anafi, as well as military systems like Global Hawk, used for long-duration surveillance.

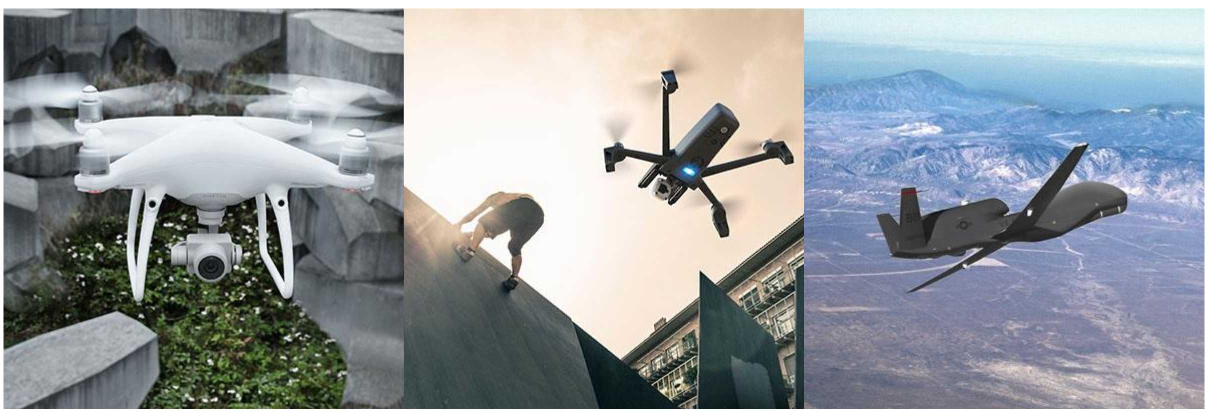

Figure I.10: Photos of drone examples (DJI's Phantom, Anafi and Global Hawk).

- **Military & Security:** Military robots include ground systems like Endeavor Robotics' PackBot, used to scout for improvised explosive devices, and BigDog, to assist troops in carrying heavy gear. Security robots include autonomous mobile systems such as Cobalt.

Figure I.11: BigDog, Cobalt and PackBot.

- **Self-Driving Cars:** Many robots drive themselves around. Early autonomous vehicles include the ones built for DARPA's autonomous-vehicle competitions and also Google's pioneering self-driving Toyota Prius, later spun out to form Waymo.

Figure I.12: Examples of self-driving cars.

- **Education:** This broad category is aimed for use at home or in classrooms. It includes hands-on programmable sets from Lego, 3D printers with lesson plans, and even teacher robots like EMYS.

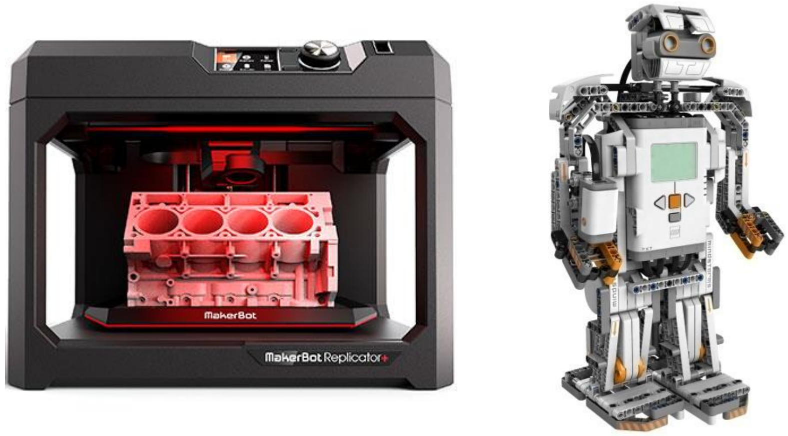

Figure I.13: A 3-D printer and a LEGO MINDSTORMES robot.

- **Research:** The vast majority of today's robots are created in universities and corporate research labs. With the primary intent to help researchers.

- **Humanoids:** This is the type of robot that most people think of when they imagine a robot. Examples of humanoid robots include Honda's Asimo, which has a mechanical appearance, and also androids like the Geminoid series, which are designed to look like people.

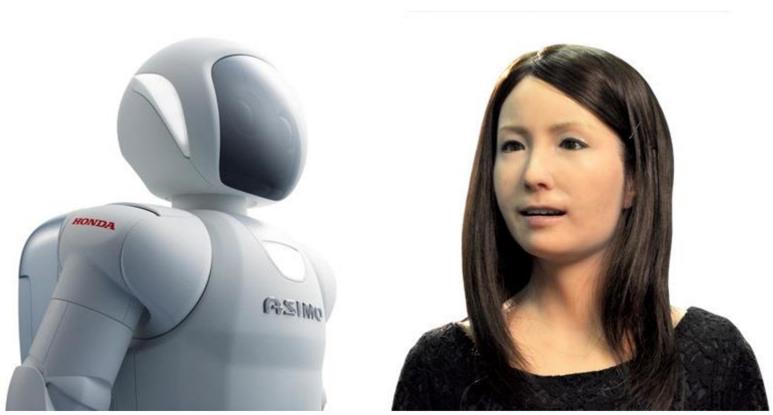

Figure I.14: Humanoid robots Asimo and Geminoid.

- **Telepresence:** robots that allow you to be present at a place without actually going there. You log on to a robot avatar via the internet and drive it around, seeing what it sees, and talking with people. Workers can use it to collaborate with colleagues at a distant office, and doctors can use it to check on patients.

Figure I.15: Examples of Telepresence robots cars.

- **Underwater:** They consist of deep-sea submersibles like Aquanaut, diving humanoids like Ocean One, and bio-inspired systems like the ACM-R5H snakebot.

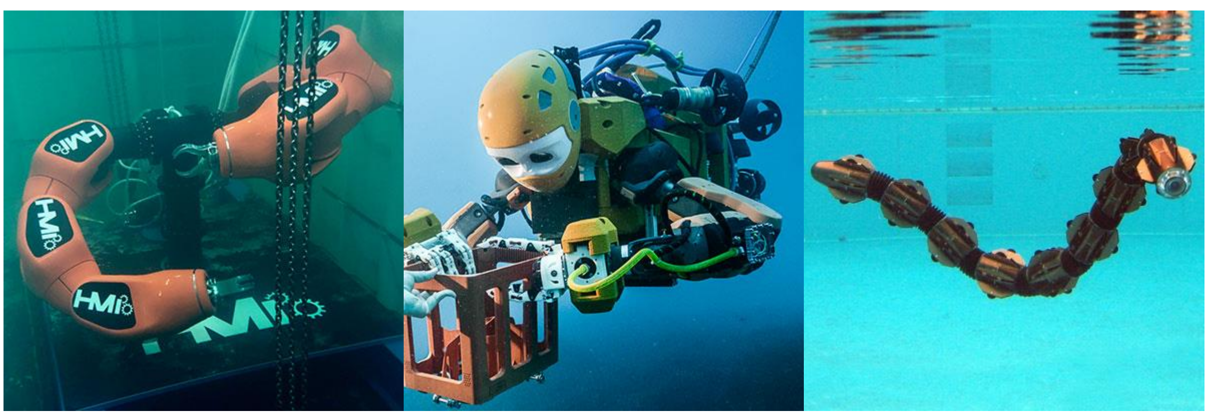

Figure I.16: Aquanaut, Ocean One, and ACM-R5H snakebot.

An essential part of robot development is the integration of other developing technologies; among them, wireless communication plays an important role in networked robots application. Such as: Robot-to-robot (R2R), robot-to-sensor/actuator/machine (R2S/R2A/R2M) and robot-to-cloud (R2C).

I.3. Wireless communication :

Wireless communication is the transfer of information between two or more points using an electromagnetic wave, not a physical electrical conductor, as a channel, and it’s a key part of our lives. Some commonly used Wireless Communication Systems in our day–to–day life are: Mobile Phones, GPS, Remote Controls, Bluetooth and Wi-Fi etc.

Figure I.17: Connection between multiple devices by wireless communication.

I.3.1. Electromagnetic wave :

Electromagnetic waves are synchronized oscillations of electric and magnetic fields. They are created due to periodic changes of the electric or magnetic field [4].

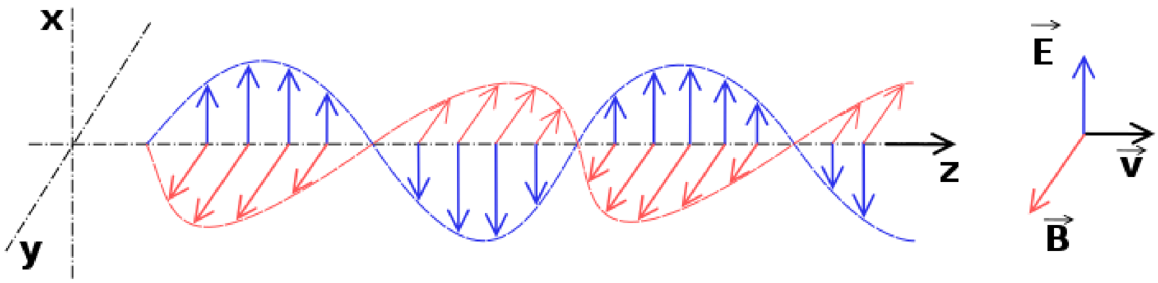

Figure I.18: A diagram showing the electric (blue) and magnetic (red) fields of an electromagnetic wave [5].

Electromagnetic waves include gamma rays (γ rays), X-rays, ultraviolet rays, visible light, infrared rays, microwave rays and radio waves; all of these waves form part of the electromagnetic spectrum. Electromagnetic waves (usually radio waves) are used in wireless communication to carry signals [6].

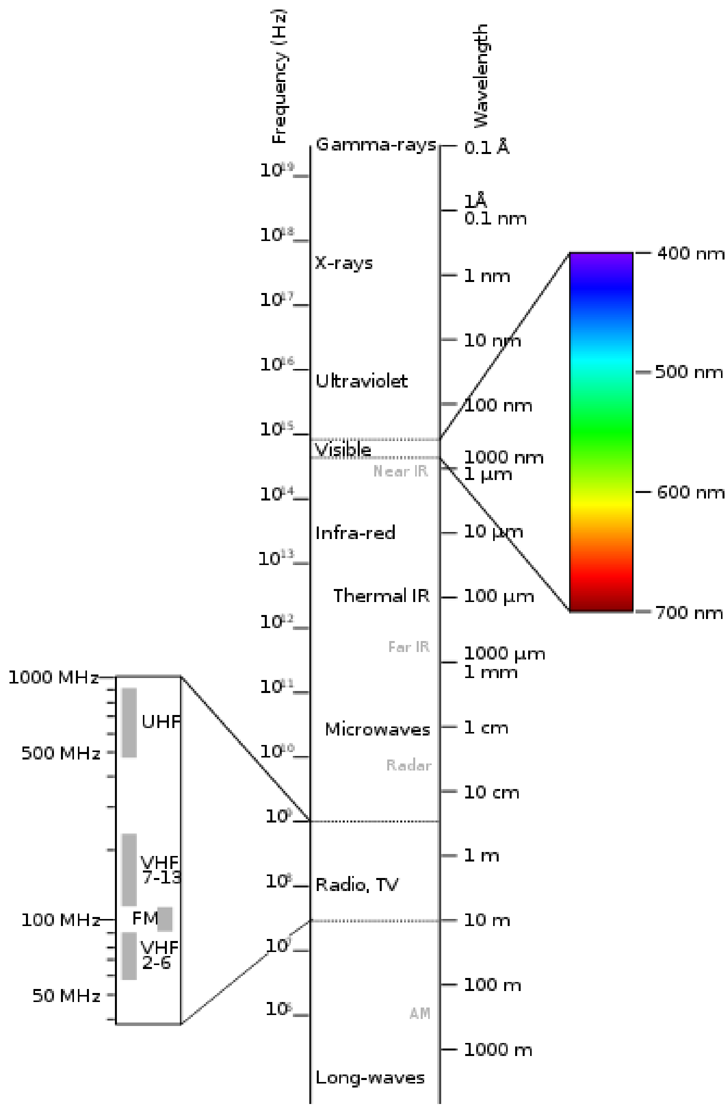

Figure I.19: The electromagnetic spectrum [7].

I.3.2. Wireless transmission modes :

The transmission mode describes the flow direction of the signal between two devices. And we define three modes of transmission: simplex, half duplex, and full duplex. The main difference between them is that a simplex is unidirectional whereas, in a half-duplex is two directional, but the channel is alternately used by one of the connected devices, a full duplex is bidirectional, and the channel is used by both the devices simultaneously.

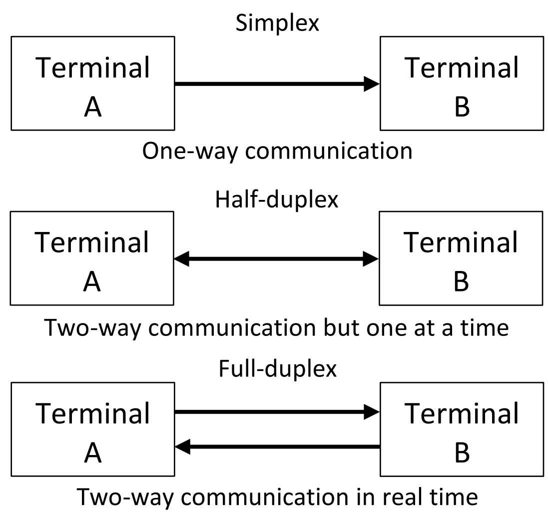

Figure I.20: Representation of simplex, half-duplex and full duplex.

I.3.3. Different wireless communication technologies :

Due to the need for a variety of communication services, different types of wireless communication systems are developed. Some of the important wireless communication systems available today are:

- **Radio and Television Broadcasting:** Considered to be the first wireless service to be broadcast. It is an example of a Simplex Communication System where the information is transmitted only in one direction and all the users receiving the same data [8].

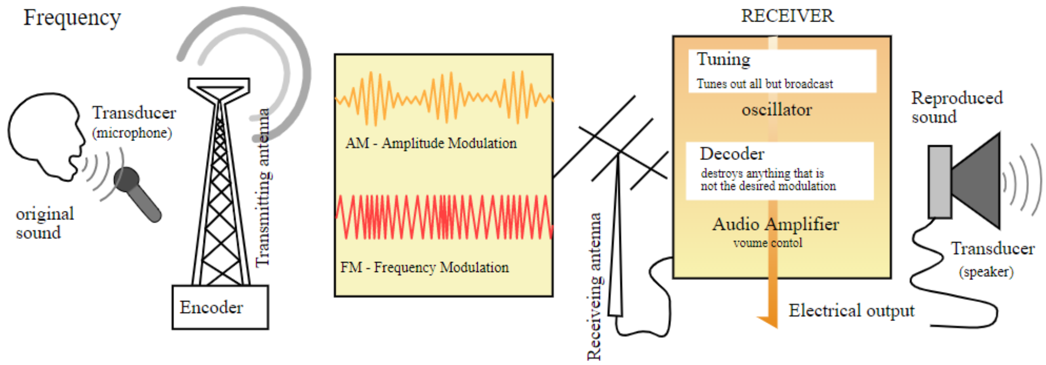

Figure I.21: Overview of radio broadcasting.

- **Satellite Communication:** Satellite Communication System is an important type of Wireless Communication. It provides worldwide coverage independent to population density. Satellite Communication Systems offer telecommunication (Satellite Phones), positioning and navigation (GPS), broadcasting, internet, etc. Other wireless services like mobile, television broadcasting and other radio systems are dependent on Satellite Communication Systems [8].

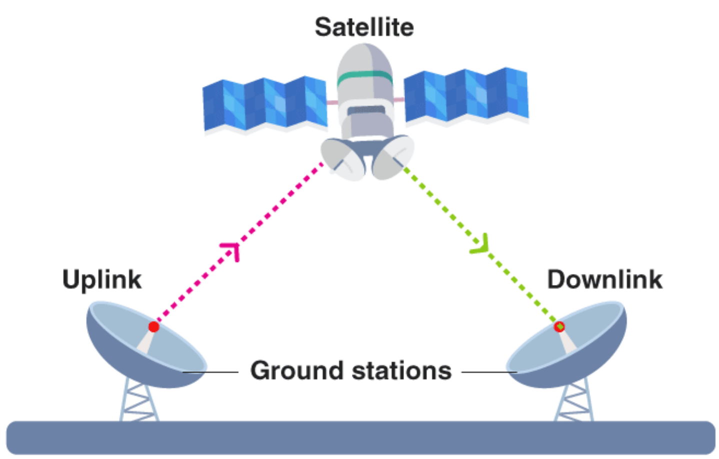

Figure I.22: How Satellite Communications Work.

- **Radar:** R.A.D.A.R. or RADAR, for Radio Detection and Ranging, is a detection system that uses radio waves to determine the distance (range), angle, or velocity of objects. A radar system consists of a transmitter producing electromagnetic waves in the radio or microwaves domain, a transmitting antenna, a receiving antenna and a processor to determine the properties of the object.

