

**T.C.
ISTANBUL SABAHATTIN ZAIM UNIVERSITY
GRADUATE EDUCATION INSTITUTE
COMPUTER SCIENCE AND ENGINEERING**

**DESIGN AND IMPLEMENTATION OF
EIGHT-WHEELED SEMI-AUTONOMOUS DELIVERY
ROBOT**

M.Sc. THESIS

Ömer Mutlu Türk KAYA

**Istanbul
June-2022**

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**Supervisor
Assoc. Prof. Dr. Gökhan ERDEMİR**

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THESIS APPROVAL

This study has been approved in full fulfillment of the requirements for M.Sc. Degree in Computer Science and Engineering.

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DECLARATION OF SCIENTIFIC ETHICS AND ORIGINALITY

This is to certify that this M.Sc. thesis dissertation titled “**Design and Implementation of Eight-Wheeled Semi-Autonomous Delivery Robot**” is my own work, and I have acted according to scientific ethics and academic rules while producing it. I have collected and used all information and data according to scientific ethics and guidelines on thesis writing of Istanbul Sabahattin Zaim University. I have fully referenced, in both the text and bibliography, all direct and indirect quotations and all sources I have used in this work.

Ömer Mutlu Türk KAYA

Istanbul, June 2022

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Ömer Mutlu Türk KAYA
Istanbul, June 2022

ABSTRACT

DESIGN AND IMPLEMENTATION OF EIGHT-WHEELED SEMI-AUTONOMOUS DELIVERY ROBOT

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During the last decade, delivery robot employment has increased worldwide. A considerable amount of delivery robots are utilized in America, Europe, and Asia nowadays. The essential purpose of delivery robots is to solve the last-mile delivery problem by serving goods such as food, groceries, parcels, etc. On the other side, delivery robot technology brings its interior problems at the same time. Climbing up and down on the curbs and ramps are some of them. Four and six-wheeled delivery robots get into this trouble from time to time. At this point, several cases appeared in the press. According to the cases, the opinion of insufficiency of robot wheel numbers and mechanisms has emerged. The aim of the thesis is to design and implementation of an eight-wheeled semi-autonomous delivery robot that paves the way for climbing up and down the curbs and ramps easily while being able to proceed with various semi-autonomous delivery tasks. The developed delivery robot has eight wheels and one apiece bogie mechanism on the front and back of the robot. The mechanical structure was designed in the Catia v5 3D CAD software, and then built the prototype by assembling the parts. The electrical and electronic structure was determined. The components, such as converters, sensors, controllers, etc., were tested and calibrated. The building of the robot software structure came after electrical electronics and mechanical structures. At the end of the thesis, a variety of real environment tests were realized. By the end of the study, while the manual control of the robot and climbing up and down on the curbs were realized, the autonomy studies were lacking because of being faced with a lot of mechanical problems.

Key Words: Delivery Robot, 8-Wheeled Robot, Semi-Autonomous Robot

ÖZET

SEKİZ TEKERLEKLİ YARI ÖZERK TESLİMAT ROBOTU TASARIMI VE UYGULAMASI

Ömer Mutlu Türk KAYA
Yüksek Lisans, Bilgisayar Bilimler ve Mühendisliği
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Gün geçtikçe teslimat robotu istihdamı tüm dünyada artıyor. Günümüzde Amerika, Avrupa ve Asya'da önemli sayıda teslimat robotu kullanılmaktadır. Teslimat robotlarının temel amacı, gıda, bakkaliye, koli vb. ürünlerin teslimatını yaparak son kilometre teslimat sorununu çözmektir. Diğer yandan teslimat robotu teknolojisi aynı zamanda kendi iç problemlerini de beraberinde getirmektedir. Kaldırımlardan ve rampalardan inip çıkmak bunlardan bazılarıdır. Dört ve altı tekerlekli teslimat robotların başları zaman zaman bu belaya giriyor. Bu noktada, birkaç vaka basına yansımıştır. Vakalara göre robotların tekerlek sayıları ve mekanizmalarının yetersiz olduğu görüşü ortaya çıktı. Tezin amacı, çeşitli yarı otonom teslimat görevlerini yerine getirirken kaldırımlardan ve ramplardan kolayca inip çıkmanın önünü açan sekiz tekerlekli yarı otonom bir teslimat robotunun tasarlanması ve uygulanmasıdır. Geliştirilen teslimat robotu sekiz tekerleğe, robotun önünde ve arkasında olmak üzere birer adet boji mekanizmasına sahiptir. Mekanik yapı Catia v5 3B BDT yazılımında tasarlandı ve ardından parçaların birleştirilmesiyle prototip oluşturuldu. Elektrik ve elektronik yapısı belirlendi. Dönüştürücüler, algılayıcılar, kontrolörler vb. bileşenler test edildi ve kalibre edildi. Robot yazılım yapısının inşası, elektrik-elektronik ve mekanik yapılardan sonra geldi. Tezin sonunda çeşitli gerçek ortam testleri gerçekleştirilmiştir. Çalışmanın sonunda robotun elle kontrolü ve bordürlere inip çıkma işlemleri gerçekleştirilirken, birçok mekanik sorunla karşı karşıya kalındığı için özerklik çalışmaları eksik kalmıştır.

Anahtar Kelimeler: Teslimat Robotu, Sekiz Tekerlekli Robot, Yarı Özerk Robot

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LIST OF SYMBOLS

$^{\circ}$: Angle (degrees)
Δ	: Delta (Difference)
Δt	: Time Difference
3B	: Üç Boyutlu
3D	: Three Dimensional
A	: Ampere
C	: The capacity of energy the battery can safely discharge
C	: Celsius/Centigrade
cm	: Centimeter
D	: Dimension
D-PHY	: High speed, low power, source-synchronous physical layer
e	: Error
$e(t)$: Error Signal
$u(t)$: Control Signal
$e_r(t)$: Error Signal of the Control System of the Right Motor
$e_l(t)$: Error Signal of the Control System of the Left Motor
e_{prev}	: Previous Error
$\frac{de}{dt}$: Derivative of the Error
e_{int}	: Integral of the Error
Gb	: Gigabits
Hz	: Hertz
I ² C	: Inter-Integrated Circuit
I ² S	: Inter-IC Sound
IP66	: Ingress Protection 66 which rated as "dust tight" and protected against heavy seas or powerful jets of water
K	: Thousand
K5	: A model of Knightscope robots
Kg	: Kilogram
k_p	: PID Proportional constant
k_i	: PID Integral constant

k_d	: PID Derivative constant
lt	: Litre
L	: The width between the wheel centers on the sides of the robot
M	: Motor
m	: Meter
M.2 Key E	: A slot / connector designed for mostly wireless communications
M2	: A model of Keenon robots
mA	: Mili Amper
mAh	: Mili Amper Hour
MHz	: Mega Hertz
mm	: Milimeter
MPU-9250	: Motion Processing Unit
p	: Progressive Scan
P3-DX	: A model of Pioneer robots
pos_r	: Measured Position of the Right Motor
pos_l	: Measured Position of the Left Motor
R	: Wheel Radius
rad	: Radian
s	: Second
S1	: Switch 1
S2	: Switch 2
S3	: Switch 3
S4	: Switch 4
SAMD21	: A series of low-power microcontrollers
T1	: A model of Keenon robots
T2	: A model of Keenon robots
W3	: A model of Keenon robots
T5	: A model of Keenon robots
T6	: A model of Keenon robots
Type C	: A type of USB connector
V	: Voltage
v	: Velocity
v5	: Fifth version

V_{cc}	: Common Collector Voltage
v_r	: Linear velocity of the right wheels
v_l	: Linear velocity of the left wheels
W	: Watt
ω	: Angular Velocity
ω_r	: Angular velocity of the right wheel
ω_l	: Angular velocity of the left wheel
XL robot	: A part of the model name of the Australian Droid Explora model



LIST OF ABBREVIATIONS

AWG	: American Wire Gauge
BDT	: Bilgisayar Destekli Tasarım
bps	: Bits Per Second
CAD	: Computer-Aided Design
CSI	: Camera Serial Interface
DC	: Direct Current
DoF	: Degrees of Freedom
ELE D/R	: Elevator Dual Rate
eMMC	: embedded Multi-Media Card
E-Stop	: Emergency Stop
FPS	: Frame Per Second
GEA	: Gear switch
GLONASS	: Globalnaya Navigazionnaya Sputnikovaya Sistema, or Global Navigation Satellite System
GNSS	: Global Navigation Satellite System
GPIO	: General Purpose Input/Output
GPS	: Global Positioning System
GUSS	: Global Unmanned Spray System
HEVC	: High-Efficiency Video Coding
IMU	: Inertial Measuring Unit
IO	: Input/Output
IZU	: Istanbul Sabahattin Zaim University
LIDAR	: Light Detection And Ranging
Li-Po	: Lithium Polymer
LPDDR	: Low Power Double Data Rate
Max.	: Maximum
MIT	: Massachusetts Institute of Technology
MuSHR	: Multi-agent System for non-Holonomic Racing
MP	: Megapixels
MIPI	: Mobile Industry Processor Interface
NASA	: American Aeronautics and Space Administration