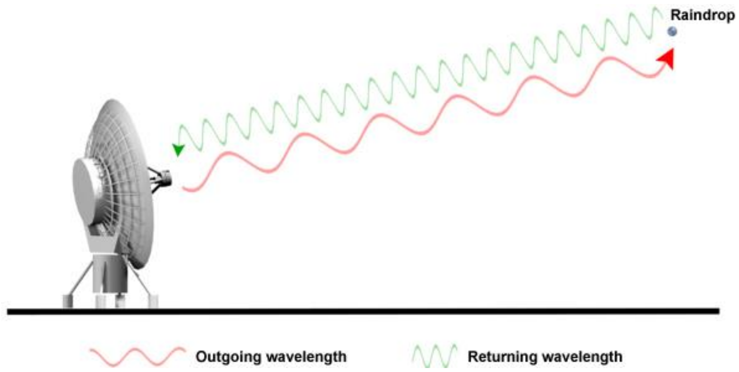

Figure I.23: How R.A.D.A.R Works [9].

- **Mobile Telephone System (Cellular Communication):** the most commonly used wireless communication system. Today's mobile phones are not limited to just making calls but are integrated with numerous other features like Bluetooth, Wi-Fi, GPS, and FM Radio. The latest generation of Mobile Communication Technology is 5G. Apart from increased data transfer rates, 5G Networks are also aimed at Internet of Things (IoT) related applications and future automobiles [8].

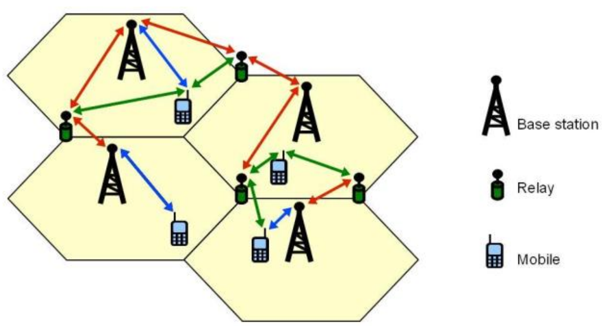

Figure I.24: How Cellular Communications work.

- **Global Positioning System (GPS):** GPS is a subcategory of satellite communication. GPS provides different wireless services like navigation, positioning, location, speed etc. with the help of dedicated GPS receivers and satellites [8].

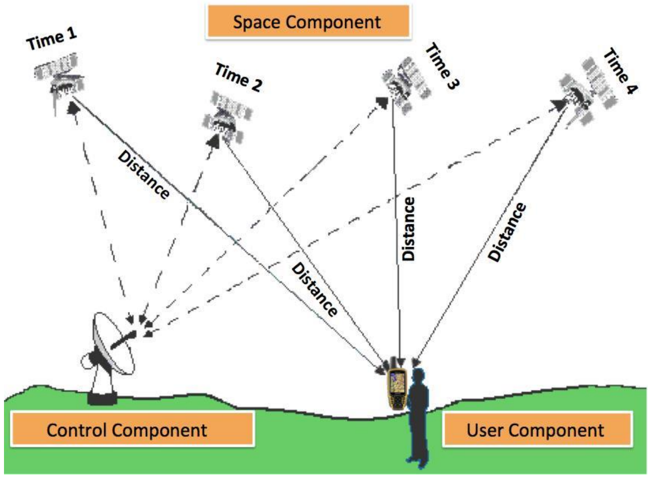

Figure I.25: Diagram of how the GPS determines geographic location.

- **Infrared Communication:** Infrared Communication uses the infrared waves of the Electromagnetic (EM) spectrum. Infrared (IR) Communication is used in remote controls of Televisions, cars, audio equipment etc. [8].

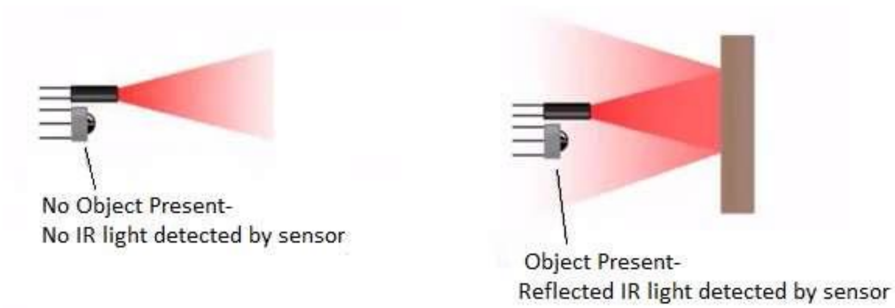

Figure I.26: Infrared Sensor working.

- **WLAN (Wi-Fi):** Wireless Local Area Network or WLAN (Wi-Fi) is an internet related wireless service. Using WLAN, different devices like laptops and mobile phones can connect to an access point (like a Wi-Fi Router) and access the internet. Wi-Fi is one of the widely used wireless networks, usually for internet access (but sometimes for data transfer within the Local Area Network). It is very difficult to imagine the modern World without Wi-Fi [8].

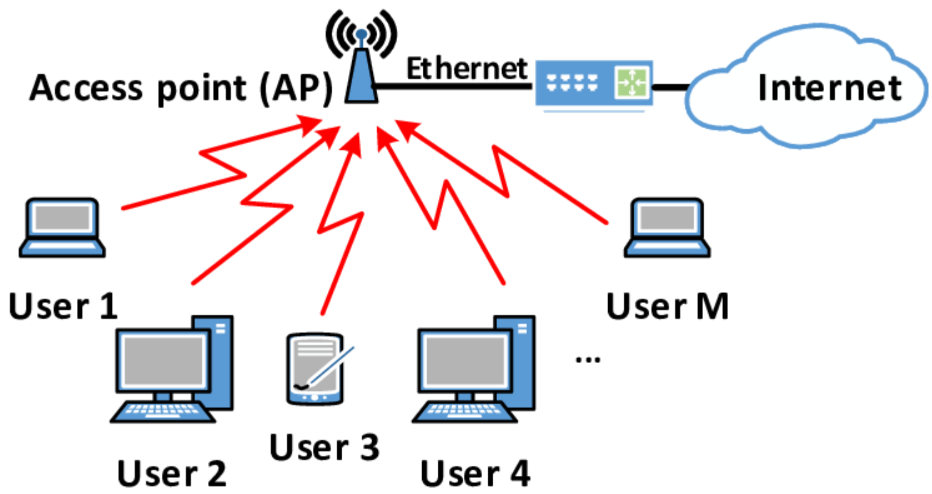

Figure I.27: Wireless Local Area Network (WLAN).

- **Bluetooth:** Bluetooth is a low range wireless communication system. It provides data, voice, and audio transmission with a transmission range of 10 meters. Almost all mobile phones, tablets, and laptops are equipped with Bluetooth devices. They can be connected to wireless Bluetooth receivers, audio equipment, cameras etc. [8].

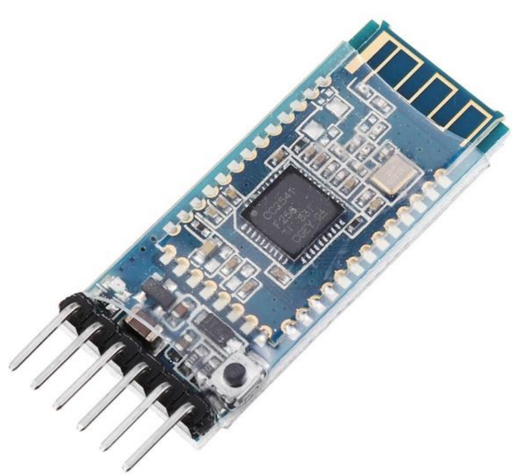

Figure I.28: Bluetooth chip used in an Arduino.

- **ZigBee:** ZigBee is a low-cost, low-power, wireless mesh network standard targeted at battery-powered devices in wireless control and monitoring applications. ZigBee delivers low-latency communication. Its chips are typically integrated with radios and with microcontrollers. ZigBee operates in the industrial, scientific and medical (ISM) radio bands: 2.4 GHz in most jurisdictions worldwide; though some devices also use 784 MHz in China, 868 MHz in Europe and 915 MHz in the US and Australia, however even those regions and countries still use 2.4 GHz for most commercial ZigBee devices for home use. Data rates vary from 20 Kbit/s (868 MHz band) to 250 Kbit/s (2.4 GHz band).

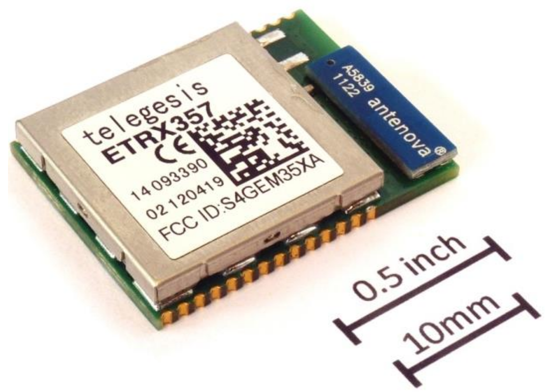

Figure I.29: ZigBee chip.

- **Paging:** paging was a major success before the widespread use of mobile phones. Paging provides information in the form of messages and it is a simplex system [8].
- **Radio Frequency Identification (RFID):** RFID tags, or simply "tags", are small transponders that respond to queries from a reader by wirelessly transmitting a serial number or similar identifier. They are heavily used to track items in production environments and to label items in supermarkets [10].

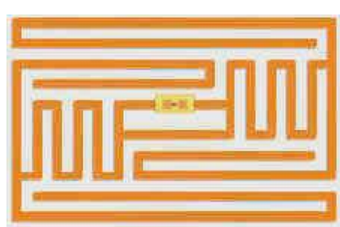

Figure I.30: A passive RFID tag.

I.3.4. The advantages and drawbacks of wireless communication :

I.3.4.1. The advantages of wireless communication :

- Mobility is the main advantage of the wireless communication system. It offers the freedom to move around while remaining connected to the network.
- The cost of installing wires, cables and other infrastructure is eliminated in wireless communication and therefore lowers the overall cost of the system as compared to a wired communication system.
- Setting up and installing the wireless communication network equipment and infrastructure is very easy as we don't have to worry about the hassle of cables.
- Since there are no cables and wires involved in wireless communication, there is no risk of communication failure due to damage to these cables which can be caused by environmental conditions.
- Fewer cables to deploy, and therefore a reduction in cable investment as well as in the workload during installation.
- In accidents due to fires, floods or other disasters, the loss of communication infrastructure may be minimal.

I.3.4.2. The drawbacks of wireless communication :

- Speeds often lower than that of a wired communication system.
- The distance that prevents a transmitter from detecting a collision at the same time.
- The inevitability of interference. Radio transmissions are not isolated and the number of available channels is limited, which forces sharing. Interference can be of different types (transmitters working at frequencies that are too close, environmental noise, attenuation, reflection, and multipath phenomena due to the environment, etc.).
- Energy limitation by battery autonomy, Transmitting or receiving data consumes power.
- Weak security, it is easy to passively spy on a radio channel.

- These drawbacks of most wireless communication systems can be solved using **Visible Light Communication (VLC) technology,** which is a subset of optical wireless communication technologies.

I.4. Conclusion :

In this chapter, we define what is a robot and the origin of the word. (Originated from the Slavic word Robota that means labour or work). We categorized them by their type of movements, with three major groups (Manipulator, Wheeled and Legged) and other minor groups (Flying, Swarm, Modular, Micro, Nano and Soft/Elastic). We also remark their use in many fields such as Industrial, Consumer, Medical, Exoskeletons, Disaster Response, Drones, Military, Security, Self-Driving Cars, Education, Telepresence, Underwater, Research and Humanoids. Next, we define wireless communications and electromagnetic waves. We characterize three Wireless transmission modes (simplex, half-duplex, and full-duplex) and the plethora of wireless technologies (Radio, GPS, Bluetooth, Wi-Fi, ZigBee etc…). Finally, we list their advantages and drawbacks.

Chapter II

VISIBLE LIGHT COMMUNICATION

CHAPTER II: VISIBLE LIGHT COMMUNICATION

II.1. Introduction:

During the last decade, the exponential growth of mobile devices and wireless services created a huge demand for radio frequency-based technologies. Meanwhile, the lighting industry has been revolutionized due to the popularization of LED light bulbs, which are more economical and efficient. In that context, Visible Light Communication (VLC) is a technology based on LEDs that offers a free spectrum and high data rate, which can potentially serve as a complementary technology to the current radio frequency standards [11].

II.2. Visible Light Communication (VLC) technology :

Visible Light Communication (VLC) systems employ visible light for communication that occupies the spectrum from 380 nm to 750 nm, corresponding to a frequency spectrum of 430 THz to 790 THz. The low bandwidth problem in RF communication is resolved in VLC because of the availability of a large bandwidth [12].

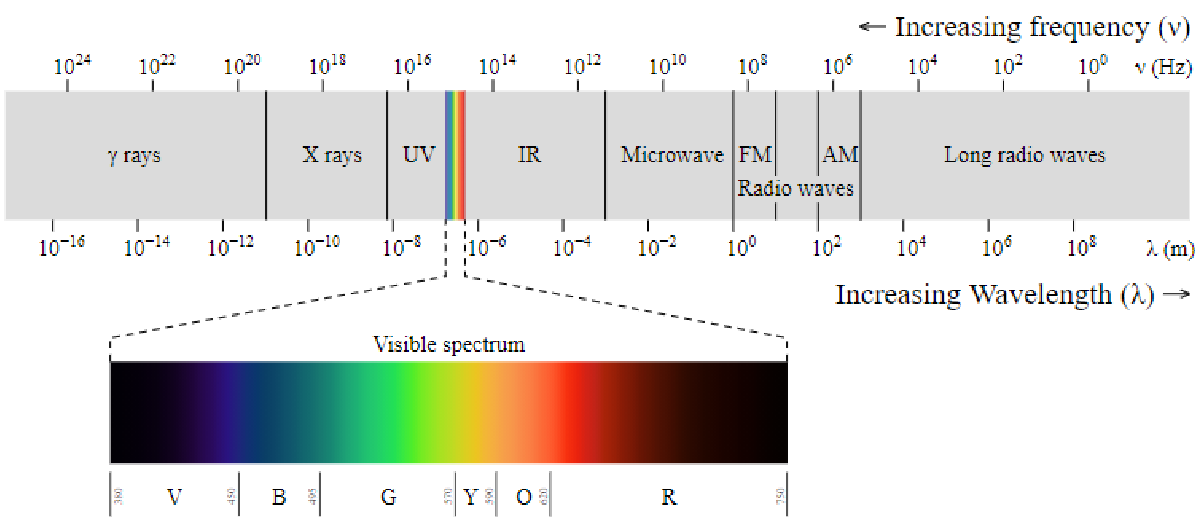

Figure II.1: Range of electromagnetic waves and the placement of the visible spectrum [13].

II.3. The architecture of a VLC communication system :

Visible Light Communication uses light to transmit information. In addition, the idea behind VLC applications is to provide lighting and communication at the same time. Thus, VLC systems will always have components to transmit and receive light. In the vast majority of literature available on this subject, LEDs are used as transmitters. These LEDs are used to modulate the intensity of light in order to send data. On the receiver side, photo-sensors are responsible for capturing this light directly (Direct Detection), converting it into a data stream [11]. In VLC, it is important that lighting illumination brightness is not affected by the manipulation of light while transmitting information; hence the type of LED has an impact on the performance of a VLC system.

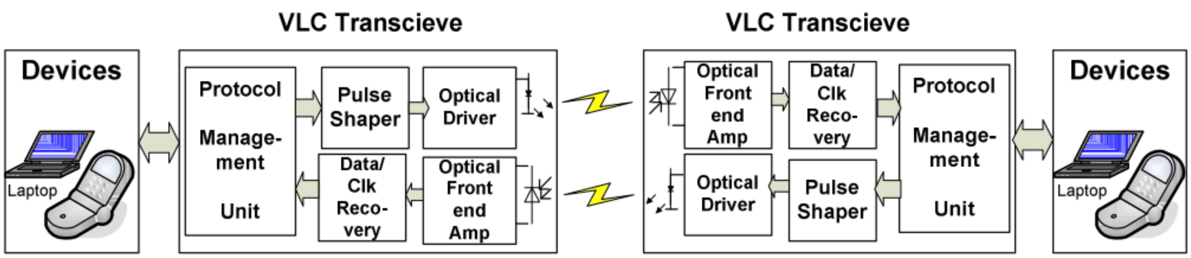

Figure II.2: Architecture of a full-duplex VLC communication system. [14]

II.3.1. The Transmitter :

LEDs and Lasers are used as transition sources for VLC. The LED should be used when both communication and illumination have to be performed using a single device. The white light based on LEDs and wavelength converters is one of the attractive candidates for being used as the VLC source. The most commonly used method for the generation of white light using LEDs is trichromatic (red, green, and blue). The advantage of using an RGB LED for white light generation is the high bandwidth and thus, high data rates. The downside of the RGB LED is their high complexity and difficulty in modulation. Different methods have been adopted for the characterization of the optical wireless channel. The appropriate LED is selected based on the channel model [12].

II.3.1.1. LED :

Due to its characteristics such as price, LED light bulbs have become the main medium used for Visible Light Communication. In addition, LED light bulbs became increasingly popular, integrating various environments where it would be advantageous to use light as a form of communication [11].

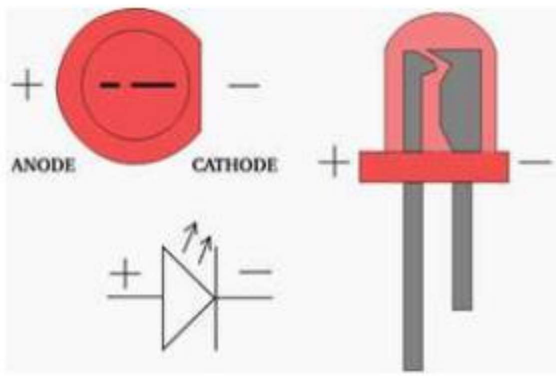

Figure II.3: Basic representation of a standard LED.

LEDs have the ability to turn on and off in a nanosecond. When we turn it on and off thousands of times per second, we can transmit information by creating a frequency. If an LED is on, it transmits a 1 bit, if it is off, a 0 bit. The frequency changes are so rapid that they are not visible to the human eye, which does not perceive the flicker and sees only constant light. In terms of speed, this corresponds to 1 Gbps against a speed of around 100 Mbps for Wi-Fi.

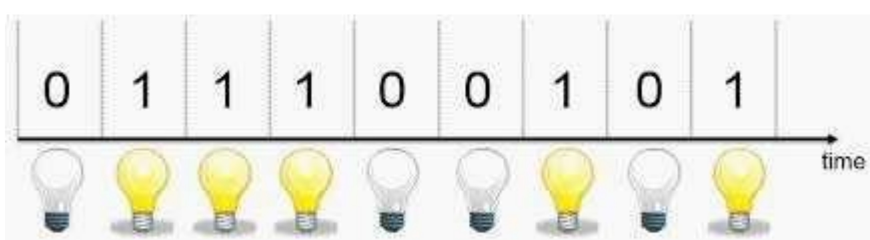

Figure II.4: Basic representation of data transfer using an LED.

- **Phosphor Converted LEDs (pc-LEDs):** The pc-LEDs are widely used, and have low complexity and low cost. They consist of a blue LED chip coated with a phosphor layer, whose function is to convert part of the blue light to green, yellow, and red; while a fraction of the blue light is emitted, resulting in white light. This type of LED has a limited band due to the slow response of phosphorus [11].

- **Multi-chip LEDs:** The structure of this type of LED consists of three or more chips that emit lights of different colours. Normally, the different chips emit the RGB colours in order to produce white light. The great advantage of this type of LED is the ability to control the colours that are emitted, through the intensity of each chip. It is important to note that modulation was created especially for this type of LED, called Colour-Shift Keying [11].

- **Organic LEDs (OLEDs):** This type of LED consists of a series of thin organic layers between two conductors. Light is emitted when an electric current is applied. They are widely used in displays of smartphones [11].

- **μ-LEDs:** The μ - LEDs are usually coupled in displays, enabling parallel communication of high density, reaching very high speeds [11].

II.3.2. The receiver :

The VLC receiver is used to extract the data from the modulated light beam; it transforms the light into an electrical signal which will be decoded by the built-in decoder. The performance of the VLC system is influenced by the performance of the receiver, the detected light is not only that of the transmitter but other light sources (natural or artificial), which causes strong interference. The performance of the VLC receiver can be improved by using an optical filter that removes unwanted spectral components. The most commonly used light sensor is a photodiode due to its high sensitivity. Solar cells can be used as a simultaneous receiver of solar power and visible light communication (VLC) signals. Besides, the modulated VLC optical signal can be converted into an electrical signal without having to supply external power [26].

II.3.2.1. Photodiode

A photodiode converts incident light into current. It works on the principle called photo-conduction, whereas LED works on the principle of electro-luminance. The photodiode is a type of photo-detector that converts the light to either current or voltage [15].

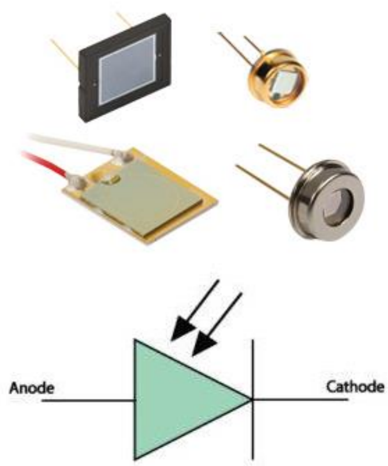

Figure II.5: Photodiode icon and examples.

II.3.3. Transmission Channel :

Most wireless optical systems are direct sensing, Intensity Modulation / Direct Detection systems. In an IM / DD system, information is not carried by frequency or phase but by the intensity of the optical signal. The conversion between the electrical signal and the optical intensity x (t) is carried out by a light emitting diode (LED). The optical wave is then propagated over the wireless optical channel. In reception, it is necessary to carry out the reverse conversion making it possible to return to the electrical domain. This function is performed by the photodiode. The photodiode performs direct detection i.e. it produces a photo-current y (t) proportional to the received optical intensity. The main objective of the receiver is to determine the information contained in x (t) from the received signal y (t) [17].

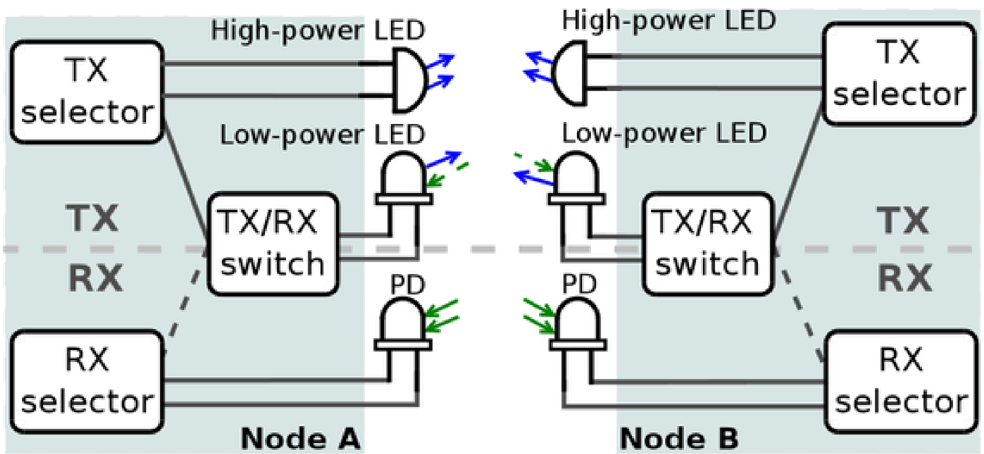

Figure II.6: Open-VLC 1.0 transceivers [18].

II.4. Classification of optical links :

There are many criteria for classifying the different types of optical links. As the presence of a direct link between the transmitter and the receiver (LOS, NLOS), the opening angle of the transmitter and the field of view (FOV) of the receiver.

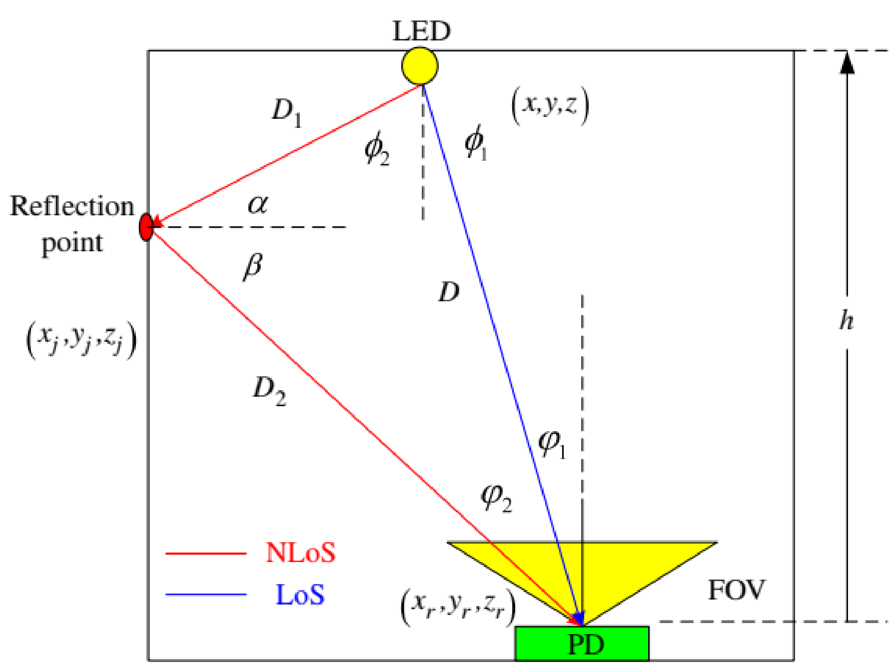

Figure II.7: Geometry of LoS and NLoS channels [19].

II.4.1. LOS :

The LOS optical link is characterized by the presence of a direct link between the transmitter and the optical receiver. The presence of a forward link increases the optical power received by the photodiode while reducing the impact of symbol interference. Thus, LOS links offer excellent performance. However, these links are extremely sensitive to blocking phenomena. A locating device is required to maintain alignment between the transmitter and receiver. And for this there are several types of tracking, depending on the alignment of the transmitter and/or receiver. Full Tracked (FT) LOS links, this link has very low attenuation to achieve a high signal to noise ratio (SNR). For Half Tracked (HT) LOS links, only the transmitter maintains alignment with the receiver. The LOS HT link relaxes the constraints on the receiver by eliminating the tracking system. This solution is particularly suitable in multi-user cases (with several transmitters). Untracked LOS links (NT), the orientations of the transmitter and receiver are fixed and vertical regardless of the position of the transmitter [17].

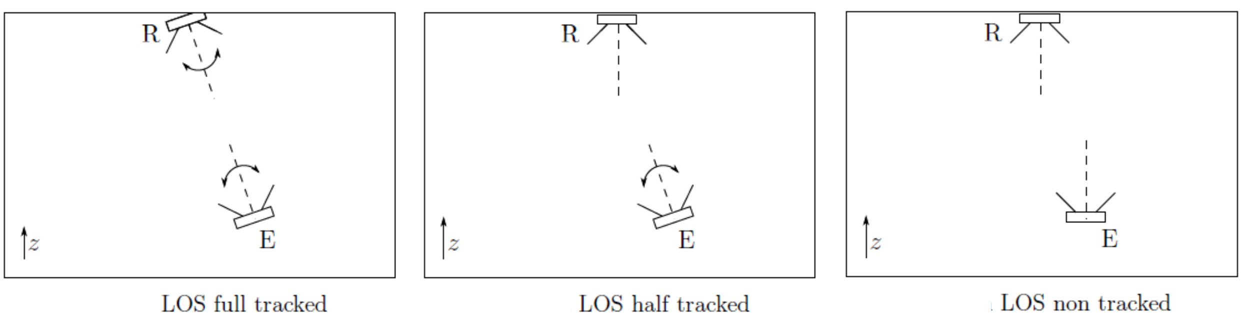

Figure II.8: Types of LOS optical links.

II.4.2. NLOS :

Diffuse optical links establish a link between the transmitter and the receiver via at least one reflection on a wall of the indoor environment and use high opening angles for the transmitter and a large FOV for the receiver. This topology is more robust against blocking phenomena than LOS links. These links provide a high degree of mobility at the cost of greater attenuation (which decreases the optical power received) [17].

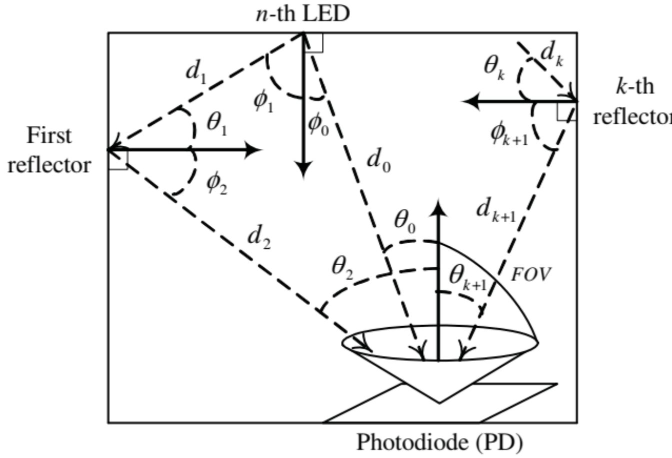

Figure II.9: NLOS optical link [18].

II.5. Modulations associated with VLC communications :

There is several modulation techniques associated with wireless optical communications:

II.5.1. OOK modulation :

OOK is a simple type of Amplitude Shift Keying (ASK) modulation, in which the digital data is represented by the presence or absence of the source signal. In other words, bits 0 and 1 are directly related to the amplitude of the source signal. The concept of OOK is adaptable to VLC technology, because it achieves communication by modulating light. A simple and easy way to modulate the light consists of turning the LED on and off, which in turn will be received and demodulated as 1 and 0, respectively. Some of the drawbacks of OOK are related to the flickering and limited data rate [11].

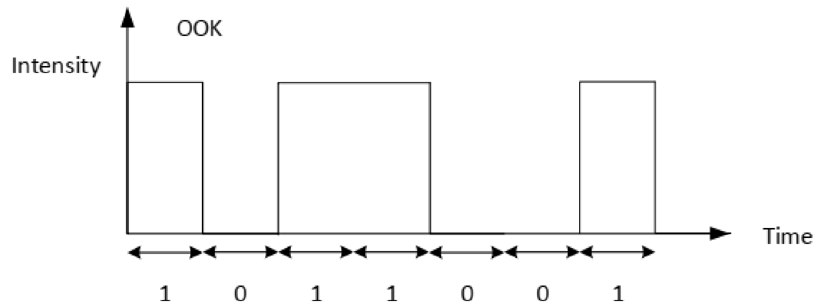

Figure II.10: Basic principle of OOK modulation [21].

II.5.2. VPPM modulation :

Another technique widely used in VLC systems is VPPM. This method uses two different modulation types: Pulse Position Modulation (PPM) and Pulse Width Modulation (PWM). In Pulse Position Modulation, the width and amplitude of the pulse are constant. However, the digital value of the signal is given by the position in which the pulse is located, according to the time. One of the advantages of PPM is the ease of implementation. However, only one pulse is emitted for each symbol, which limits the data rate. Pulse Width Modulation works based on the length of the signal, which determines the width according to time. In Pulse Width Modulation, the length of the pulse determines its value, given a time period [11].

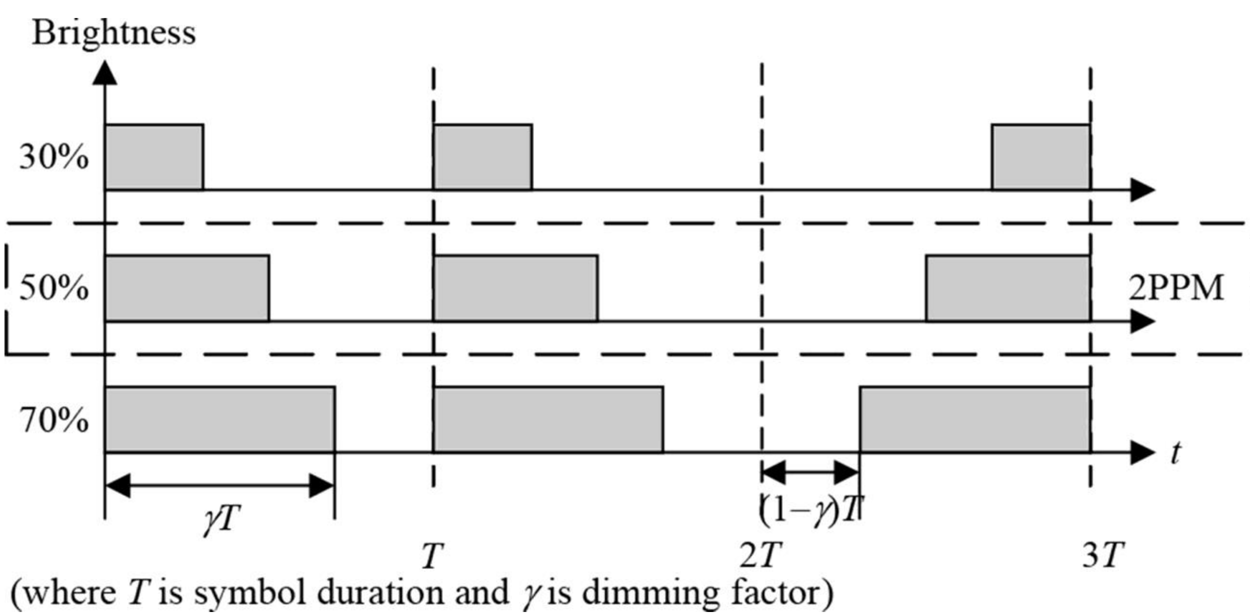

Figure II.11: Basic principle of VPPM modulation [36].

II.5.3. OFDM modulation :

(Orthogonal frequency division multiplexing) is a parallel data transmission scheme in which high data rates can be achieved by transmitting orthogonal subcarriers. OFDM systems do not require complex channel equalizers, the time varying channel can easily be estimated using frequency-domain channel estimation, and adaptive modulation can be applied based on the uplink/downlink requested data rates and quality of service. Also, the possibility to combine OFDM with any multiple access schemes makes it an excellent preference for visible light communication application [21].