NC	: Normally Closed
OS	: Operating System
PID	: Proportional Integral Derivative
PIT.TRIM	: Pitch Adjustment Trim
PrOP	: Pribori Ochenki Prokhdimosti
PWM	: Pulse Width Modulation
RADAR	: Radio Detection And Ranging
RAM	: Random-Access Memory
RC	: Radio-Control
RIFMA	: Roentgen Isotopic Fluorescent Method of Analysis
RPM	: Rotation Per Minute
RTK	: Real-Time Kinematics
SDG	: Self-Driving Group
Sec	: Second
SPI	: Serial Peripheral Interface
TOF	: Time Of Flight
TTL	: Transistor-Transistor Logic
UART	: Universal Asynchronous Receiver-Transmitter
UGV	: Unmanned Ground Vehicle
USA	: United States of America
USB	: Universal Serial Bus
USSR	: Union of Soviet Socialist Republics

CHAPTER I INTRODUCTION

Delivery robots have gradually become a part of daily life since 2014. They are actually the outcomes of the increased e-commerce industry. People can reach, find and purchase products on the internet from anywhere. Therefore someone needs to deliver the ordered products. The addresses of customers can be quite different from each other. At this point, the last-mile problem emerges. The term ‘last-mile’ is the final stage of the delivery process as described in (Macharis & Melo, 2011). There are a lot of solutions for the last-mile problem, such as bike couriers or motorcycle couriers, etc. One of them is the delivery robots, as well. These robots solve the last-mile problem to a considerable extent by delivering goods such as food, groceries, parcels, etc. However, the concept of the delivery robot has a vast meaning at first glance. Because the term ‘robot’ stands for an electro-mechanical machine that can perform some predefined tasks autonomously or remote-controlled. Therefore, delivery robots might be understood as all electro-mechanical machines that can fly, swim, step on land, or move with their wheels by delivering goods. But, the term ‘delivery robot’ is commonly used for the wheeled or tracked unmanned small ground vehicles that deliver the goods with the cargo compartments. Their cargo carriage capacities are presented in Table 2.2. Besides, the delivery robots are equipped with sensors that detect the environment in various ways. These are mostly ultrasonic sensors, LIDAR sensors, cameras, etc. However, not every delivery robot has to use all of these sensors. For instance, in Starship Delivery Robots, RADAR sensors are used instead of LIDAR sensors (Swiss Post, 2017). Compared to Starship Delivery Robots, TinyMile Delivery Robots have fewer sensors and neither RADAR sensor nor LIDAR. TinyMile Delivery Robots have only a front camera (Lightfoot, 2020a). Delivery robots, which have the ability to sense their environment, perform their tasks either remote-controlled or autonomously. The ability to perform fully autonomous missions is the targeted top point in the delivery robots area. However, it is a very difficult target for delivery robots to carry out their tasks fully autonomously in an environment full of moving and fixed obstacles, where

the daylight changes, wind, rain, snow, etc., weather conditions are always open to changes. While accepting that full autonomy is challenging, engineers and researchers work intensively to achieve the goal.

In this thesis, an eight-wheel semi-autonomous delivery robot was designed, and the prototype was developed. In the design stage, other wheeled delivery robots were examined, and the pros and cons were evaluated. In this context, the four-or-less-wheeled delivery robots are observed to be prone to tip over while climbing up or down on the curbs. Six-wheeled delivery robots are better at climbing up and down than the four-or-less-wheeled delivery robots. However, they showed various deficiencies in some cases which appeared in media. Because their only two wheels stay touched on the ground sometimes while climbing up a curb. That causes to get the robots to be stuck in there. Therefore, in order to get rid of getting stuck in such situations, developing an eight-wheeled delivery robot is decided and realized to some extent in this study. While focusing on that, the autonomy side of the robot was not ignored. The semi-autonomy was aimed at the developed robot.

1.1 The Statement of the Problem

There are many problems that commonly used delivery robots face while performing their duties. One of them is the pavement or ramp they will encounter in the trajectory they follow during the delivery. In areas with a high urbanization rate, there are ramps that can be easily accessed from the pedestrian sidewalks. Although these ramps are actually made for wheelchairs and baby carriages, they also provide an essential convenience for delivery robots. Unfortunately, these ramps are not available on every sidewalk. Therefore, delivery robots must climb the pavements to use them. This can often lead to snagging or the wheels coming off during climbing. When this situation, which is one of the most undesirable situations, is encountered, the robot stays on the road and cannot fulfill its delivery task. In order to eliminate this problem, an eight-wheeled robot design was proposed. The design also has a double bogie system that eases the climbing actions. The main advantage of eight wheels is to ensure that four wheels of the robot stay in contact with the ground at all stages of climbing up and down actions on the curbs and ramps. The bogie system provides great convenience at the same time. The prototype of the proposed robot was developed, assembled, and tested

in the thesis study. The outcomes of the study are satisfactory to some extent. They are discussed comprehensively in Chapter IV.

A second problem is the autonomy of the delivery robot. A remotely guided delivery robot also includes the human factor. The human factor needs to be quite less in order to increase efficiency. Therefore, the basic obstacle avoidance and trajectory tracking algorithms were planned to implement on the developed robot in the study. However, these semi-autonomy studies were not accomplished because of losing time on some serious mechanical problems, which are explained in the rest of the study.

1.2 The Rationale of the Study

The aim of this study is to propose new solutions to the problems presented in the previous section. These problems are mainly due to the stoppage and autonomous tasks that delivery robots encounter when crossing sidewalks and climbing up and down on curbs and ramps. Therefore, a semi-autonomous delivery robot with eight wheels was designed and developed to some extent. A brushed DC gear motor was used for each wheel. Additionally, the double bogie system was designed. Utilizing the realized developments, it is aimed to prevent snags while climbing the pavement step. In addition, it was considered to lighten the burden of the robot supervisor by wanting to perform some tasks autonomously. Thus, the remote robot supervisor will not have to constantly guide and follow the robot. The robot will be able to perform several simple tasks on its own, and in case of complex or dangerous tasks, it will warn the remote robot supervisor and request either direct guidance or follow-up. Thus, a safe and fast delivery process will be experienced.

1.3 Significance of the Study

In the context of the significance of the study, the thesis is aimed to be one of the pioneer studies in the delivery robots area. The existing and commonly used delivery robots have two, three, four, or six wheels. As a result of the research, no eight-wheeled delivery robot was found. There are eight-wheeled robots, but they are not delivery-driven robots. Their development purpose is totally different from the delivery tasks. They are mostly related to exploration, disabled people, or something else. Therefore, the eight wheels and double bogie mechanisms on a delivery robot are the first original

value of the study. The semi-autonomy studies on the proposed unique-mechanical-structured delivery robot are the second original value. Naturally, it will also give a different perspective to experience how the semi-autonomy studies on the delivery robots in use will work in the case of an eight-wheeled delivery robot. In addition, it is also essential in terms of contributing to the development of the field of delivery robots, which is still new in Turkey.

1.4 Limitations of the Study

Since the concept of the delivery robot has a vast meaning, this study was started by determining some limits. First of all, the environment where the delivery robots will work has been determined. Delivery robots will work in urban areas to address the problem of the last step in the delivery process. These robots will deliver cargo by land, not by air or sea. The road to be used will be pavements and pedestrian roads used by pedestrians, not the vehicle road used by vehicles such as cars and trucks that people can get on. Delivery robots such as Nuro (Nuro, 2022) and Refraction REV-1 (Refraction, 2019) were not examined in this study as they are too large to use sidewalks or pedestrian paths. In addition, Spot Mini (Boston Dynamics, 2022) developed by Boston Dynamics or Digit (Washington, 2019) robots supported by Ford are legged robots capable of delivering. Since the cost of these robots is high, it is out of the focus of the thesis study. While considering the costs, it should not be overlooked to determine which product types these delivery robots will carry or deliver. At this point, it is mostly packable food, beverage, etc. It is more feasible to deliver other products of different sizes and weights. The delivery robots examined within the scope of this thesis and the delivery robot designed and developed have the following features:

- Using sidewalks or pedestrian ways in urban areas,
- Detection and obeying the road signs and signals and also street traffic control lights,
- Having dimensions that will not completely cover the sidewalks or pedestrian roads and will not cause problems for pedestrian traffic,
- Ability to carry mostly packable food and beverage,
- Being able to go from one point to another by having a wheeled body,
- Perceiving the environment by hosting sound and light sensors,
- Programmable multiple times according to various algorithms,

- Being able to be monitored and directed by a remote robot supervisor,
- Ability to perform several tasks autonomously.

1.5 The Research Questions and The Hypotheses of the Study

There are two main questions to be solved in this thesis. These:

1. Will the designed delivery robot be able to easily climb sidewalks and ramps without damaging the cargo and itself?

2. Will the robot be able to perform an autonomous task in the delivery process without harming people, its environment, and itself?