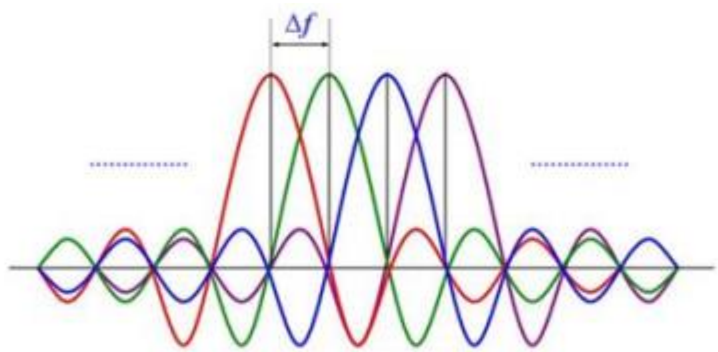

Figure II.12: Schematic of OFDM Modulation Scheme [21].

II.5.4. CSK modulation :

In CSK, the signal is modulated according to the intensity of the three colours that make up a type of LED known as multi-chip. This LED is composed of three or more LED chips, usually red, green, and blue. These three colours, together, are used to generate white light. The OOK and VPPM modulations have low data rates, There are seven wavelength bands available, from which the RGB source can be chosen. This origin determines the vertex of a triangle in which the constellation points of the CSK symbols are. The colour point of each symbol is produced by modulating the intensity of the RGB chips [11].

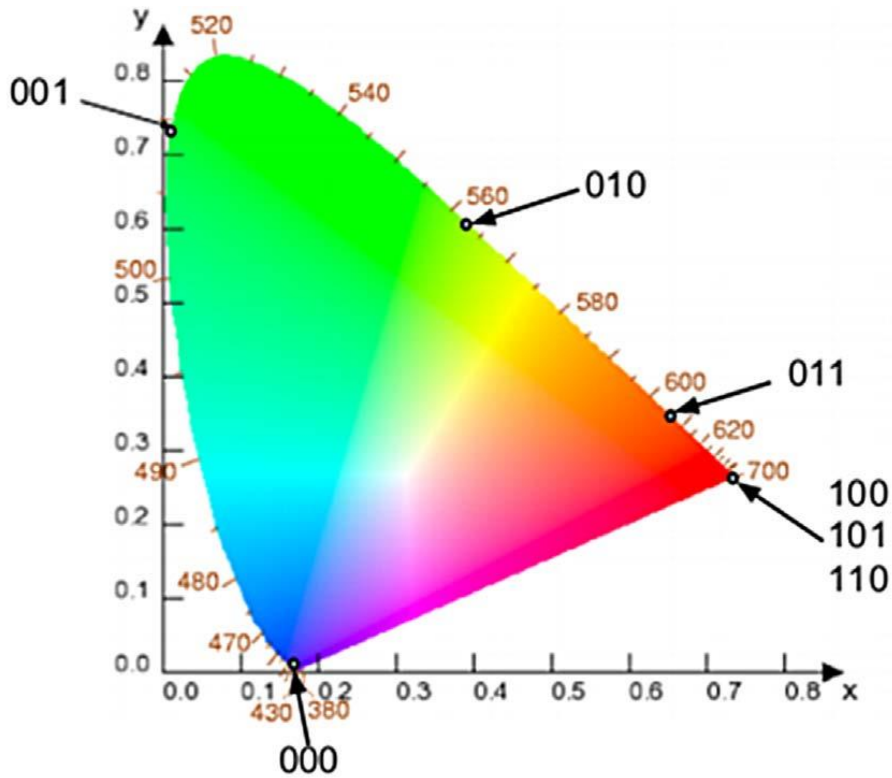

Figure II.13: Chromaticity diagram [22].

II.6. Noise and interference :

In a Wi-Fi network, devices that transmit on the same frequency can interfere with each other. When light is used as a communication medium, natural light becomes a source of interference in communication, especially in the case of outdoor applications. In addition to natural light, artificial lights also interfere with communication, and may even saturate the receiver. Another factor that causes interference at the receiver is the multi-path problem. Unlike wired communication, where the transmission of the signal is generally restricted to the wire. In Visible Light Communication, the signal can spread in the environment in the direction of the LED lamps, but also including refraction and reflection, reaching the receiver more than once [11].

For the artificial light sources, three distinct classes of interfering devices showing similar characteristics are identified: incandescent, and two types of fluorescent lamps. To solve the interference and noise problem, we use an optical filter (custom lens).

This is a common approach, which can be found in several works where VLC systems are implemented [24]. Signal amplifiers are also used to mitigate noise [25].

Photodiodes tend to be extremely sensitive because they can capture light in the visible spectrum, infrared and ultraviolet waves. We can also use an LED as a light sensor; however, they can only pick up waves close to the ones they transmit, serving as a filter for natural lights [11].

In general, interference and noise are unavoidable for VLC systems, due to natural and artificial light.

II.7. Applications of VLC communications :

II.7.1. Indoor :

- **Mobile connectivity (Li-Fi):** In 2011, Harald Haas was the first to coin the term Light Fidelity (Li-Fi). Li-Fi is a high speed bi-directional fully connected, visible light wireless communication system and is analogous to Wi-Fi, which uses radio frequency for communication. The Wi-Fi signals have the problem of interference with other RF signals such as its interference with pilot navigational equipment signals in aircraft. Therefore, in the areas that are sensitive to electromagnetic radiation (such as aircraft) Li-Fi can be a better solution. A Li-Fi also lends support to the Internet of Things (IoT). A speed up to 10Gbits/s is obtained using Li-Fi, which is 250 times more than the speed of super-fast broadband [12].

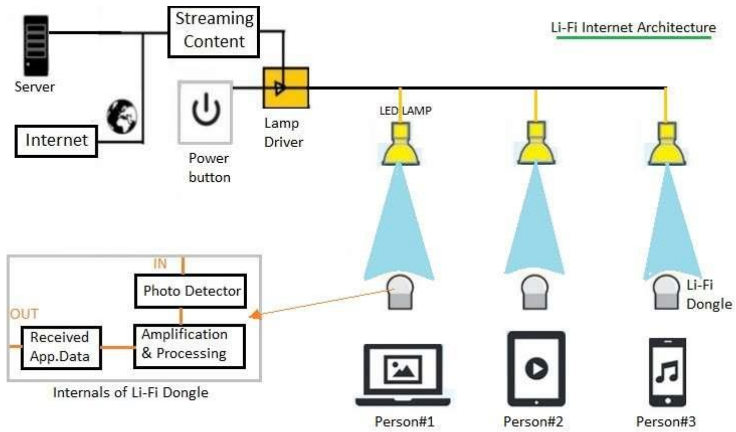

Figure II.14: Li-Fi internet networking.

- **Hospitals and Healthcare:** In hospitals, electromagnetic wave sensitive areas (such as MRI scanners) are likely to switch to VLC because it will not interfere with radio waves of the other machines. A robot called HOSPI was proposed that was used for transportation in hospitals. The control system enhancements in HOSPI were made using VLC installed in a building and navigational sensors of the robot [12].

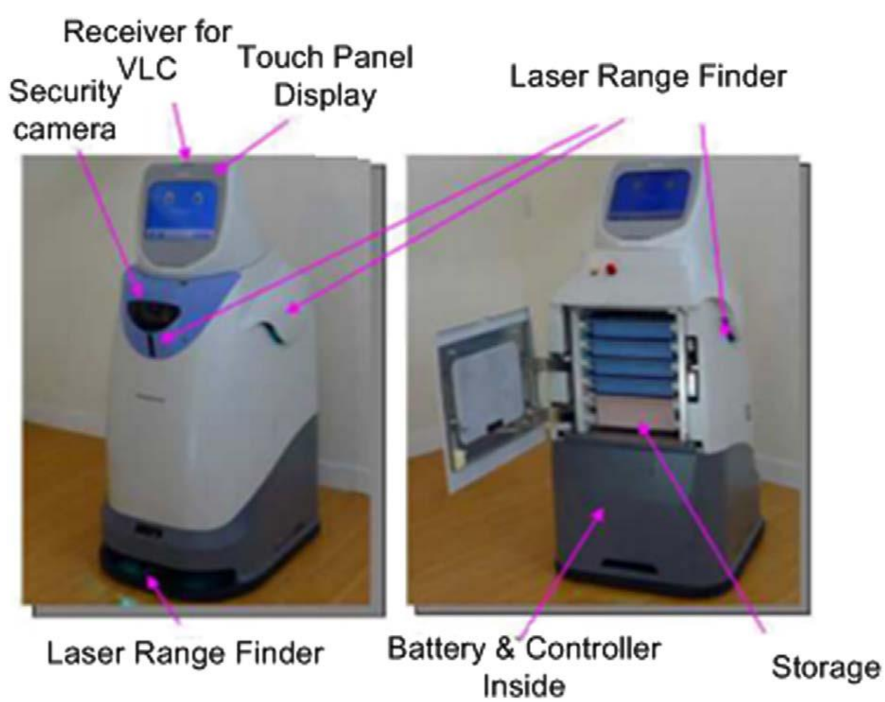

Figure II.15: HOSPI robot [12].

- **Wi-Fi Spectrum Relief:** Wi-Fi cannot meet the growing demand for wireless data. VLC can provide higher data rates than Wi-Fi. This can be done at a low cost since radio frequency (RF) components and antenna systems are eliminated.

- **Aircraft:** Radio waves are not desirable in passenger compartments of aircraft. LEDs are already being used for lighting and can also be used in place of wires to provide multimedia services. This reduces the costs and weight of building an aircraft.

- **Positioning:** To perform a high precision positioning using VLC, a receiver must pick up the signals from the LEDs in a room and calculate the distance from them, using various algorithms to establish the exact position of the receiver. One of these techniques is based on RSS (received signal strength), which is commonly used in radio frequency systems. However, extending the distance between the transmitters and the receiver reduces the signal strength. Obstacles may interfere with the RSS as they block or reflect the waves, thus limiting the accuracy of this method. Another widely used method is performed by calculating the Time of Arrival (TOA). However, this technique requires the transmission of rigidly synchronized signals between transmitter and receiver, which may require more expensive features. Finally, there is a method that considers the Angle of Arrival (AOA). This technique is not common in radio frequency systems since it requires a direct Line of Sight (LOS). However VLC systems require LOS for communication so AOA methods are also feasible. [11].

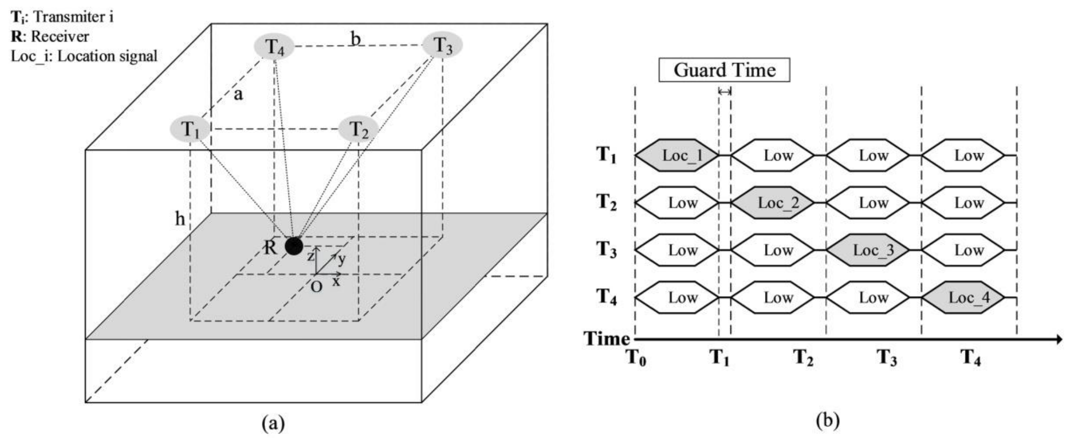

Figure II.16: Basic diagram on indoor positioning using VLC.

II.7.2. Outdoor :

- **Vehicles and Transportation:** The widespread use of LEDs in traffic applications and the growing interest in intelligent transport systems (ITS) presents a number of opportunities for VLC applications. While previous studies have documented the effectiveness of vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication using radio technology in terms of improving automotive safety. Since VLC links are visible, installation of roadside equipment is much easier. Additionally, previously installed facilities, such as LED traffic lights or LED signboards, can be used. Furthermore, since the transmitters are designed for lighting purposes (and thus generally has high radiation power); the signal-to-noise ratio (SNR) is high for VLC. The visible light spectrum is not regulated globally, and its bandwidth extends from 400 up to 790 THz. The large (390 THz) available bandwidth provides attractive opportunities for ITS applications. Furthermore, V2I and V2V communications using radio technology can be used simultaneously with VLC, with each using a different spectrum. VLC provides an additional feature if the receiver incorporates an image sensor or a camera. Specifically, by using an image or video processing to detect and recognize moving vehicles, safety applications can be integrated. For example, methods of enhancing driving safety, adaptive cruise control, collision warning, pedestrian detection, and providing range estimations for nearby vehicles are potential candidates for incorporation into VLC systems [27].

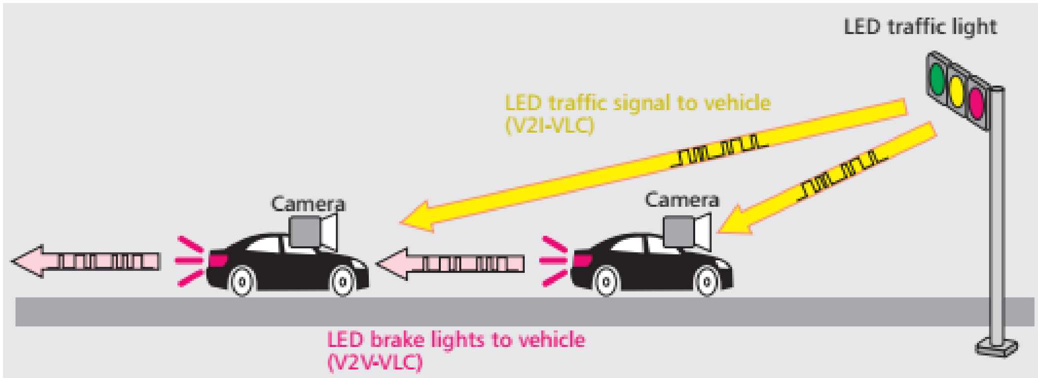

Figure II.17: V2V and I2V communication [27].

- **Underwater Communication:** RF waves do not travel well in seawater because of its good conductivity. Therefore, VLC communication should be used in underwater communication networks. The Untethered Remotely Operated Vehicle (UTROV) is another application of the VLC in underwater communication. The different jobs that can be performed using UTROV include observatory maintenance of the oceans and deployment opportunity from the ships [12].

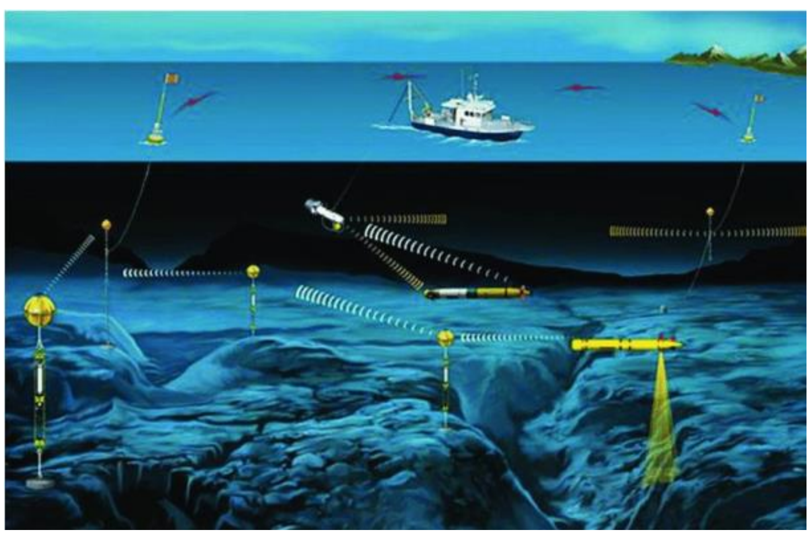

Figure II.18: VLC Underwater Communication [12].

II.8. The advantages and drawbacks of VLC technology :

II.8.1. The advantages of VLC technology :

- The bandwidth available for this technology extends over several GHz and can be used without restriction.
- Due to the values of the wavelengths (≈nm) compared to the dimensions of the receivers (≈cm) this technology is not subject to multipath fading.
- The use of light waves makes it possible to overcome the problems of disturbance that arise in the RF field, specifically in environments such as airplanes, trains or even hospitals.
- This technology makes it possible to combine lighting and communication functions and therefore relies on transmitters scattered throughout the environment. Each lamp is indeed capable of transmitting provided that the bulb is LED. Thus, the needs in terms of installation and maintenance have been reduced.

II.8.2. The drawbacks of VLC technology :

- The fact that the light cannot pass through the opaque material poses serious blocking problems, if the receiver is blocked by an object, no light signal can reach it, breaking its link with the transmitted signal.
- There are some cases in which visible light can also see a physiological impact. (It is possible to see flickering effects when sending information). This results in visual discomfort and sometimes even nausea. However, there are many methods of modulating the signal to solve this problem.
- It can be noted that this technology can be disturbed by many sources of ambient optical noise such as the sun, incandescent lamps or any other light source.
- Limited transmission range (3-5,5m), when standard commercially available LEDs are used.
- It requires both source and receiver to be in direct Line Of Sight LOS.

II.9. Conclusion :

In this chapter we defined what VLC is and its work principle; we also studied its architecture, the most suitable LEDs to use, classification of optical links, how to reduce noise and interference from other light sources and its current potential uses. It offers a great opportunity to complement the current wireless infrastructure, as it offers increased performance especially in environments such as offices and homes, where distance is short. In addition to that, indoor positioning, underwater and vehicular communication systems are some examples of applications that can utilize visible light. In summary, VLC is a broad study area that also attracts the interest of researchers. Even so, it still demands more exploration, which should happen in the next years, considering the popularization of the area and the increasing implementation of ideas such as the Internet of Things and Smart Lighting.

Chapter III

REALIZATION OF A VLC INTEGRATED 4WD ROBOT CAR

III.1. Introduction :

In this chapter, we will realize and study the performance of a 4-wheel drive robot using a basic VLC based wireless communication system. First, we introduce the hardware, equipment, and programming languages. Next, we describe the robot-VLC system produced as well as the program used. Finally, we present the results of the studied system and its performance.

III.2. Equipment and programs :

In this part we present the hardware, the equipment and the programming languages used.

III.2.1. Software :

III.2.1.1. Arduino IDE :

The Arduino Integrated Development Environment (IDE) is a cross-platform application (for Windows, macOS, Linux) that is written in functions from C and C++. It is used to write and upload programs to Arduino compatible boards.

Figure III.1: Arduino IDE program icon.

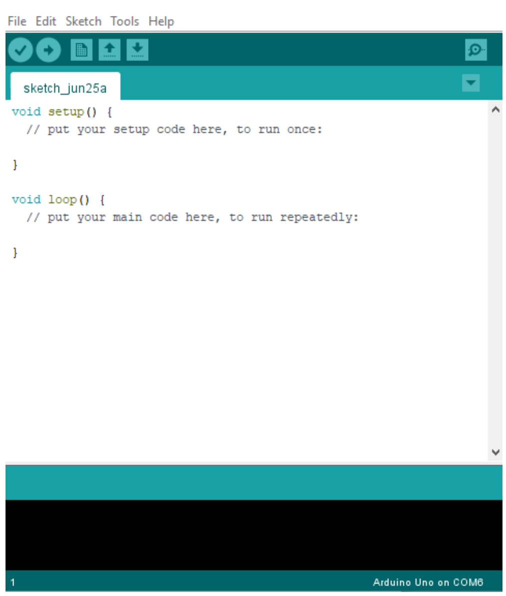

Figure III.2: Arduino IDE interface.

III.2.2. Hardware :

III.2.2.1. Microcontroller (Arduino board) :

- **Arduino Uno:** Arduino/Genuino Uno is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started [28].

Figure III.3: Arduino UNO and Genuino UNO [28].

- **Arduino Mega:** The Mega 2560 is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started [29].

Figure III.4: Arduino MEGA 2560 & Genuino MEGA 2560 [29].

III.2.2.2. LED :

An LED or a Light-Emitting Diode is a semiconductor device that emits light due to the Electroluminescence effect. An LED is a PN Junction Diode, which emits light when forward biased. [30], the used LED is the module STARLED_1W_WW.

Figure III.5: A 1W High-Power LED.

III.2.2.3. Photodiode :

BPW34 is a PIN photodiode with high speed and high radiant sensitivity in a miniature, flat, top view, clear plastic package. It is sensitive to visible and near infrared radiation [31].

Figure III.6: A BPW34 Photodiode.

III.2.2.4. Arduino Robot Car Chassis Kit :

We use a standard kit used in many Robot car projects and it’s suitable for our work. It has the required frame and 4 DC gear motors.

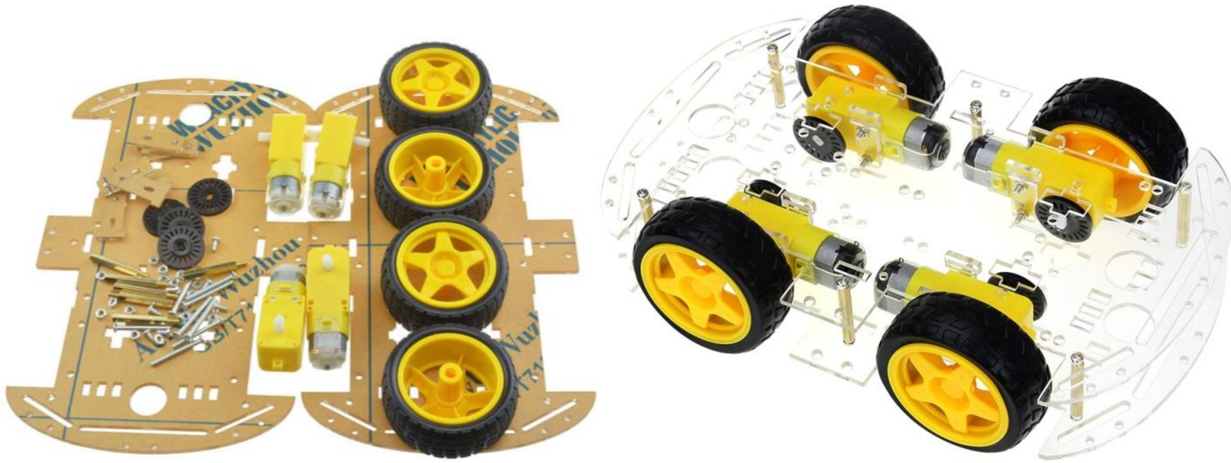

Figure III.7: 4WD Arduino Robot Car Chassis Kit (disassembled and assembled).

III.2.2.5. Motor Controller :

L298N Dual H-Bridge Motor Driver, This dual bidirectional motor driver is based on the very popular L298 Dual H-Bridge Motor Driver Integrated Circuit. The circuit allows us to easily and independently control two motors of up to 2A each in both directions. It is ideal for robotic applications and well suited for connection to a microcontroller, requiring just a couple of control lines per motor. It can also be interfaced with simple manual switches, TTL logic gates, relays, etc. This board is equipped with power LED indicators, an on-board +5V regulator and protection diodes.

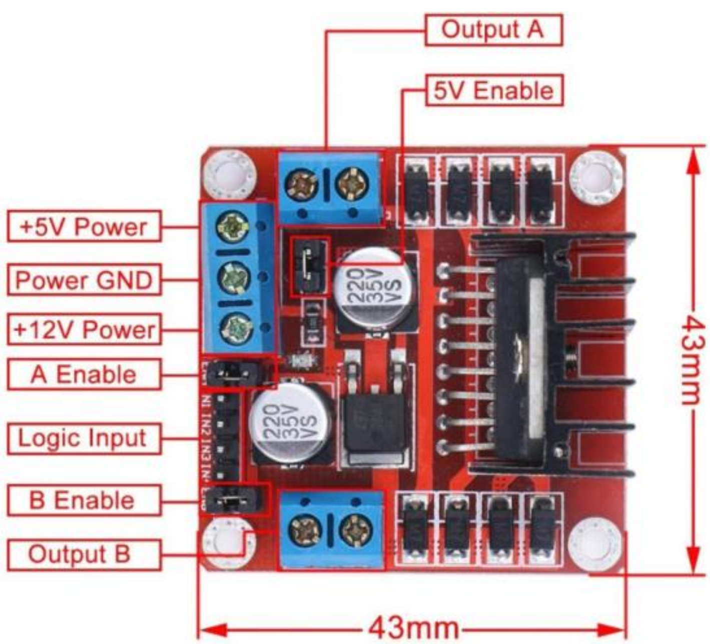

Figure III.8: L298N Dual H-Bridge Motor Driver.

III.2.2.6. Bluetooth module :

HC-05 Bluetooth Module is an easy-to-use Bluetooth SPP (Serial Port Protocol) module, designed for a transparent wireless serial connection setup. Its communication is via serial communication, which makes an easy way to interface with the controller or PC. HC-05 Bluetooth module provides switching mode between master and slave mode, which means it is able to use neither receiving nor transmitting data.

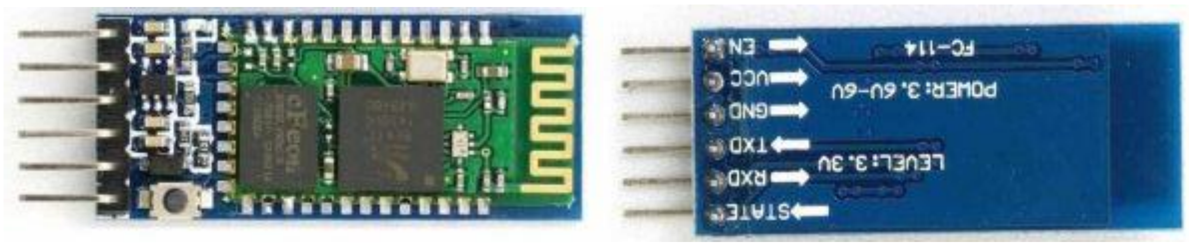

Figure III.9: HC-05 Bluetooth Module.

III.2.3. Assembly :

III.2.3.1. Bluetooth car :

A Bluetooth car is the most commonly constructed robot due to its simplicity and versatility, making it the most suitable robot for our goal. First, we assemble the frame with the motor and wheels, and then we wire the circuit as follows:

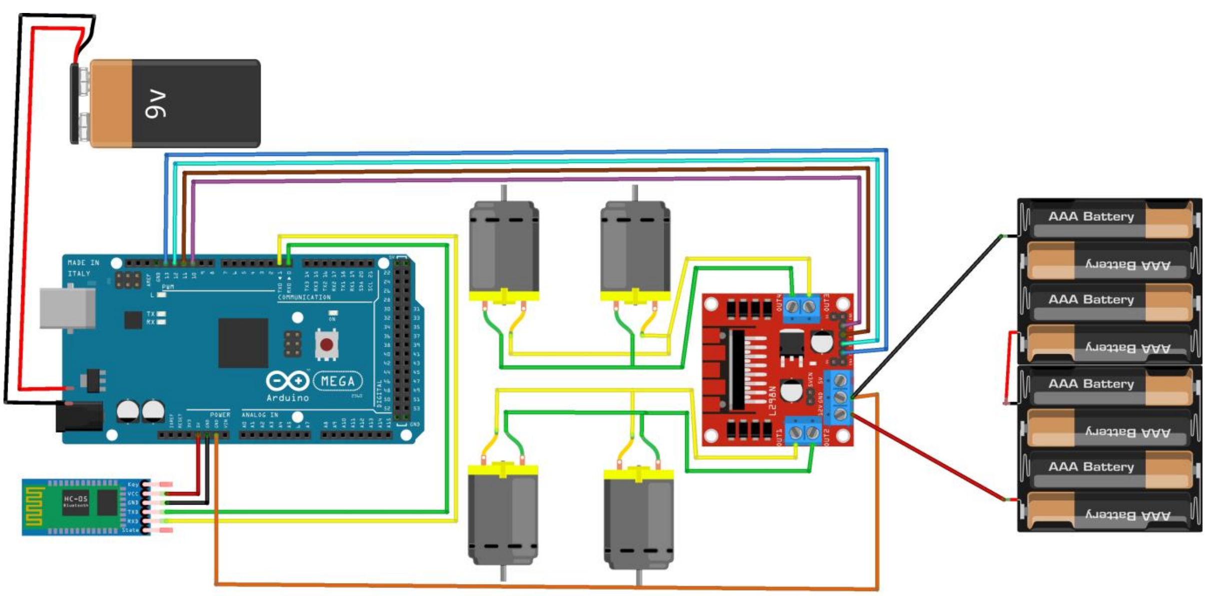

Figure III.10: Bluetooth Car circuit guide.

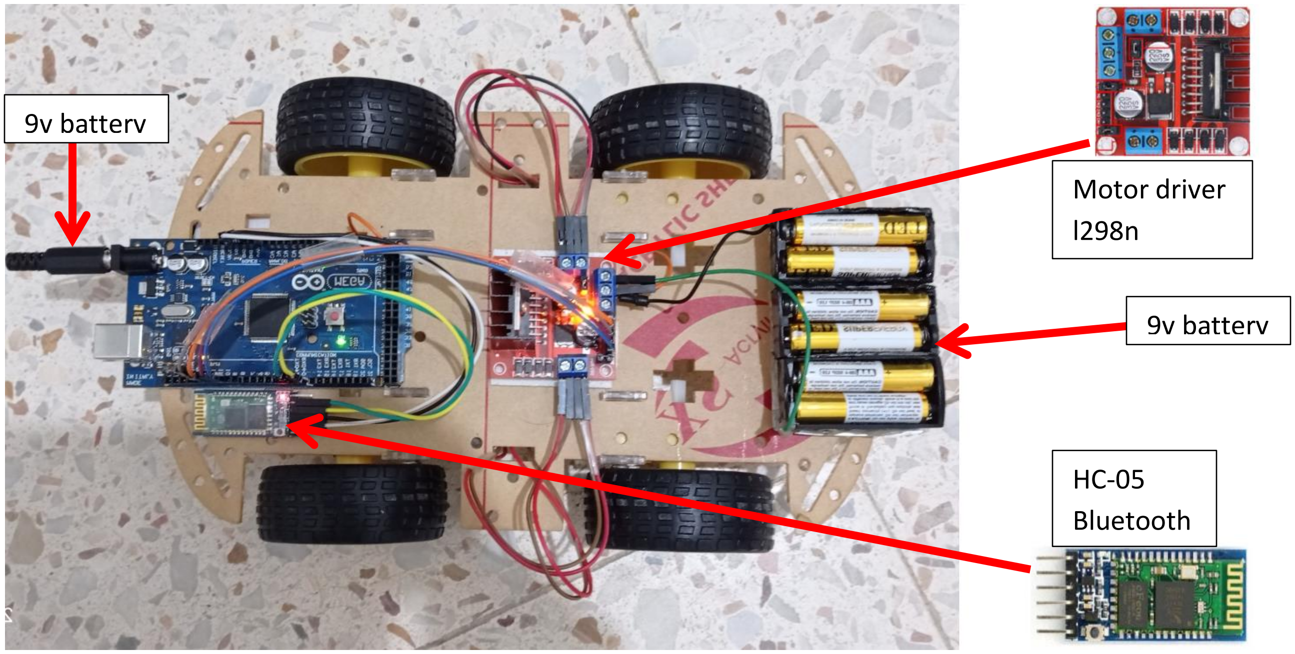

Figure III.11: Bluetooth Car assembled.

The code used in the robot car (in annex 1) is designed to allow us to move the car in four directions. Forward and backwards linearly and rotate left or right with its centre point as its axis of rotation, this movement system is Skid steering. This method engages one side of the tracks or wheels and turning is done by generating differential velocity at the opposite side of a vehicle as the wheels or tracks in the vehicle are non-steerable.

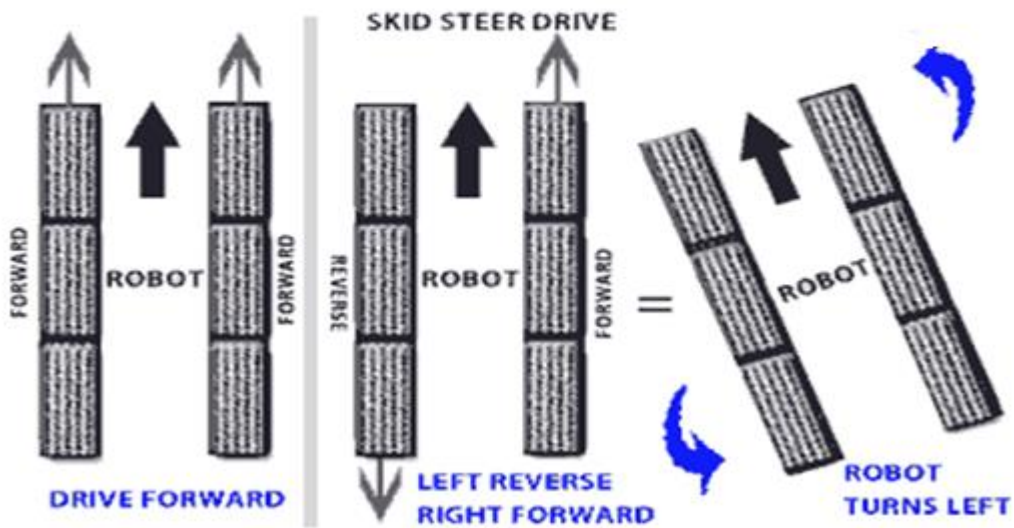

Figure III.12: representation of skid steering.

Another part of the Bluetooth car is the Bluetooth controller and for that we use the Arduino Bluetooth RC Car android app.