For the first question, the sidewalks and ramps in the Halkalı Campus of Istanbul Sabahattin Zaim University (IZU) were examined. Field trials were also realized by carrying a parcel on the same campus. The successful results were obtained on the pavements. The design and experiment process is explained in detail in the relevant section of the study. For the second question, testing of basic obstacle avoidance and trajectory tracking algorithms was considered. However, due to the losing time on some serious mechanical problems of the robot, the second task was not completed. It is discussed in detail in the relevant part of the study.

1.6 The Outline of the Study

This study consists of five main parts. In the first part, the concept of the delivery robot and the 8-wheel semi-autonomous delivery robot designed and developed within the scope of the thesis study are mentioned, and an introduction is made. Again in this section, the problems identified in the field of delivery robots are revealed, and the thesis's purpose is explained. Then, the original value of the thesis, the limits of the study, and the research questions and assumptions are stated. The general framework of the thesis was drawn, and the first chapter was concluded with keywords. In the second part, related studies in the field of delivery robots, driving mechanisms used in delivery robots, eight-wheeled mobile robots, and autonomous/semi-autonomous mobile robots are examined, and information about these studies is given. In the third chapter, the methods and stages followed in designing and developing the proposed 8-wheeled semi-autonomous delivery robot are explained in detail. Mechanical design, electronic connections, software, programming, and assembly of the first instance are given in this section with visuals. In the fourth chapter, the results obtained as a result

of the experiments are presented, and evaluations are made based on these results. In the last part, the results obtained as a result of the whole thesis work are briefly explained, and information about future studies is given.



CHAPTER II LITERATURE REVIEW

2.1 Mobile Robots & Fields of Usage

Mobile robots are robots that have the ability to move from one point to another, and they are not fixed or attached to any point. They can act with external directions or according to pre-programmed algorithms. Mobile robots are used in various fields, from space missions to military missions, from agriculture to the service sector. Lunokhod 1 (Harvey, 2007), the first rover robot to move on the lunar surface and was sent by the Soviet Union in the 1970s, is a rover robot used within the scope of space missions. Again, the Soviets' Lunokhod 2 (Harvey, 2007) and China's YUTU Scout (Zhou, Li, Xu, & Dong, 2016) are examples of other roaming robots sent to the Moon. Humankind has gone beyond these developments and sent mobile robots to Mars. Sojourner (Erickson, 2022), sent by the American Aeronautics and Space Administration (NASA) and landed on Mars in 1997, is the first rover to be sent to Mars as part of the space mission. This robot was followed by Spirit and Opportunity (Erickson, 2022) in 2004, Curiosity (Erickson, 2022) in 2012, and finally Perseverance (Erickson, 2022) in 2021. All mentioned space robots are shown in Fig. 2.1.

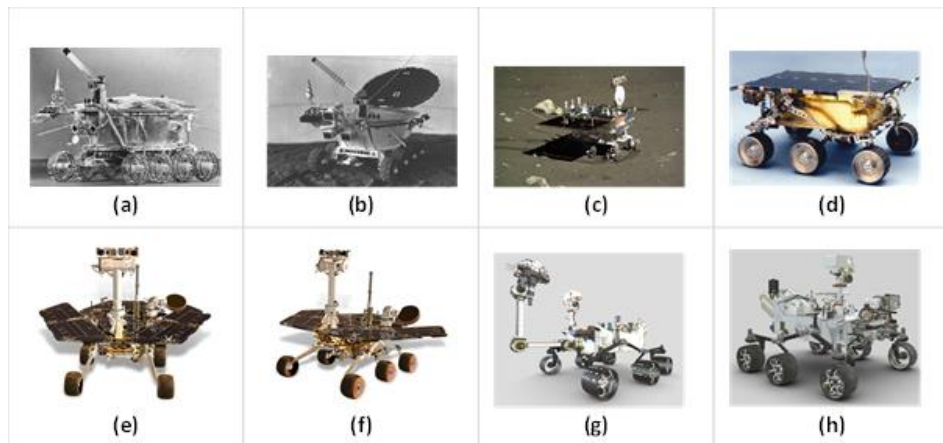


Fig. II.1: **a)** Lunokhod 1 (Nasennik, 2014), **b)** Lunokhod 2 (Nasennik, 2014), **c)** Yutu Rover (Wall, 2016), **d)** Sojourner (“Overview - NASA Mars,” n.d.), **e)** Spirit (“Overview - NASA Mars,” n.d.), **f)** Opportunity (“Overview - NASA Mars,” n.d.), **g)** Curiosity (“Summary | Rover – NASA Mars Exploration,” n.d.), **h)** Perseverance (“Learn About the Rover - NASA Mars,” n.d.)

Apart from the mobile robots developed within the scope of space missions, there are some mobile robots developed for security and military missions. Throwbot is a remotely guided spy robot that can be manually thrown into the operation area and can transmit wireless audio and video (Robots, 2021c).

The Rheinmetall Mission Master family of unmanned land vehicles (Rheinmetall AG, 2022) and the HDT Hunter Wolf unmanned land vehicle (HDT Global, 2022) are other mobile robots developed to provide logistical support to military units in dangerous missions on rough terrain. As these vehicles can carry military cargo, they can also become military robots with the weapon systems placed on them. Robotic military targets (Marathon Targets, 2015) developed by an Australia-based company to prepare military personnel before the operation are another example of a mobile robot used in the military field. These robots consist of inanimate human dummies placed on a four-wheeled mobile platform and can make various human voices during exercises. This is an essential factor that maximizes the preparation of military personnel.

In (Jr et al., 2013), two double-armed mobile robot prototypes, named Johnny-T and RoboSally, requiring two-handed guidance, were developed. These are robots that can perform unmanned ground vehicle missions such as remotely guided bomb disposal. Developed at the John Hopkins Applied Physics Laboratory, these robots are designed for complex tasks with a single end-effector control. They can also be used in civilian settlements.

In addition to these robots (Robots, 2021b), K5 security robots developed by Knightscope are also examples of mobile robots used in the field of security. Equipped with various cameras and sensors, these robots detect criminal events in places with high pedestrian density, such as shopping malls. The explained security and military robots are displayed in Fig. 2.2.

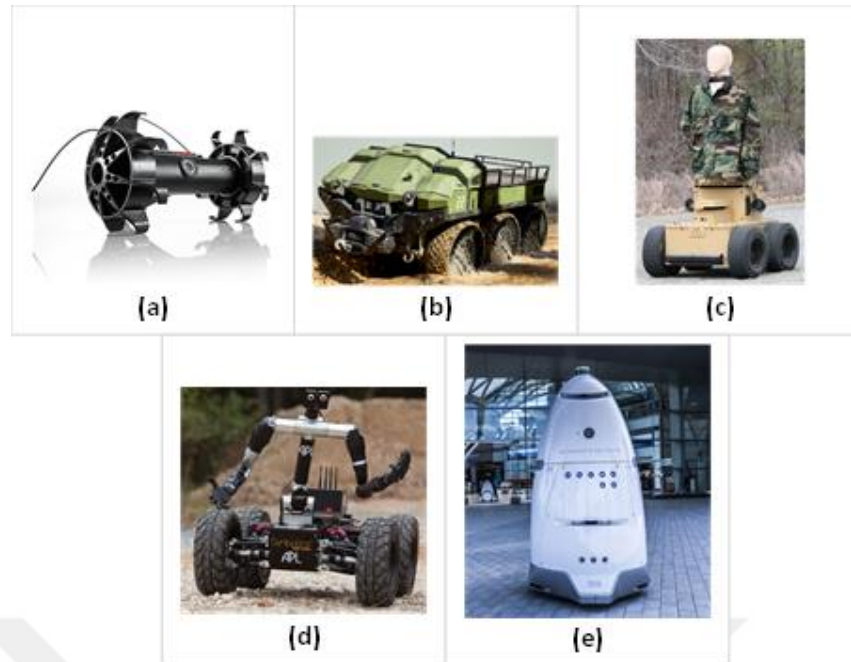


Fig. II.2: **a)** Throwbot (Robots, 2021c), **b)** HDT Hunter Wolf (HDT Global, 2022), **c)** Marathon Targets (Marathon Targets, 2015), **d)** RoboSally (Jr et al., 2013), **e)** K5 Knightscope (Robots, 2021b)

Mobile robots are widely used outside the space and military fields, where technology is developing rapidly. The most well-known of these are the mobile robots used in Amazon’s warehouses. These robots were developed by Kiva Systems, which was founded in 2003. The name of the company, which was acquired by Amazon in 2012, was changed to Amazon Robotics in 2014. These robots act by accepting the warehouse floor as a matrix where each element will fit a robot. Each robot carries an inventory pod. There are also multiple products in these inventory pods. A mobile robot first removes the inventory pod containing the product requested by the inventory station, then chooses the most appropriate path, brings it to the station, and leaves it there. The station receives the desired product, and then the mobile robot removes this inventory pod and returns it to its place in the warehouse (Ma & Koenig, 2017; Robots, 2021a; Wurman & Andrea, 2008).

Similar to Amazon Robots, mobile robots developed by Omron company (OMRON Corporation, 2020) is also used in factories, warehouses, or similar indoor environments. These robots have been developed to automate handling and shipping tasks within facilities. These robots, which can keep up with changing environments in which humans can work, offer flexible solutions. A kind of the various type of Omron mobile robots can be seen in Fig. 2.3.