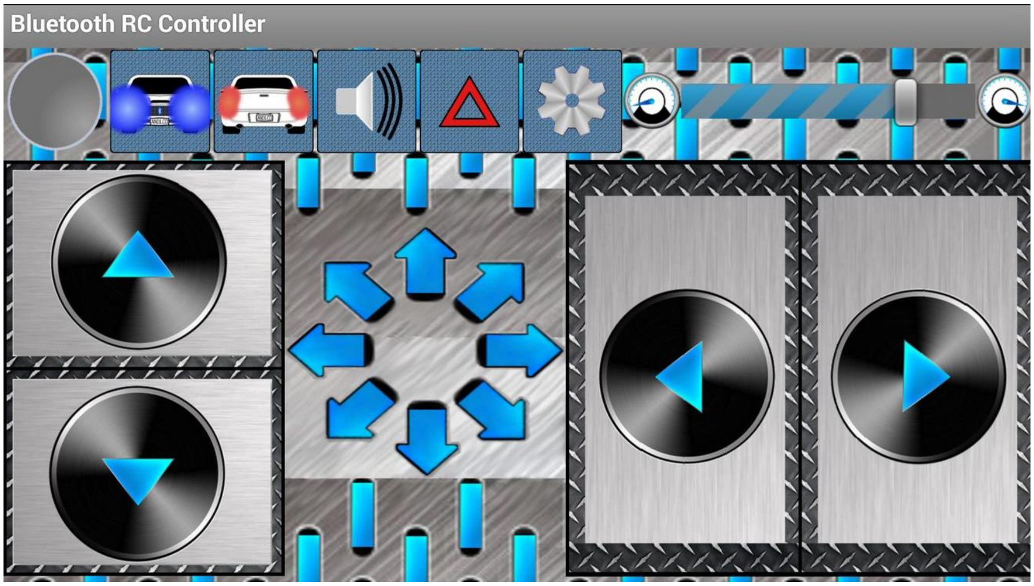

Figure III.13: Android Bluetooth RC Car application interface.

The purpose of this prototype is to construct a functioning four wheel-drive car to test the control code and the car movement. The result is a functioning car suiting our future prototypes.

III.2.3.2. Basic simplex VLC module :

Our second prototype is a basic VLC system, which can be created using standard and widely used parts, plus a microcontroller for the decryption and encryption of data. We use a cone to focus the LED light and overcome the range limitations of the LED and a 1M Ω resister installed in parallel to the photodiode to avoid capturing noise on the analog input.

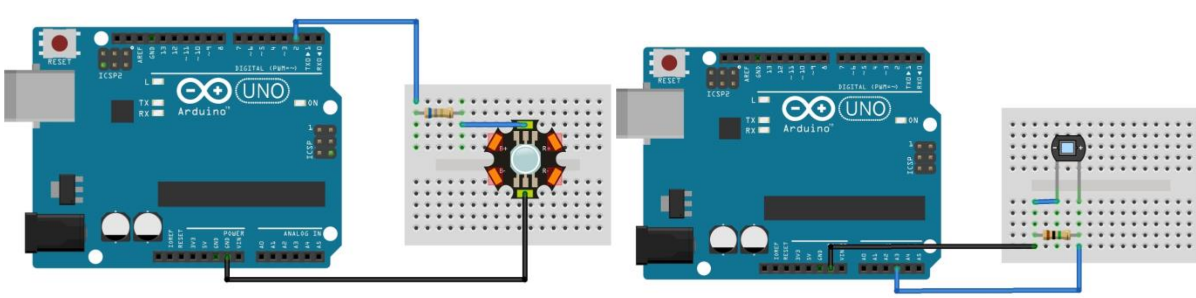

Figure III.14: VLC transmitter and receiver circuit.

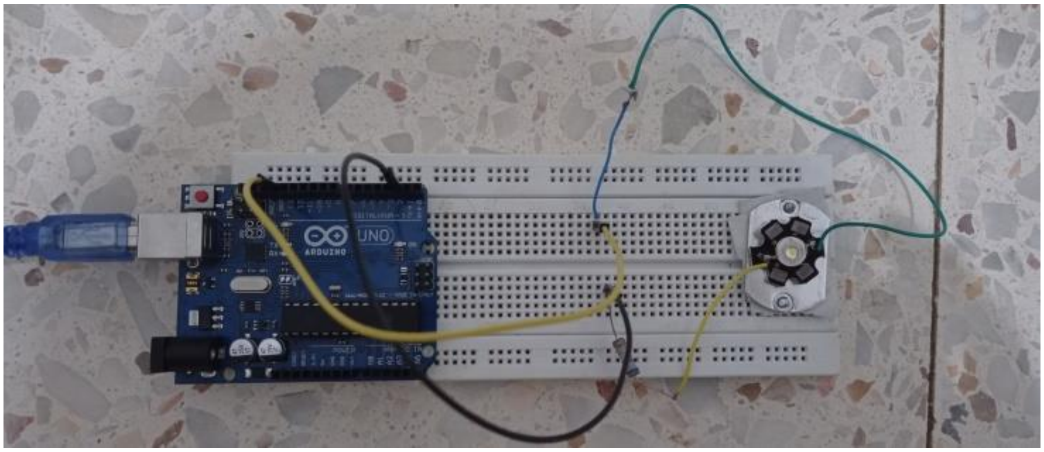

Figure III.15: VLC transmitter.

Due to the weak light emitted by the LED we add a reflector cone to focus the light allowing us to reach more distances than what was possible with an LED alone.

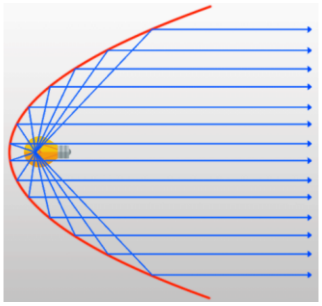

Figure III.16: A cone diagram.

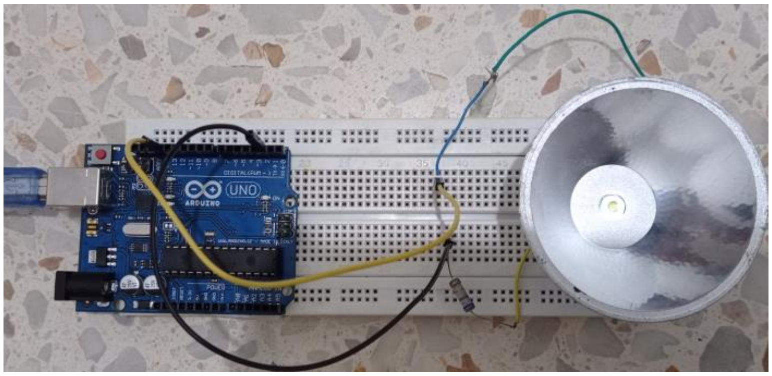

Figure III.17: VLC transmitter with reflector cone.

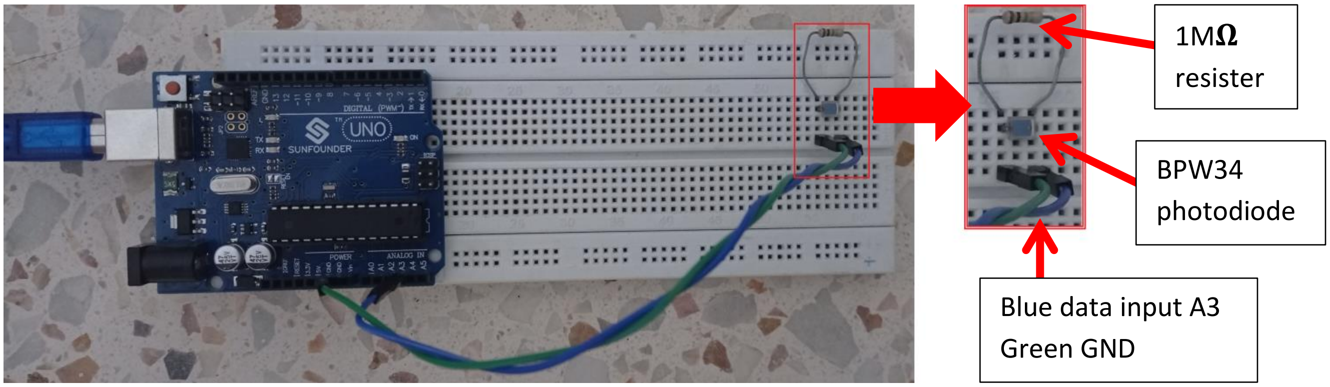

Figure III.18: VLC receiver.

In this VLC simplex we will use OOK modulation by sending data encoded in binary (0, 1) as on-off signals using an LED, a microcontroller as an encoder, a computer as an interface to write the information. While on the receiving end we will use a photodiode as a signal detector with a 1M Ω resistor installed in parallel, another microcontroller as a decoder and a computer as an interface to read the information.

In this project, the data to send is serialized with a start and a stop bit (Start (0) 8bit data Stop (1), LSB first: 0 b0 b1 b2 b3 b4 b5 b6 b7 1) and Manchester encoded to drive the LED. As a consequence the LED appears to be ON all the time for the user.

To help with the synchronization of the receiver and transmitter, the data to send is encapsulated into a frame. This frame is composed of a synchronization preamble (0x55) that helps to compute the binarization threshold. A 0x5D then breaks the synchronization (helps detect the Manchester encoding phase), and an STX (0x02) symbol indicate the start of the frame. A sequence of maximum 32 bytes then follows, and an ETX (0x03) ends the transmission. This simple frame helps with synchronization recovery, but a better frame model would be to add a CRC for error detection in the frame.

Manchester code (also known as phase encoding, or PE) is a line code in which the encoding of each data bit is either low then high, or high then low, for equal time. It is a self-clocking signal with no DC component.

- Data is represented using logic-level transitions rather than logic levels.
- The clock signal does not need to be sent to the receiver because the clock is embedded in the modulated data stream.

The following diagram shows how a data-plus-clock pair corresponds to a Manchester-encoded signal:

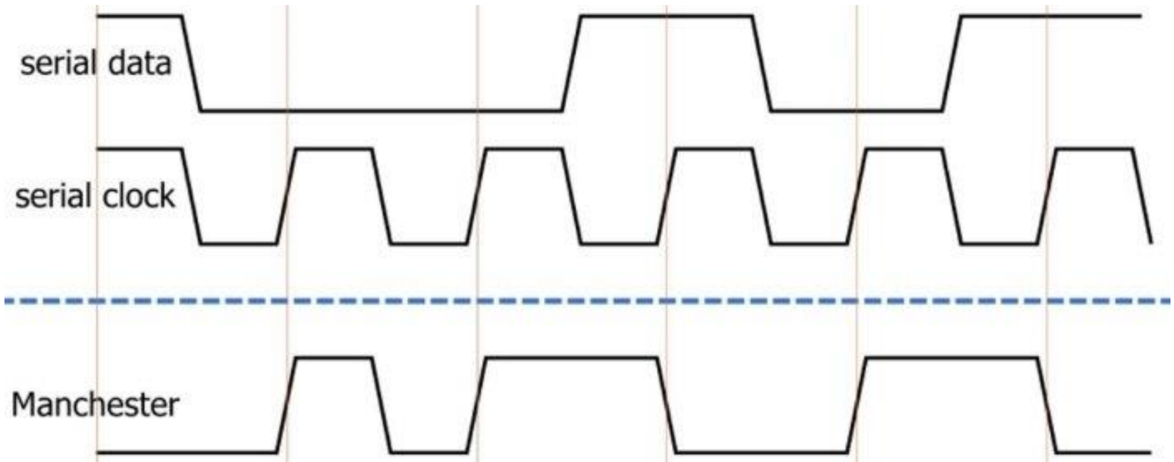

Figure III.19: A Manchester-encoded signal.

The constructed transmitter/receiver allows us to send text information between two computers at a distance up to 2.5 meters in a direct line of sight configuration.

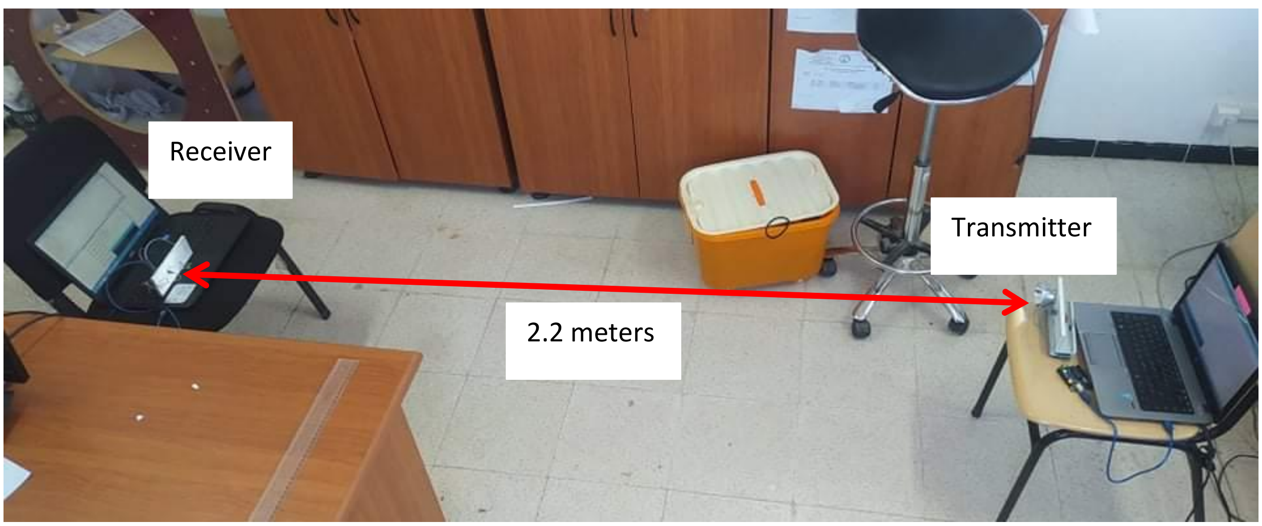

Figure III.20: Prototype of a VLC simplex system.

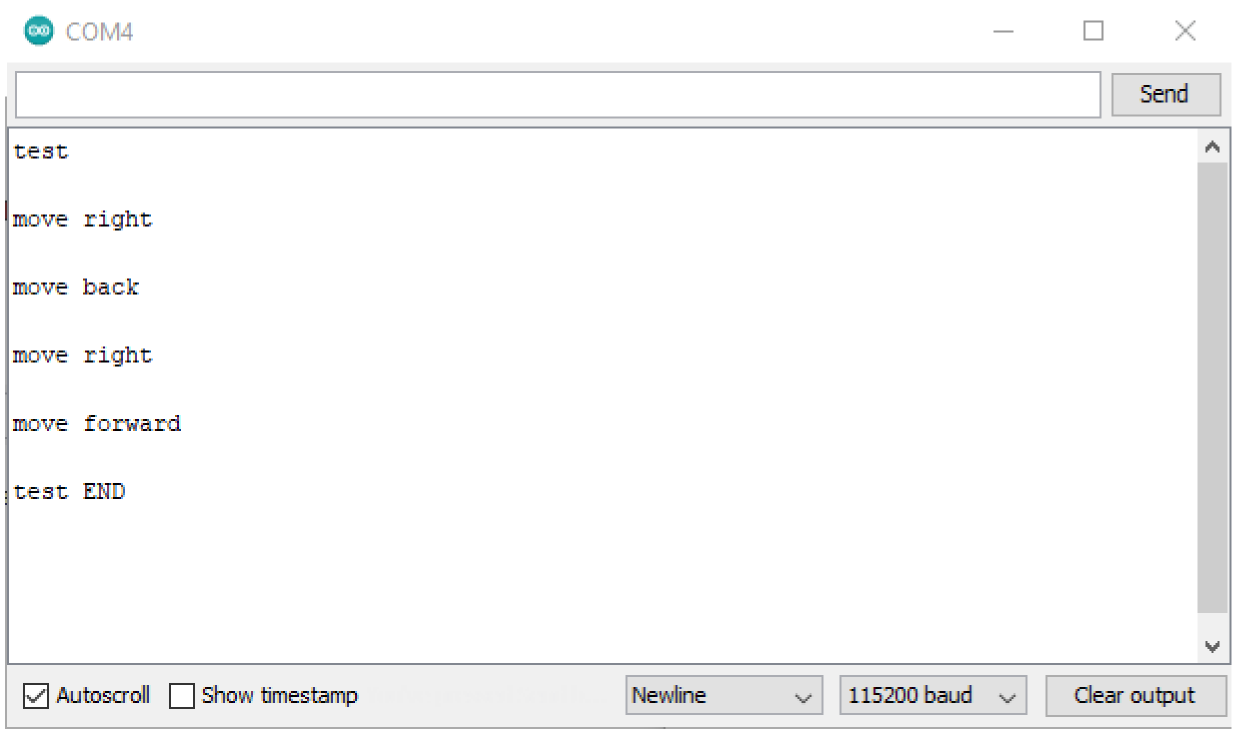

Figure III.21: Serial monitor of the transmitter module.

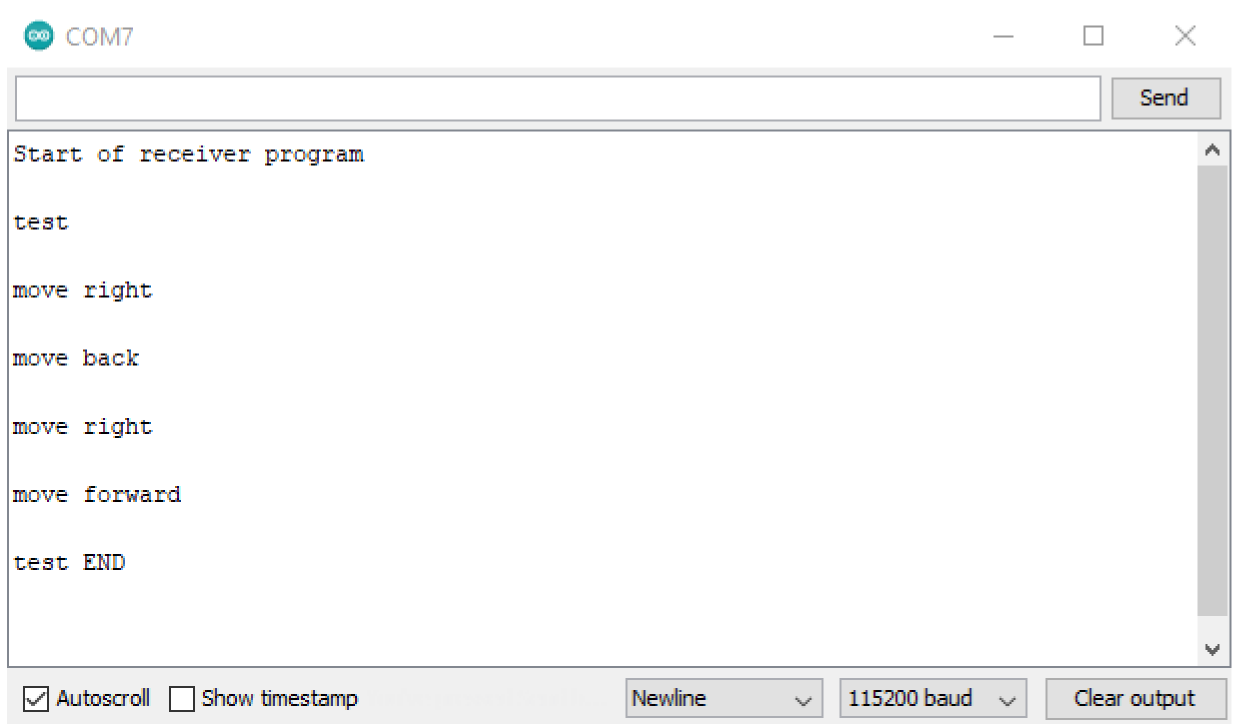

Figure III.22: Serial monitor of the receiver module.

III.2.3.3. Basic VLC car :

With the previous prototypes assembled and working, we assemble a VLC car by replacing the Bluetooth module with a VLC receiver.

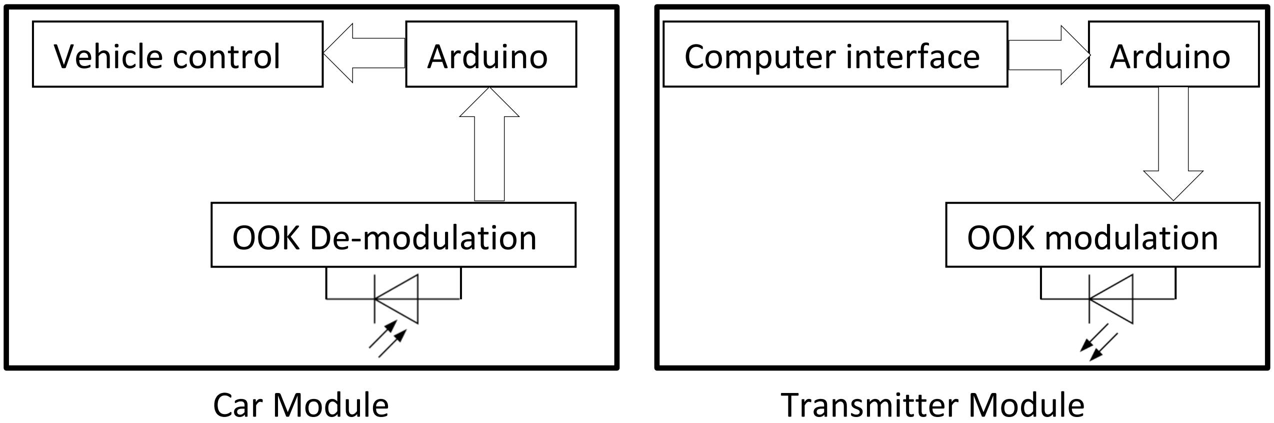

Figure III.23: VLC car functional structure.

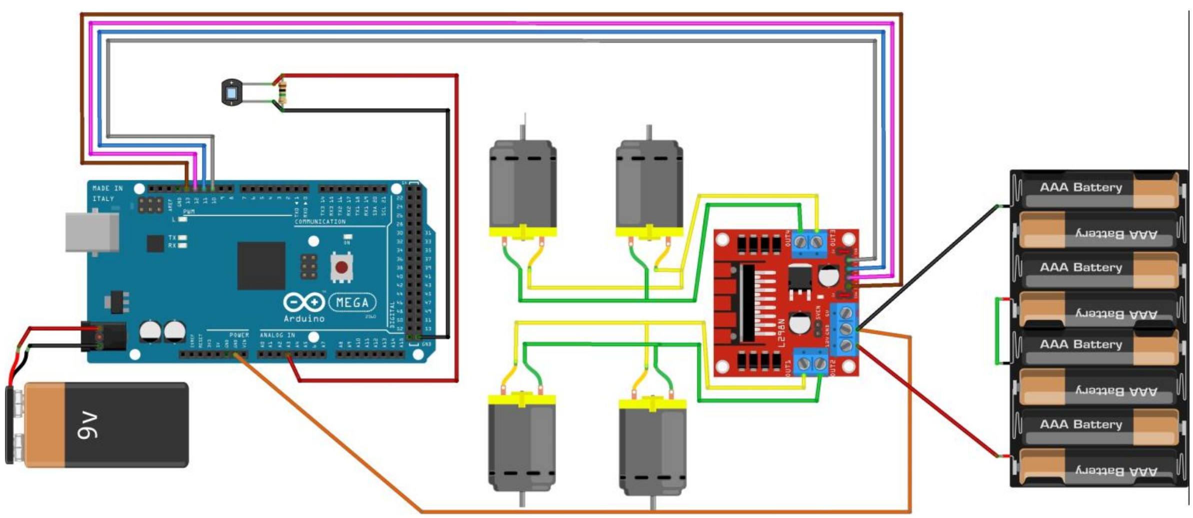

Figure III.24: VLC-Car circuit.

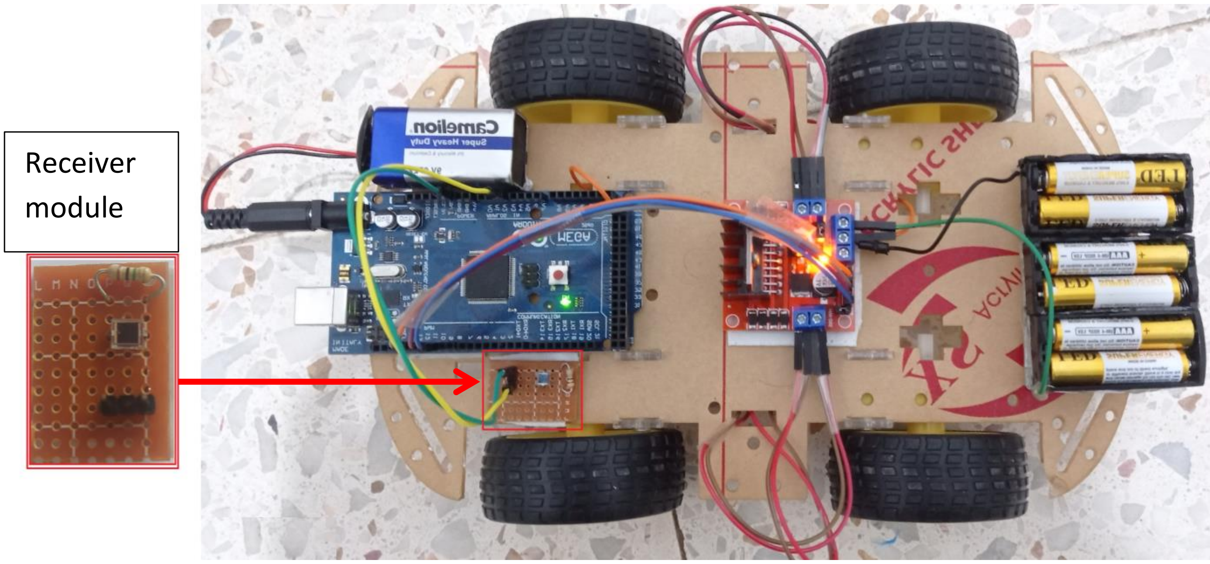

Figure III.25: VLC-Car.

The code of the VLC-car is a simple grouping of the previous two prototypes, with the required commands as letters.

Table III.1: movement commands.

Movement	Command	ASCII code	binary code
Forward	F	102	01000110
	f	070	01100110
Back	B	066	01000010
	b	098	01100010
Left	L	076	01001100
	l	108	01101100
Right	R	082	01010010
	r	114	01110010

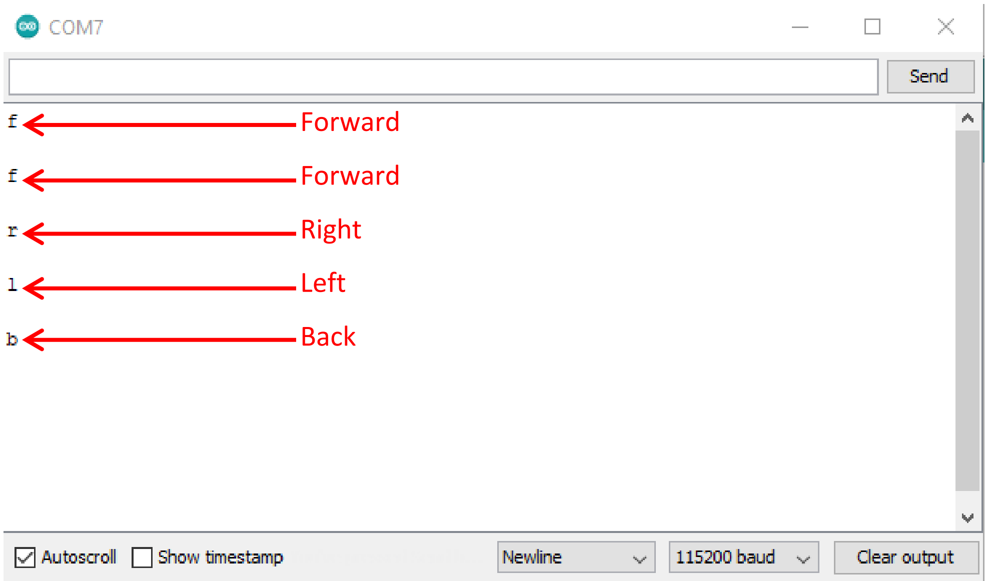

Figure III.26: The interface of the command transmitter module.

This prototype is a proof of concept that shows us the viability of a wheeled robot controlled through VLC; the result is a 4WD robot that requires direct LOS (Line Of Sight) VLC up to 1 meter. This range problem can be addressed by adding a laser diode to the transmitter and an amplifier circuit to the receiver [32].

- We note that the difference between the Bluetooth car and VLC car is due to the nature of their wave form. Bluetooth radio waves allow us to control the car even through physical obstacles, while VLC visual waves need to directly touch the receiver to pass information.

III.2.4. Implementations of a VLC car:

There are many applications for a robot car operating using VLC:

- **Medical field:** robots are already prevalent in medical use however the use of other wireless communication (Bluetooth, WI-FI) cases interferences with other medical equipment and in certain cases may negatively affect the patient health.
- **Industrial field:** with factories and warehouses constantly keeping the lights on, they make for the most ideal environment for VLC integrated robots, for example Automated Storage And Retrieval System (ASRS).
- **Transport and vehicular systems:** The cost associated with implementing VLC systems where infrastructure already exists is relatively low and roads offer an environment rich in light sources, considering traffic lights, light poles, and car headlights.

III.2.5. Performance study and comments on results :

- Limited range of function between 1.2 to 1.5 meters due to limitations light power of the used LED, a recommended solution is the use of laser LEDs [32] or strong industrial LEDs.
- The system necessitates direct Line Of Sight due to the mobile nature of the receiver; a recommended solution is a half-track/full-track LOS system.
- Noise effect from sunlight cases corruption of received data and limits the operational range of function, a recommended solution is the implementation of filters (optical lens or amplifier circuit [32]).

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III.2.6. Future work :

- Implementing of an ultrasonic detector to prevent collision with the environment.
- Implementing an accelerometer.
- Improving the system by adding a convex lens to the receiver.
- Upgrading the system from a simplex to a half-duplex.
- Implementing a thermometer, sound detector and smoke detector.

III.3. Conclusion :

In this chapter, we propose a VLC integrated 4WD car, which moves by Skid steering with a simplex VLC system that encompasses a transmitter and an integrated receiver module. The encrypting and decrypting of data is through Manchester encoding, and OOK modulated. The user interface (Arduino IDE) is used to send data at a range of 1.2 meters with ambient lamp light. We observe the functionality and limitations of the project, allowing us to plan for future improvements to the system and its probable uses in the industrial and medical fields.

General conclusion:

With the constant advancement of robots and robotic engineering, integration of other technological fields is necessary to reach greater developments; one of them is wireless communication. Most wireless technologies use radio waves/Radio Frequency (RF) that suffers from interference and high latency issues. To solve most of these problems an alternative technology is proposed which is Visible Light Communication (VLC).

Visible Light Communication offers the features of high bandwidth, non-interference with the radio waves in electromagnetic sensitive areas and non-hazardous to health, all of these features have made VLC a preferred technology for the future of wireless communication. A few examples of VLC applications are: Li-Fi, visible light ID system, Hospital robots, underwater communication, and traffic communication systems.

In this work, we realized and studied the performance of a basic 4WD car robot with an integrated wireless communication system based on visible light communication (VLC). Our first step was constructing a functional wireless 4WD car that moves by the skid-steering method; we used a Bluetooth module to test it. Our next step was constructing a simplex VLC system using commercially available components; we used OOK modulation due to its simplicity, the resulting prototype allows us to send text up to 24 letters at a range of 2.2 meters. The final step of our work is integrating the VLC technology into the 4WD robot to control it, where it can be controlled at a distance of 1.3 meters.

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Annex 1

Bluetooth car code:

```
char t;
void setup() {
  pinMode(13, OUTPUT);
  pinMode(12, OUTPUT);
  pinMode(11, OUTPUT);
  pinMode(10, OUTPUT);
  Serial.begin(9600);
}
void loop() {
  if (Serial.available()) {
    t = Serial.read();
  }
  if (t == '1' || t == 'F') {
    forward();
  }
  else if (t == '2' || t == 'B') {
    reverse();
  }
  else if (t == '3' || t == 'R') {
    right();
  }
  else if (t == '4' || t == 'L') {
    left();
  }
  else {
    STOP();
  }
}
void forward() {
  digitalWrite(13, HIGH);
  digitalWrite(12, LOW);
  digitalWrite(11, HIGH);
  digitalWrite(10, LOW);
}
void reverse() {
  digitalWrite(13, LOW);
  digitalWrite(12, HIGH);
  digitalWrite(11, LOW);
  digitalWrite(10, HIGH);
}
void left() {
```

```
  digitalWrite(13, LOW);
  digitalWrite(12, HIGH);
  digitalWrite(11, HIGH);
  digitalWrite(10, LOW);
}
void right() {
  digitalWrite(13, HIGH);
  digitalWrite(12, LOW);
  digitalWrite(11, LOW);
  digitalWrite(10, HIGH);
}
void STOP() {
  digitalWrite(13, LOW);
  digitalWrite(12, LOW);
  digitalWrite(11, LOW);
  digitalWrite(10, LOW);
}
```

Annex 2

VLC transmitter /receiver code:

Transmitter:

```
#include <TimerOne.h>
#include <util/atomic.h>
#define TRANSMIT_SERIAL
#define SYMBOL_PERIOD 500
#define WORD_LENGTH 10
#define SYNC_SYMBOL 0xD5
#define ETX 0x03
#define STX 0x02
#define OUT_LED() DDRD |= ((1 << 2))
#define SET_LED() PORTD |= ((1 << 2))
#define CLR_LED() PORTD &= ~((1 << 2))
unsigned char frame_buffer [38];
char frame_index = -1;
char frame_size = -1;
unsigned char bit_counter = 0 ;
unsigned short data_word = 0 ;
unsigned char half_bit = 0 ;
unsigned long int manchester_data ;
void to_manchester(unsigned char data, unsigned long int * data_manchester) {
  unsigned int i ;
  (*data_manchester) = 0x02 ;
  (*data_manchester) = (*data_manchester) << 2 ;
  for (i = 0 ; i < 8; i ++) {
    if (data & 0x80) (*data_manchester) |=  0x02 ;
    else (*data_manchester) |= 0x01 ;
    (*data_manchester) = (*data_manchester) << 2 ;
    data = data << 1 ;
  }
  (*data_manchester) |= 0x01 ;
}
void emit_half_bit() {
  if (manchester_data & 0x01) {
    SET_LED();
  } else {
    CLR_LED();
  }
  bit_counter -- ;
  manchester_data = (manchester_data >> 1);
  if (bit_counter == 0) {
    manchester_data = 0xAAAAAAAA ;
```

```
    if (frame_index >= 0 ) {
      if (frame_index < frame_size) {
        to_manchester(frame_buffer[frame_index], &manchester_data);
        frame_index ++ ;
      } else {
        frame_index = -1 ;
        frame_size = -1 ;
      }
    }
    bit_counter = WORD_LENGTH * 2 ;
  }
}
void init_frame(unsigned char * frame) {
  memset(frame, 0xAA, 3);
  frame[3] = SYNC_SYMBOL ;
  frame[4] = STX;
  frame_index = -1 ;
  frame_size = -1 ;
}
int create_frame(char * data, int data_size, unsigned char * frame) {
  memcpy(&(frame[5]), data, data_size);
  frame[5 + data_size] = ETX;
  return 1 ;
}
int write(char * data, int data_size) {
  if (frame_index >=  0) return -1 ;
  if (data_size > 32) return -1 ;
  create_frame(data, data_size, frame_buffer);
  ATOMIC_BLOCK(ATOMIC_RESTORESTATE) {
    frame_index = 0 ;
    frame_size = data_size + 6 ;
  }
  return 0 ;
}
int transmitter_available() {
  if (frame_index >=  0) return 0 ;
  return 1 ;
}
void init_emitter() {
  manchester_data = 0xFFFFFFFF ;
  bit_counter = WORD_LENGTH * 2 ;
}
void setup() {
  Serial.begin(115200);
  OUT_LED();
```

```
  init_frame(frame_buffer);
  init_emitter();
  Timer1.initialize(SYMBOL_PERIOD);
  Timer1.attachInterrupt(emit_half_bit);
}
char com_buffer [32] ;
char com_buffer_nb_bytes = 0 ;
void loop() {
#ifdef TRANSMIT_SERIAL
  if (Serial.available() && transmitter_available()) {
    char c = Serial.read();
    com_buffer[com_buffer_nb_bytes] = c ;
    com_buffer_nb_bytes ++ ;Serial.println(c);
    if (com_buffer_nb_bytes >= 32 || c == '\n') {
      if (write(com_buffer, com_buffer_nb_bytes) < 0) {
        Serial.println("Transmitter is busy");
      } else {
        com_buffer_nb_bytes = 0 ;
      }
    }
  }
  delay(10);
#endif
}
```