In (Locus Robotics, 2022), mobile robots developed by Locus Robotics are other flexible robots. These robots are also designed to work with humans in warehouses. Unlike mobile inventory pods, as in Amazon warehouses, Locus Mobile robots provide a great convenience in warehouses with fixed inventory pods. Here, the robots carry the card instead of carrying the inventory pod. Warehouse personnel in charge of each section can put products on these mobile robotic cards and take them from there. With the help of a screen on the robot, it shows the relevant warehouse personnel which product will be taken from the pod or which product will be placed in the pod.

(KUKA AG, 2022) While Amazon, Omron, and Locus robots have been developed to carry loads that can be carried by humans in factories, warehouses, or production facilities, Kuka omniMove mobile robots have been developed by the Kuka company to carry loads that are too heavy for humans to carry. These robots can work autonomously or remotely. Mecanum wheels are used in the robots that allow going in all directions. Designed to carry heavy loads such as aircraft fuselages, these robots have a carrying capacity of up to 90 tons and can reach up to 30 meters in length.

All mentioned warehouse or facility robots are displayed in Fig. 2.3 below.



Fig. II.3: a) Amazon Robots (Robots, 2021a), b) Omron Robot (“LD-60/90 | OMRON, Türkiye,” n.d.), c) Locus Robots (Locus Robotics, 2022), d) Kuka Omnimove (KUKA AG, 2022)

Mobile robots have gone out of factories and facilities and have come to areas where people stay and spend time, such as houses, hotels, and restaurants. The most well-known of these is the Roomba cleaning robot developed by the iRobot company. With the suggestion made by Jones et al. To the iRobot company in 1999, the first-floor cleaning robot for consumers was developed. The prototype of the Roomba, this robot was initially called Scamp. This differential drive mobile floor cleaning robot had ON/OFF and mode selection switches. The robot was doing the cleaning process according to the three modes selected by the user. These mods are; wall tracking, spiral pattern, and random bounce (Jones, 2006). Fig. 2.4 shows the Scamp and today's Roomba.

Other robots that have become widespread, such as cleaning robots, are service robots used in places such as hotels and restaurants. Some of these robots are guide robot Guiding Robot Peanut (Keenon Robotics Co., 2020g), Indoor Food delivery robots Delivery Robot T1 (Keenon Robotics Co., 2020b), Delivery Robot T2 (Keenon Robotics Co., 2020c), Delivery Robot W3 (Keenon Robotics Co., 2020f), Delivery Robot T5 (Keenon Robotics Co., 2020d), Delivery Robot T6 (Keenon Robotics Co., 2020e) and disinfection robot M2 (Keenon Robotics Co., 2020a) developed by Keenon company. These robots are mobile robots that move with a differential drive system.

In addition, the mobile robot named "Relay" developed by the Savioke company is a service robot used in hotels. This robot can call an elevator on its own and get on this elevator and go to the target floor and provide room service (Savioke, 2022).

The images of referred service robots can be seen in Fig. 2.4.

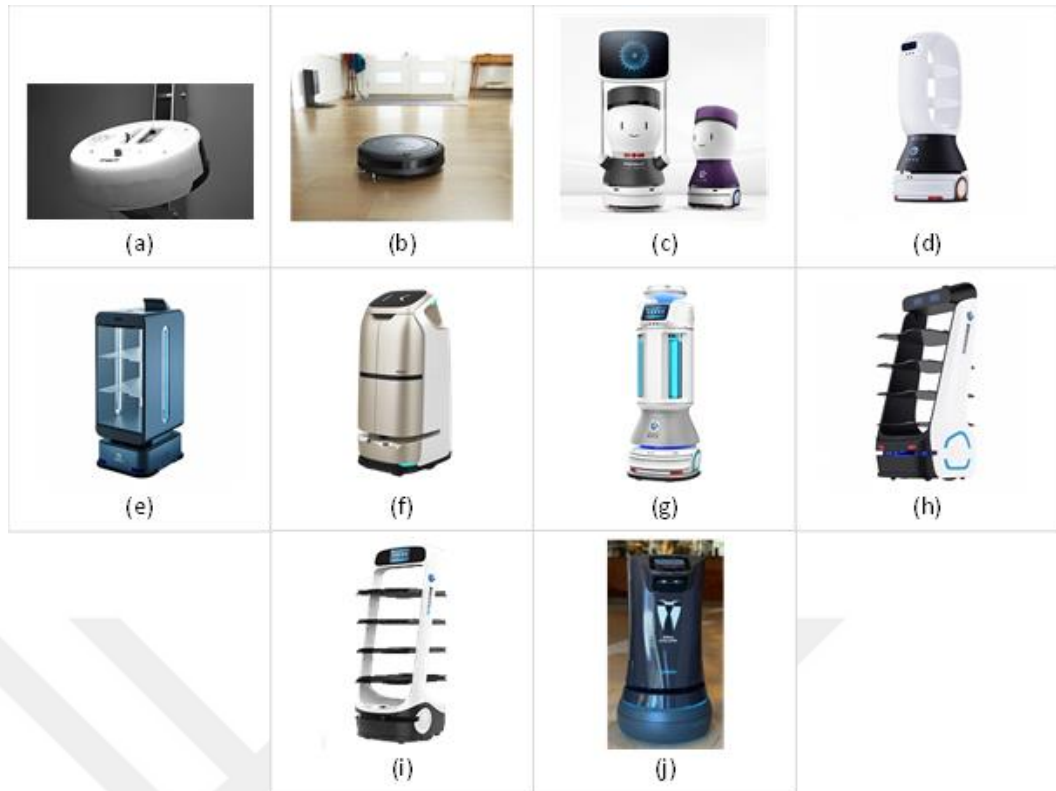


Fig. II.4: **a**) Scamp (Jones, 2006), **b**) Roomba (2022 iRobot Corporation, 2022), **c**) Guiding Robot Peanut (Keenon Robotics Co., 2020g), **d**) Delivery RobotT1 (Keenon Robotics Co., 2020b), **e**) Delivery Robot T2 (Keenon Robotics Co., 2020c), **f**) Multifunctional robot (Keenon Robotics Co., 2020f), **g**) Disinfection Robot (Keenon Robotics Co., 2020a), **h**) Delivery Robot T5 (Keenon Robotics Co., 2020d), **i**) Delivery Robot T6 (Keenon Robotics Co., 2020e) **j**) Savioke Relay (Savioke, 2022)

While mobile robots serve in the food sector, this development has also affected the agricultural lands and orchards where food is grown. Mueller-sim developed a wheeled skid-steer mobile robot called Robotanist for High-Throughput Crop Phenotyping in Mueller-Sim, Jenkins, Abel & Kantor (2017). This robot, in which cameras are used for phenotyping, is equipped with various sensors such as LIDAR and RTK GPS.

Kayacan, Zhang, & Chowdhary in (2018) and (2019) developed a low-cost and autonomous field-phenotyping robot called TerraSantia. In this robot, which is generally produced from 3D parts, 131.25:1 metal gearbox 80 RPM 12V DC Pololu brand encoder motors are used.

(Tertill, 2022) is the Tertill weeding robot, which is smaller in size compared to TerraSantia. Developed by Joe Jones, one of the creators of Roomba, this mobile robot has a different wheel structure. Tertill accepts weeds and cuts the grass that does not touch the plants in the working area, which does not touch the sensor, and that it can

pass over.

Another weed mower mobile robot is Odd.bot, developed by Den Haag-based start-up. This robot has a three-wheeled structure, and a delta robot is mounted on its ceiling (Hammon, 2020).

GUSS (Global Unmanned Spray System) is another four-wheeled mobile robot used in agriculture. This robot is used to spray orchards. It has a 90-gallon tank (GUSS, 2022). Also, when people wearing a vest carrying a wireless transmitter, produced by GUSS company, approach the robot, the robot's motors stop immediately (Hekkert, 2021). The agricultural robots mentioned in the study can be seen in Fig. 2.5.



Fig. II.5: **a)** Robotanist (Mueller-sim et al., 2017), **b)** TerraSantia (Kayacan et al., 2018), **c)** Tertill (Tertill, 2022), **d)** Odd.bot (Hammon, 2020), **e)** GUSS (GUSS, 2022)

With the widespread use of mobile robots, curricula for the use of mobile robots have begun to be created in the education sector in order to train qualified people who will use and further develop these robots (Kaya, 2021). In addition, researchers started to feel the need to test the algorithms they developed with mobile robots in laboratories. The most common mobile robot platform known to meet these needs is TurtleBot. The first Turtlebot was built in 2010 with the base iRobot Create (Kaya, 2021). To date, 3 TurtleBot families have been developed. All developed TurtleBots have a differential driving system. In addition to being mobile robots with different features in each family,

the most important feature of these robots is that they are open source.

Another popular mobile research robot family is Pioneer, as seen in (MobileRobots Inc., 2006). The first Pioneer mobile robot was introduced in 1995. Later on, Pioneers, which were produced in different versions, have both two-wheeled and four-wheeled structures and move with a differential drive system. However, it is unfortunate that MobileRobots, the Academic Research and Robotics division of Omron Adept Technologies, which has been in business for 20 years, was permanently closed on 31.01.2018 (MobileRobotsInc., 2017).

Another educational mobile robot smaller than TurtleBot and Pioneer robots is JetBot. JetBot, an open-source mobile robot platform designed by Nvidia, enables the testing of artificial intelligence applications with a small computer and camera on it. This robot, which is easy to set up, is also quite affordable. The robot, which is installed on two driven wheels and a caster wheel, provides its movement with a differential drive system (Nvidia, 2019).

Like JetBot, it is a different development robot with an Ackerman driving system in MIT Racecar, which is used in many lectures and research at MIT. This fully open source mobile robot has also pioneered the development of similar research robots such as MuSHR (Multi-agent System for non-Holonomic Racing) (Kaya, 2021).

All the members of the TurtleBot family and the other mentioned research & education-oriented mobile robots appear in Fig. 2.6.

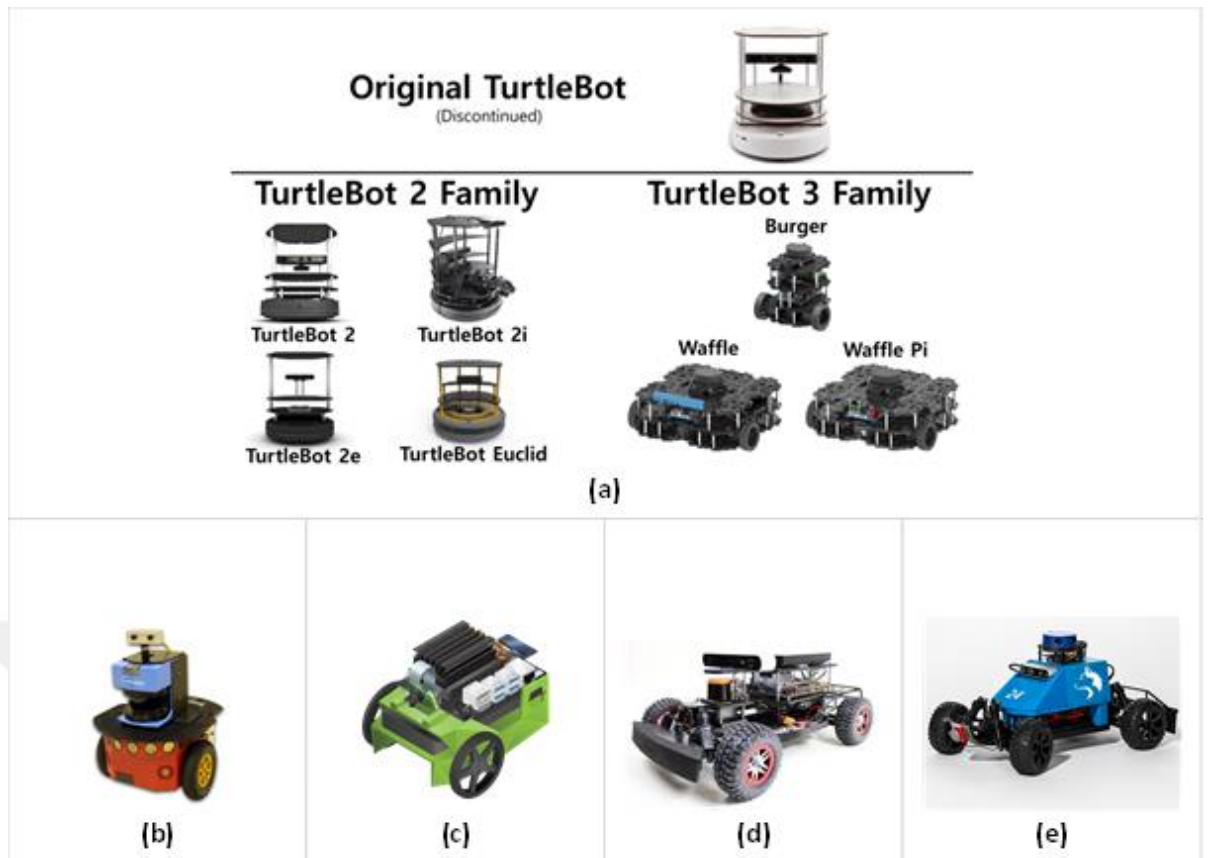


Fig. II.6: **a)** Turtlebot Family (Open Source Robotics Foundation, n.d.), **b)** Pioneer P3-DX (IEEE, 2022), **c)** JetBot (Nvidia, 2019), **d)** MIT RACECAR/J (JetsonHacks, 2022), **e)** MuSHR (Osborne, 2019)

Apart from the above-mentioned mobile robots developed mainly for indoor research, wheeled mobile robots have also been developed for outdoor research, such as Leo Rover (Kell ideas sp. z o.o., 2017), Jackal UGV (Clearpath Robotics Inc., n.d.), Husky UGV (Clearpath Robotics Inc., n.d.), Warthog UGV (Clearpath Robotics Inc., n.d.) and Moose UGV (Clearpath Robotics Inc., n.d.). The UGV robots appear in Fig. 2.7.



Fig. II.7: **a)** Leo Rover (Kell ideas sp. z o.o., 2017), **b)** Jackal UGV (Clearpath Robotics Inc., n.d.), **c)** Husky UGV (Clearpath Robotics Inc., n.d.), **d)** Warthog UGV (Clearpath Robotics Inc., n.d.), **e)** Moose UGV (Clearpath Robotics Inc., n.d.)

Mobile robots and their usage areas are not limited to the resources scanned within the scope of this study. However, since this is not a survey or review, the scope of the literature review is limited to the studies examined. In addition to the studies discussed above, mobile robots also take part in the last step of the delivery chain. At this point, the most well-known delivery robots are Starship (Starship Technologies, n.d.-c), KiwiBot (Kiwibot, n.d.), and Postmates Serve (POSTMATES INC, 2022; Serve Robotics Inc, 2022b), Cocobot (Cyan Robotics Inc., n.d.-a) and Yandex.Rover (Yandex, 2015a) and they are shown in Fig. 2.8. These robots and others are discussed in detail in section 2.4, Delivery Robots & Drive Mechanisms.

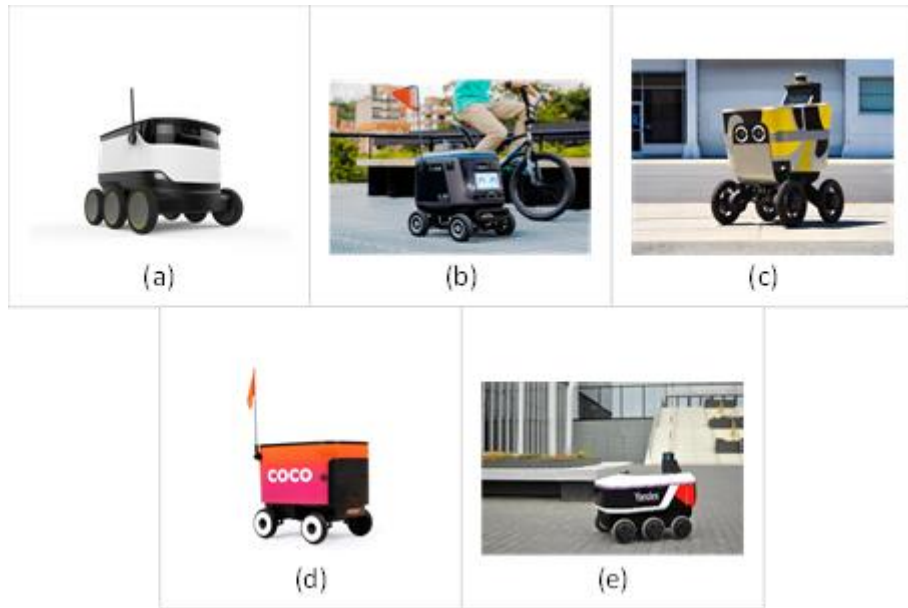


Fig. II.8: **a)** Starship Robot (Starship Technologies, n.d.-b), **b)** Kiwibot (Kiwibot, n.d.), **c)** Postmates Serve (Serve Robotics Inc, 2022a), **d)** Cocobot (Cyan Robotics Inc., n.d.-b), **e)** Yandex.Rover (Yandex Self-Driving Team, 2020)

2.2 Autonomous Mobile Robots

An autonomous robot means a robot that can operate independently of human guidance during its task. According to this definition, the first autonomous roaming robot is Elmer and Elsie, developed by William Gray Walter. These mobile robots, also known as tortoises, are robots that find their way by following the light source and continue on their way by avoiding the obstacles they encounter (Bladin, 2006).

After these robots, the most well-known general-purpose autonomous mobile robot was developed by the Artificial Intelligence Center at the Stanford Research Institute between 1960 and 1972. Nicknamed “Shakey,” this mobile robot could sense its surroundings, albeit limited, with the ability to plan, find routes, and move simple objects (Kara, 2020; Nilsson, 1984; SRI INTERNATIONAL, 2021). It has also been a source of inspiration for many scientists.