Receiver:

```
#include <TimerOne.h>
#include "receiver_types.h"
#define INT_REF
enum receiver_state frame_state = IDLE ;
#define SENSOR_PIN 3
#define SYMBOL_PERIOD 500
#define SAMPLE_PER_SYMBOL 4
#define WORD_LENGTH 10
#define SYNC_SYMBOL 0xD5
#define ETX 0x03
#define STX 0x02
char frame_buffer[38] ;
int frame_index  = -1 ;
int frame_size = -1 ;
unsigned int signal_mean = 0 ;
unsigned long acc_sum = 0 ;
```

```
unsigned int acc_counter = 0 ;
long shift_reg = 0;
void ADC_setup() {
  ADCSRA =  bit (ADEN);
  ADCSRA |= bit (ADPS0) |  bit (ADPS1) | bit (ADPS2);
#ifdef INT_REF
  ADMUX  =  bit (REFS0) | bit (REFS1);
#else
  ADMUX  =  bit (REFS0) ;
#endif
}
void ADC_start_conversion(int adc_pin) {
  ADMUX &= ~(0x07) ;
  ADMUX  |= (adc_pin & 0x07) ;
  bitSet (ADCSRA, ADSC) ;
}
int ADC_read_conversion() {
  while (bit_is_set(ADCSRA, ADSC));
  return ADC ;
}
#define START_SYMBOL 0x02
#define STOP_SYMBOL 0x01
#define START_STOP_MASK  ((STOP_SYMBOL << 20) | (START_SYMBOL << 18) | STOP_SYMBO
L)
#define SYNC_SYMBOL_MANCHESTER  (0x6665)
inline int is_a_word(long  * manchester_word, int time_from_last_sync, unsigned i
nt * detected_word) {
  if (time_from_last_sync >= 20  || frame_state == IDLE) {
    if (((*manchester_word) & START_STOP_MASK) == (START_STOP_MASK)) {
      (*detected_word) = ((*manchester_word) >> 2) & 0xFFFF;
      if (frame_state == IDLE) {
        if ((*detected_word) == SYNC_SYMBOL_MANCHESTER) return 2 ;
      }
      return 1 ;
    } else if (frame_state != IDLE && time_from_last_sync == 20) {
      (*detected_word) = ((*manchester_word) >> 2) & 0xFFFF;
      return 1 ;
    }
  }
  return 0 ;
}
inline int insert_edge( long  * manchester_word, char edge, int edge_period, int
* time_from_last_sync, unsigned int * detected_word) {
  int new_word = 0 ;
  int is_a_word_value = 0 ;
```

```
  int sync_word_detect = 0 ;
  if ( ((*manchester_word) & 0x01) != edge ) {
    if (edge_period > (SAMPLE_PER_SYMBOL + 1)) {
      unsigned char last_bit = (*manchester_word) & 0x01 ;
      (*manchester_word) = ((*manchester_word) << 1) | last_bit ;
      (*time_from_last_sync) += 1 ;
      is_a_word_value = is_a_word(manchester_word, (*time_from_last_sync), detect
ed_word);
      if (is_a_word_value > 0) {
        new_word = 1 ;
        (*time_from_last_sync) =  0 ;
        if (is_a_word_value > 1) sync_word_detect = 1 ;
      }
    }
    if (edge < 0) {
      (*manchester_word) = ( (*manchester_word) << 1) | 0x00 ;
    } else {
      (*manchester_word) = ( (*manchester_word) << 1) | 0x01 ;
    }
    (*time_from_last_sync) += 1 ;
    is_a_word_value = is_a_word(manchester_word, (*time_from_last_sync), detected
_word);
    if (sync_word_detect == 0 && is_a_word_value > 0) {
      new_word = 1 ;
      (*time_from_last_sync) =  0 ;
    }
  } else {
    new_word = -1 ;
  }
  return new_word ;
}
#define EDGE_THRESHOLD 4
int oldValue = 0 ;
int steady_count = 0 ;
int dist_last_sync = 0 ;
unsigned int detected_word = 0;
int new_word = 0;
char old_edge_val = 0 ;
void sample_signal_edge() {
  char edge_val ;
  int sensorValue  = ADC_read_conversion();
  ADC_start_conversion(SENSOR_PIN);
  if ((sensorValue - oldValue) > EDGE_THRESHOLD) edge_val = 1 ;
  else if ((oldValue - sensorValue) > EDGE_THRESHOLD) edge_val = -1;
  else edge_val = 0 ;
```

```
  oldValue = sensorValue ;
  if (edge_val == 0 || edge_val == old_edge_val || (edge_val != old_edge_val && s
teady_count < 2)) {
    if ( steady_count < (4 * SAMPLE_PER_SYMBOL)) {
      steady_count ++ ;
    }
  } else {
    new_word = insert_edge(&shift_reg, edge_val, steady_count, &(dist_last_sync),
 &detected_word);
    if (dist_last_sync > (8 * SAMPLE_PER_SYMBOL)) {
      dist_last_sync = 32 ;
    }
    steady_count = 0 ;
  }
  old_edge_val = edge_val ;
}

int add_byte_to_frame(char * frame_buffer, int * frame_index, int * frame_size, e
num receiver_state * frame_state , unsigned char data) {
  if (data == SYNC_SYMBOL) {
    (*frame_index) = 0 ;
    (*frame_size) = 0 ;
    (*frame_state) = SYNC ;
    return 0 ;
  }
  if ((*frame_state) != IDLE) {
    frame_buffer[*frame_index] = data ;
    (*frame_index) ++ ;
    if (data == STX) {
      (*frame_state) = START ;
      return 0 ;
    } else if (data == ETX) {
      (*frame_size) = (*frame_index) ;
      (*frame_index) = -1 ;
      (*frame_state) = IDLE ;
      return 1 ;
    } else if ((*frame_index) >= 38) {
      (*frame_index) = -1 ;
      (*frame_size) = -1 ;
      (*frame_state) = IDLE ;
      return -1 ;
    } else {
      (*frame_state) = DATA ;
    }
    return 0 ;
```

```
  }
  return -1 ;
}
void setup() {
  int i;
  Serial.begin(115200);
  Serial.println("Start of receiver program");
  ADC_setup();
  ADC_start_conversion(SENSOR_PIN);
  Timer1.initialize(SYMBOL_PERIOD / SAMPLE_PER_SYMBOL);
  Timer1.attachInterrupt(sample_signal_edge);

}
void loop() {
  int i;
  unsigned char received_data;
  char received_data_print ;
  int nb_shift ;
  int byte_added = 0 ;
  if (new_word == 1) {
    received_data = 0 ;
    for (i = 0 ; i < 16 ; i = i + 2) {
      received_data = received_data << 1 ;
      if (((detected_word >> i) & 0x03) == 0x01) {
        received_data |= 0x01 ;
      } else {
        received_data &= ~0x01 ;
      }
    }
    received_data = received_data & 0xFF ;
    new_word = 0 ;
    if ((byte_added = add_byte_to_frame(frame_buffer, &frame_index, &frame_size,
&frame_state, received_data)) > 0) {
      frame_buffer[frame_size - 1] = '\0';
      Serial.println(&(frame_buffer[1]));
    }
  }
}
```

Required receiver_types.h file in the same folder:

```
enum receiver_state {
  IDLE, //waiting for sync
  SYNC, //synced, waiting for STX
```

```
  START, //STX received
  DATA //receiving DATA
};
```

Annex 3

VLC integrated car:

Transmitter:

The same code used in the previous project.

Receiver:

```
#include <TimerOne.h>
#include "receiver_types.h"
#define INT_REF
enum receiver_state frame_state = IDLE ;
#define SENSOR_PIN 3
#define SYMBOL_PERIOD 500
#define SAMPLE_PER_SYMBOL 4
#define WORD_LENGTH 10
#define SYNC_SYMBOL 0xD5
#define ETX 0x03
#define STX 0x02
char frame_buffer[38] ;
int frame_index  = -1 ;
int frame_size = -1 ;
unsigned int signal_mean = 0 ;
unsigned long acc_sum = 0 ;
unsigned int acc_counter = 0 ;
long shift_reg = 0;
void ADC_setup(){
  ADCSRA =  bit (ADEN);
  ADCSRA |= bit (ADPS0) |  bit (ADPS1) | bit (ADPS2);
  #ifdef INT_REF
  ADMUX  =  bit (REFS0) | bit (REFS1);
  #else
  ADMUX  =  bit (REFS0) ;
  #endif
}
void ADC_start_conversion(int adc_pin){
  ADMUX &= ~(0x07) ;
  ADMUX  |= (adc_pin & 0x07) ;
  bitSet (ADCSRA, ADSC) ;
}
int ADC_read_conversion(){
 while(bit_is_set(ADCSRA, ADSC));
 return ADC ;
}
#define START_SYMBOL 0x02
```

```
#define STOP_SYMBOL 0x01
#define START_STOP_MASK  ((STOP_SYMBOL << 20) | (START_SYMBOL << 18) | STOP_SYMBO
L)
#define SYNC_SYMBOL_MANCHESTER  (0x6665)
inline int is_a_word(long  * manchester_word, int time_from_last_sync, unsigned i
nt * detected_word){
        if(time_from_last_sync >= 20  || frame_state == IDLE){
            if(((*manchester_word) & START_STOP_MASK) == (START_STOP_MASK)){
                  (*detected_word) = ((*manchester_word) >> 2) & 0xFFFF;
                  if(frame_state == IDLE){
                     if((*detected_word) == SYNC_SYMBOL_MANCHESTER) return 2 ;
                  }
                  return 1 ;
            }else if(frame_state != IDLE && time_from_last_sync == 20){
               (*detected_word)= ((*manchester_word) >> 2) & 0xFFFF;
               return 1 ;
            }
          }
          return 0 ;
}
inline int insert_edge( long  * manchester_word, char edge, int edge_period, int
* time_from_last_sync, unsigned int * detected_word){
   int new_word = 0 ;
   int is_a_word_value = 0 ;
   int sync_word_detect = 0 ;
   if( ((*manchester_word) & 0x01) != edge ){
             if(edge_period > (SAMPLE_PER_SYMBOL+1)){
                unsigned char last_bit = (*manchester_word) & 0x01 ;
                (*manchester_word) = ((*manchester_word) << 1) | last_bit ;
                (*time_from_last_sync) += 1 ;
                is_a_word_value = is_a_word(manchester_word, (*time_from_last_syn
c), detected_word);
                if(is_a_word_value > 0){
                   new_word = 1 ;
                  (*time_from_last_sync) =  0 ;
                  if(is_a_word_value > 1) sync_word_detect = 1 ;
                }
             }
             if(edge < 0){
              (*manchester_word) = ( (*manchester_word) << 1) | 0x00 ;
             }else{
              (*manchester_word) = ( (*manchester_word) << 1) | 0x01 ;
             }
             (*time_from_last_sync) += 1 ;
```

```
             is_a_word_value = is_a_word(manchester_word, (*time_from_last_sync), 
 detected_word);
             if(sync_word_detect == 0 && is_a_word_value > 0){
               new_word = 1 ;
               (*time_from_last_sync) =  0 ;
             }
          }else{
            new_word = -1 ;
          }
          return new_word ;
}
#define EDGE_THRESHOLD 4
int oldValue = 0 ;
int steady_count = 0 ;
int dist_last_sync = 0 ;
unsigned int detected_word = 0;
int new_word = 0;
char old_edge_val = 0 ;
void sample_signal_edge(){
  char edge_val ;
  int sensorValue  = ADC_read_conversion();
  ADC_start_conversion(SENSOR_PIN);
  if((sensorValue - oldValue) > EDGE_THRESHOLD) edge_val = 1 ;
  else if((oldValue - sensorValue) > EDGE_THRESHOLD) edge_val = -1;
  else edge_val = 0 ;
  oldValue = sensorValue ;
  if(edge_val == 0 || edge_val == old_edge_val || (edge_val != old_edge_val && st
eady_count < 2)){
    if( steady_count < (4 * SAMPLE_PER_SYMBOL)){
      steady_count ++ ;
    }
  }else{
          new_word = insert_edge(&shift_reg, edge_val, steady_count, &(dist_last_
sync), &detected_word);
          if(dist_last_sync > (8*SAMPLE_PER_SYMBOL)){
            dist_last_sync = 32 ;
          }
            steady_count = 0 ;
        }
        old_edge_val = edge_val ;
}
int add_byte_to_frame(char * frame_buffer, int * frame_index, int * frame_size, e
num receiver_state * frame_state ,unsigned char data){
  if(data == SYNC_SYMBOL){
    (*frame_index) = 0 ;
```

```
    (*frame_size) = 0 ;
    (*frame_state) = SYNC ;
    return 0 ;
  }
  if((*frame_state) != IDLE){
  frame_buffer[*frame_index] = data ;
  (*frame_index) ++ ;
    if(data == STX){
      (*frame_state) = START ;
       return 0 ;
    }else if(data == ETX){
      (*frame_size) = (*frame_index) ;
      (*frame_index) = -1 ;
      (*frame_state) = IDLE ;
       return 1 ;
    }else if((*frame_index) >= 38){
      (*frame_index) = -1 ;
      (*frame_size) = -1 ;
      (*frame_state) = IDLE ;
      return -1 ;
    }else{
      (*frame_state) = DATA ;
    }
    return 0 ;
  }
  return -1 ;
}
void setup() {
  pinMode(13,OUTPUT);
  pinMode(12,OUTPUT);
  pinMode(11,OUTPUT);
  pinMode(10,OUTPUT);
  int i;
  ADC_setup();
  ADC_start_conversion(SENSOR_PIN);
  Timer1.initialize(SYMBOL_PERIOD/SAMPLE_PER_SYMBOL);
  Timer1.attachInterrupt(sample_signal_edge);
}
void loop() {
  int i;
  char* t;
  unsigned char received_data;
  char received_data_print ;
  int nb_shift ;
  int byte_added = 0 ;
```

```
  if(new_word == 1){
    received_data = 0 ;
    for(i = 0 ; i < 16 ; i = i + 2){
             received_data = received_data << 1 ;
             if(((detected_word >> i) & 0x03) == 0x01){
                 received_data |= 0x01 ;
             }else{
                 received_data &= ~0x01 ;
             }
    }
    received_data = received_data & 0xFF ;
    new_word = 0 ;
    if((byte_added = add_byte_to_frame(frame_buffer, &frame_index, &frame_size, &
frame_state,received_data)) > 0){
      frame_buffer[frame_size-1] = '\0';
      t = (&(frame_buffer[1]));
      if(*t == 'f' || *t == 'F') {
        forward();
        delay(200);
        STOP();
      }
      else if(*t == 'b' || *t == 'B') {
        reverse();
        delay(200);
        STOP();
      }
      else if(*t == 'r' || *t == 'R') {
        right();
        delay(200);
        STOP();
      }
      else if(*t == 'l' || *t == 'L') {
        left();
        delay(200);
        STOP();
      }
    }
  }
}
void forward() {
  digitalWrite(13,HIGH);
  digitalWrite(12,LOW);
  digitalWrite(11,HIGH);
  digitalWrite(10,LOW);
}
```

```
void reverse() {
  digitalWrite(13,LOW);
  digitalWrite(12,HIGH);
  digitalWrite(11,LOW);
  digitalWrite(10,HIGH);
}
void left() {
  digitalWrite(13,LOW);
  digitalWrite(12,HIGH);
  digitalWrite(11,HIGH);
  digitalWrite(10,LOW);
}
void right() {
  digitalWrite(13,HIGH);
  digitalWrite(12,LOW);
  digitalWrite(11,LOW);
  digitalWrite(10,HIGH);
}
void STOP() {
  digitalWrite(13,LOW);
  digitalWrite(12,LOW);
  digitalWrite(11,LOW);
  digitalWrite(10,LOW);
}
```