The Elsie of the tortoises and the Shakey are displayed in Fig. 2.9.

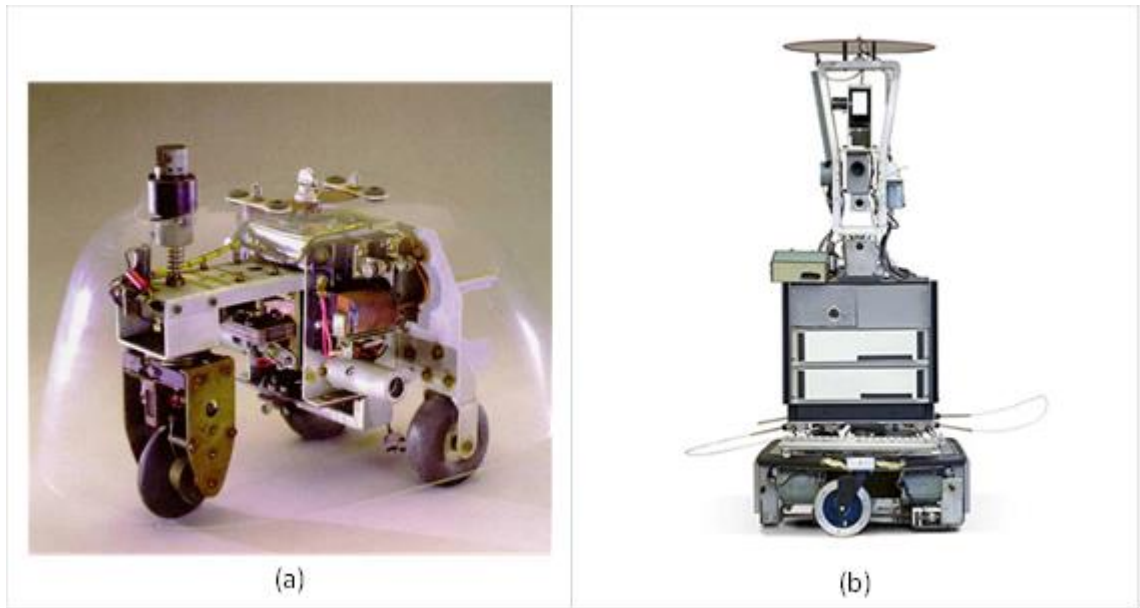


Fig. II.9: **a)** Elsie of the Walter’s Tortoises (The Old Robots, 2010), **b)** Shakey the Robot (SRI INTERNATIONAL, 2021)

With the developments in sensor, camera, and sensing technologies, these autonomous mobile robots have also developed and gained a high level of autonomy ability. These developments may also have been triggered by the need to seek remedies for repetitive tasks. Many of the robots reviewed in the previous section have a wheeled structure as well as autonomous capabilities. The robots such as Amazon warehouse robots (Robots, 2021a), Locus robots (Locus Robotics, 2022), Roomba (Jones, 2006), Guiding Robot Peanut (Keenon Robotics Co., 2020g), Keenon Delivery robots (Keenon Robotics Co., 2020b, 2020c, 2020f, 2020d, 2020e), Tertill (Tertill, 2022), Starship (Starship Technologies, n.d.-a), KiwiBot (Kiwibot, n.d.), Postmates Serve (POSTMATES INC, 2022), etc. Can be given as the examples of autonomous mobile robots. Because these robots are equipped with various sound and light sensors, they can perceive their environment, process the data they perceive, and perform their tasks with various algorithms. Some of these sensors are ultrasonic sensors, LIDAR, RADAR, GPS, etc. In Fig. 2.10, these sensors appear as examples. Mobile robots, as the name suggests, are used in jobs that require walking. While doing these works, they have to avoid the fixed and moving obstacles and follow a route. Therefore, various algorithms such as obstacle avoidance, collision avoidance, trajectory tracking are indispensable for autonomous mobile robots.

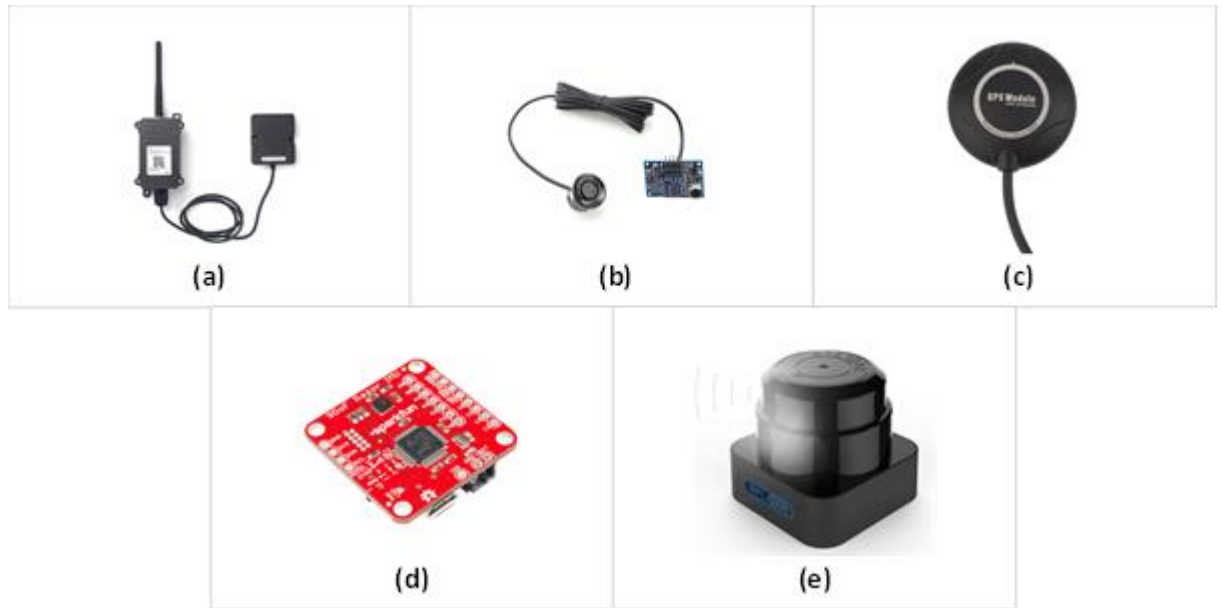


Fig. II.10: **a)** Dragino LMDS200 LoRaWAN Microwave Radar Distance Detection Sensor (US915) (RoboShop Inc., 2020a), **b)** JSN-SRO4T Ultrasonic Sensor (RoboShop Inc., 2020b), **c)** Ublox NEO M8N (AliExpress.com, 2022), **d)** SparkFun 9DoF Razor IMU M0 (SparkFun Electronics, n.d.), **e)** Slamtec RPLIDAR S1 (Shanghai Slamtec Co., 2022)

2.3 Eight-Wheeled Mobile Robots

Since an eight-wheeled mobile robot body was designed in this study, eight-wheeled robots were also examined in the sources. The first is the Explora XL, produced by the Australian Droid+Robot company. This robot is an eight-wheel skid-steering robot with independent suspension. It was developed with the request of an “indestructible robot” of a company’s customer working in the mining field. The robot consists of a fully welded aluminum body and aluminum + steel suspension system that is highly resistant to the most rugged and harshest environments. In addition, according to the company’s experience, it performs very well in climbing or descending pavements (Australian Droid + Robot, 2022; Australian Droid and Robot, 2021).

Another eight-wheeled mobile robot platform was developed by Robot-Nest company to strengthen its law enforcement and has many Latvian patents. It is planned to continue the development of this non-commercial robot. (RobotNest, 2022). The robot appears in Fig. 2.11.

The eight-wheeled robots in (Harvey, 2007) are Lunokhod 1 and 2, the first roaming robots to navigate the lunar surface. The first Lunokhod was sent to the Moon by the

Soviet Union on November 10, 1970, with the Luna 17 spacecraft. This robot, which inspired science fiction artworks in the space races between the USA and the USSR, was first developed to pave the way for the Russians to land on the manned moon. One of them is the story “Lunnaya Doroga (Lunar Road)” by Alexander Kazanstev, in which a Soviet space traveler robot saves an American stuck on the Moon. Lunokhod means Moon Walker in English. Sojourner, which the Americans landed on Mars in 1997, was relatively small. But the Russians started by designing a large rover in traditional Soviet style. The vehicle, which emerged as a result of design and development studies, weighed 756 kg, was 4.42 m long, 2.15 m in diameter, and 1.92 m high with the lid open. Splitter the wheelbase of the rover was 2.22 m by 1.6 m—camera, transmitters, etc. The main vessel carrying scientific instruments was a pressure vessel resembling a bathtub. The wheels of Lunokhod, which consists of eight wheels, each with a diameter of 510 mm, are manufactured at the Kharkov National Bicycle Factory. Each wheel was driven by an electric motor. If one of the wheels got stuck in one place, the rover could cause that wheel to separate from the main body with a small explosion. The rover could climb 20° uphill and navigate horizontally on slopes of 40° to 45°. Rover’s designers include Alexander Kermurdzhian, Gary Rogovsky, Pavel Sologub, Valery Gromov, Anatoli Mitskevich, and Slava Mishkinjuk. Lunokhod is equipped with four panoramic cameras, each weighing 1.3 kg, to perceive its surroundings in 360°. It is also equipped with two 50° television cameras to perceive the future. Panoramic cameras were able to take high-resolution photos of 6000 x 500 pixels. The driver’s camera was sending pictures to the world every 20 seconds. At the ground station in Crimea, the ground control team of 5 people was looking at these pictures and directing the robot on the lunar surface. The ground crew included a commander, a driver, a direction finder, an engineer, and a radio operator. If the robot tilts forward or backward too much, it stops its movement thanks to the Gyroscopes it contains. As Harvey (2007) said of Lunokhod 1: *“It was an unlikely-looking contraption – on first impression more the outcome of a Jules Verne or HG Wells type of sketch rather than a tool of modern moon exploration”*(p. 253). On November 17, 1970, Lunokhod came into contact with the lunar surface by descending from one of the two-sided ramps designed with the negativities in the landing area in mind. His first move was 20 m. He advanced 90 m that day. The next day was 100 m, and this distance increased in the following days. All the wheels of the robot were spinning at the same speed. It was like a tank on the turns.

The wheels on one side were spinning faster, while those on the other side were turning slower. Thus, the robot took the corner. With this structure, it was a skid-steering mobile robot. Lunokhod 1 stopped working again on October 4, 1971, while on duty. Lunokhod 1, which was intended to serve for 3 months, achieved a surprising success and served for approximately 11 months. In this process, it covered an area of 80.000 m² by covering 10.54 km. Lunokhod 1, which sent a total of 20,000 images, 200 of which were panoramic, to the world, conducted experiments by exposing 25 different regions on the Moon's surface to X-Ray rays.

Table 2.1 shows the features of Lunokhod 1 and the scientific measurement tools it carries.

Table II.1: The specifications and scientific measurement tools of the Lunokhod 1

Parameter	Specification
Weight	756 kg
Diameter	2100 mm
Height	1350 mm
Wheel Base	2220 x 1600 mm
Number of Wheels	8
Wheel Diameter	510 mm
Speed	0.8 to 2 km/hr
Operation Duration	Three months
Measuring Instruments	
Laser Reflector	
RIFMA (Roentgen Isotopic Fluorescent Method of Analysis) X-Ray Fluorescent Spectrometer	
Extra-Galactic X-Ray Telescope	
Cosmic Ray Background Radiation Detector	
PrOP (Pribori Ochenki Prokhodimosti) Penetrometer	

Yuan (2004) was designed as an eight-wheeled stair-climbing robot for use in outdoor environments for the physically handicapped. This robot named "Zero Carrier" consists of eight legs with prismatic joints. There are four active wheels at the ends of four of these legs, and the remaining ones have caster wheels. Each of the legs glides independently of the others. It is a robot with eight linear leg movements and four active

wheels, with a total of twelve degrees of freedom. The developed robot demonstrated the operability of the proposed concept by climbing a two-step ladder.

Takita (2004) designed and developed an eight-wheeled mobile robot for bumpy environments and stair climbing. The most crucial point in this robot is the mechanism consisting of two wheels and an arm. There are a total of four of these mechanisms, two of which are on one side of the robot, and two are on the other side. The rotation of the wheels in the mechanism and the rotation of the arm are provided by servo motors. Thus, the robot can transform into a four-wheeled and an eight-wheeled form. This robot, called the “Octal Wheel,” was tested with a two-step ladder, each step of which is equal to the diameter of the wheels. The robot successfully climbed this ladder and then descended it.

All mentioned eight-wheeled mobile robots are shown in Fig. 2.11 below.

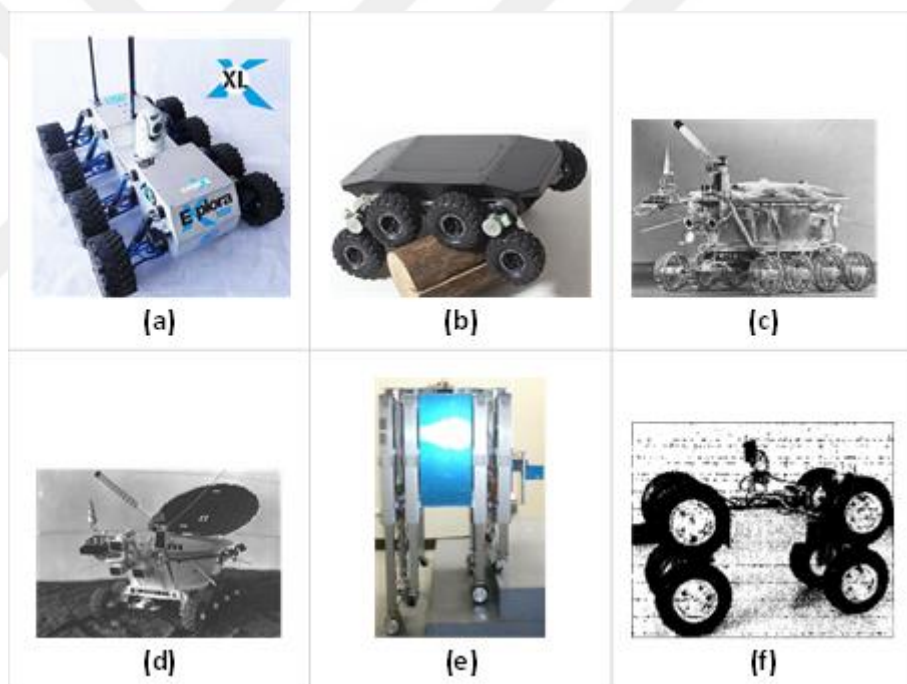


Fig. II.11: **a)** Explora XL (Australian Droid + Robot, 2022), **b)** RobotNest (RobotNest, 2022), **c)** Lunokhod 1 (Nasennik, 2014), **d)** Lunokhod 2 (Nasennik, 2014), **e)** Zero Carrier (Yuan, 2004), **f)** Octal Wheel (Takita et al., 2004)

2.4 Delivery Robots & Drive Mechanisms

2.4.1 Starship Delivery Robot



Fig. II.12: Starship Delivery Robot (Starship Technologies, n.d.-b)

Founded in 2014 by Skype co-founders Ahti Heinla and Janus Friis, Starship Technologies has grown into a gigantic delivery robot company capable of delivering tens of thousands of deliveries in just one day. Starship, an Estonia-based company, has spread to various countries from Estonia to the USA, with the first robot starting to spin its wheels in 2015. It is widely used in cities and university campuses. Customers can order Parcels, groceries, and food via the mobile application of the company. The robot delivers these orders to its customers on the same day using the sidewalk. The travel speed of the robot is up to one arc. Also, the robot's cargo bay is locked until it fulfills its delivery mission. Only customers can unlock the mobile application. Robots have gained an autonomous structure with the improvements made in computer vision, path planning, and obstacle detection. However, in some cases, it requires human intervention. Also another critical issue for these robots is reliability. When the robots are disconnected, they stay where they are. This makes them reliable (Boysen, Fedtke, & Schwerdfeger, 2021; Heinla, 2018; Kosonen, 2020; Lääne, 2020; Starship Technologies, n.d.-a).

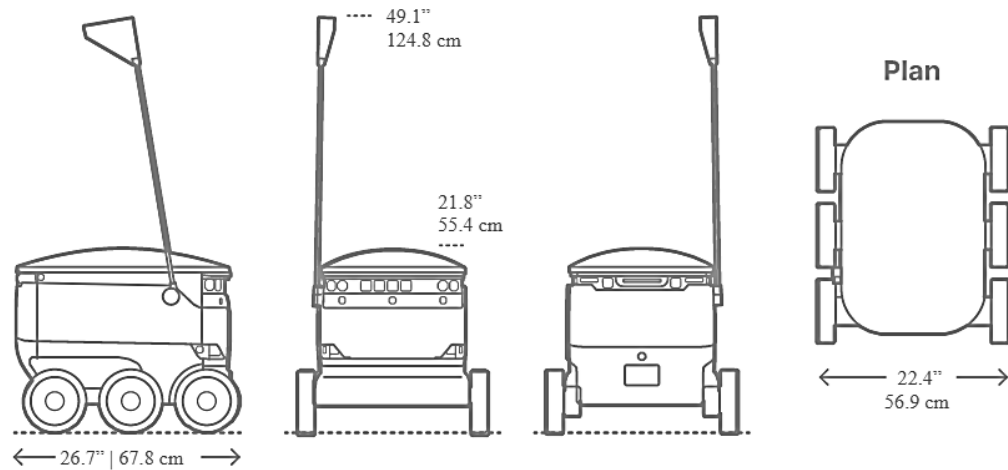


Fig. II.13: Starship Delivery Robot’s Outer Dimensions (Martinez, 2020d)

The outer dimensions of the Starship Delivery robot, which is a six-wheeled Skid-Steer robot, are given in Fig. 2.13. Other technical specifications are presented in Table 2.2. It has a Bogie mechanism for curb climbing (Kosonen, 2020). Despite this, the robot occasionally has problems with curb climbing.

2.4.2 KiwiBot Delivery Robot

Kiwibot, seen in Fig. 2.14, is a Colombian delivery robot company founded in 2017 under the leadership of Felipe Chávez. It conducted its first pilot study at the University of California-Berkeley campus. The journey that started on university campuses with the aim of delivering food to students has spread out of the campus with the increase in demand and reached the streets. Kiwibot, which continues its rapid rise, has spread to countries such as Colombia, Taiwan, and Australia outside the USA (Kiwibot, 2019, 2022; Sodexo, 2022).



Fig. II.14: KiwiBot Delivery Robot (Kiwibot, 2022)

The outer dimensions of the Kiwibot Delivery Robot, which is a four-wheeled Ackerman-Steer robot, are given in Fig. 2.15. Other technical specifications are presented in Table 2.2.

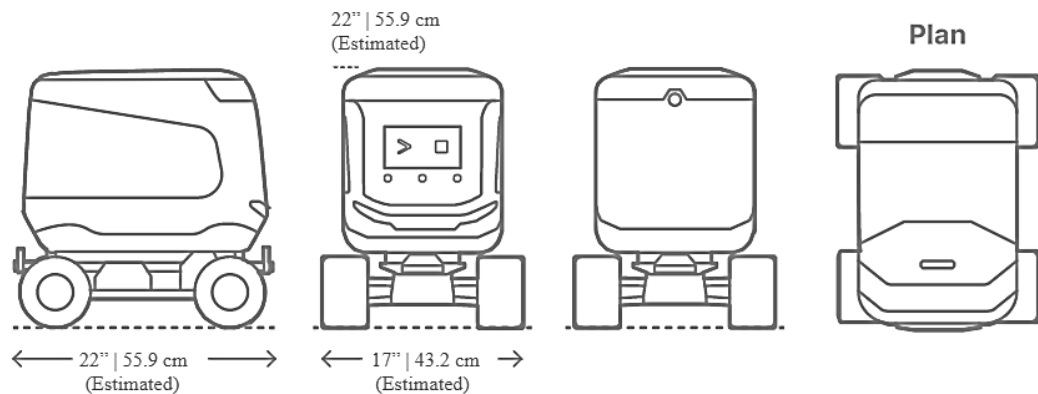


Fig. II.15: KiwiBot Delivery Robot's Outer Dimensions (Martinez, 2020c)

(Kiwibot, 2021) has clearly demonstrated the evolution of Kiwibot. These are as follows:

- **Stage 0:** Efforts within the concept frame. There is no robot but a prototype being controlled remotely for delivery in a small area

- **Stage 1:** In this stage, in order to assist the KiwiBots the robot operators were assigned. The company aimed to provide safer and faster delivery operations.
- **Stage 2:** During stage 3, the KiwiBot 3.0 series was introduced. The robot was partially automatized, especially the perception was improved. The various sensors were employed to robot cope with the environmental challenges.
- **Stage 3:** In Stage 3, from the beginning until today, the new KiwiBot 4.0 series was launched. The company developed and deployed the semi-autonomous driving system by means of previous experiences.

2.4.3 Postmates Serve Delivery Robot



Fig. II.16: Postmates Serve Delivery Robot (Serve Robotics Inc, 2022a)

Serve Robotics was founded in 2017 as the Robotics division of food delivery company Postmates. The firm describes itself as the first autonomous vehicle company to complete commercial deliveries at Level 4 autonomy (Serve Robotics Inc, 2022c).

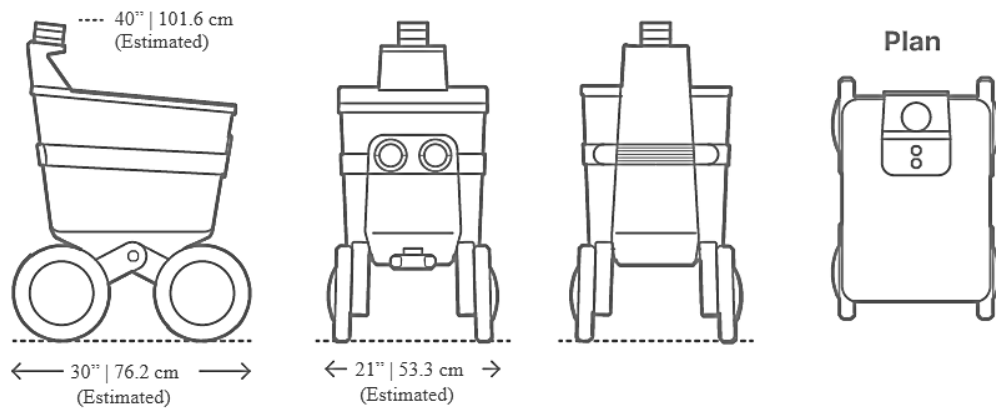


Fig. II.17: Postmates Serve Delivery Robot’s Outer Dimensions (“Serve (Serve Robotics) Dimensions & Drawings | Dimensions.Com,” 2022)

Postmates Serve Delivery Robot, which has four independent wheels as in Fig. 2.16, has the ability to rotate in two different axes with its two front wheels. This is reminiscent of the Ackerman-Steering drive mechanism. However, these two front wheels are not fixed to the same mechanical axle or similar parts. They can be driven independently of each other.

In addition, the Postmates Serve Delivery Robot, whose design is similar to a grocery cart, was among TIME Magazine’s 100 best inventions of 2019. Other features of the robot, whose outer dimensions are given in Fig. 2.17, are also presented in Table 2.2.

To achieve Level 4 autonomy, a single operator can monitor 4 Postmates Serve Delivery Robots simultaneously. (Serve Robotics, 2022). The operator only directs the robot when the robots ask for help.

2.4.4 Cocobot Delivery Robot



Fig. II.18: Cocobot Delivery Robot (Cyan Robotics Inc., n.d.-b)

Founded under the leadership of Zach Rash, Coco Delivery carries out its deliveries with remote-controlled delivery robots. One of them is shown in Fig. 2.18. Unlike Starship, Kiwi, and Postmates Serve, Cocobot is not an autonomous delivery robot. Cocobot is a remotely guided delivery robot, although it has various sensors such as a camera and GPS. Therefore, each robot is guided by a single operator. They are also equipped with sound systems to communicate with pedestrians and customers. Cocobots used by Coco Delivery company are manufactured by Segway company (Bellan, 2021; Cyan Robotics Inc, n.d.; Gibson, n.d.; Mendez, 2021; Segway Inc., 2015).

There is no clear and detailed information about the external dimensions and technical features of Cocobot, which has four wheels and a suspension system. The obtained information is presented in Table 2.2.

2.4.5 Yandex.Rover Delivery Robot



Fig. II.19: Yandex.Rover Delivery Robot (Yandex Self-Driving Team, 2021)

Developed by Yandex Self-Driving Group, the delivery robot is named Yandex.Rover has a six-wheeled structure and has Skid-Steer steering. It has suspension systems to tolerate curb climbing and road disturbances. The front axle of the robot has independent leaf spring suspension, while the rear two axles have leaf spring bogie suspensions. In addition, the robot has a height of more than 100 mm from the ground when fully loaded. The technology developed by Yandex SDG for self-driving cars has been transferred to this robot with some adjustments. The first tests were conducted at Yandex's campus in Moscow. His first task was to deliver documents to Yandex's management office in Skolkovo. These robots, which have an autonomous structure, are not monitored instantly, as in Starship and Postmates Serve. However, when the robot needs it, it sends a signal to the operator, and the operator takes control of the robot. After the need is met, the robot continues its task autonomously. (Shveyko, 2019; Yandex, 2015b, 2019; Yandex Self-Driving Team, 2020).



Fig. II.20: Suspension Test Device (Yandex Self-Driving Team, 2021)

On another critical issue, a test track has been prepared that will constantly test the robot. The robot is tested with various scenarios, talking about location and season. The company has developed its unique winter tire for winter conditions and has tried it on its track containing artificial snow (sodium polyacrylate). (Yandex Self-Driving Team & Alexey, 2021).

A test device has also been developed for testing suspension systems. (Yandex Self-Driving Team, 2021; Yandex Self-Driving Team & Alexey, 2021). It can be seen in Fig. 2.20. Table 2.2 presents the technical specifications of the robot.

2.4.6 Amazon Scout Delivery Robot



Fig. II.21: Amazon Scout Delivery Robot (Scott, 2019)

Amazon started working a few years ago to take advantage of its robots in the outer environment after indoors. As a result of these studies, Amazon Scout Delivery Robot seen in Fig. 2.21 took the stage in 2019 to be used in the last step of the supply chain. (Gantenbein, 2020; Scott, 2019).

This robot has a six-wheeled structure and has a bogie system like Starship and Yandex.Rover. The bogie system is a handy and straightforward suspension system for curb climbing, small ascents, and descents.

Autonomy tests of the unused Amazon Scout, which is not yet commercial, continue. No detailed technical information was found about the robot, and the external dimensions were presented in Fig. 2.22.

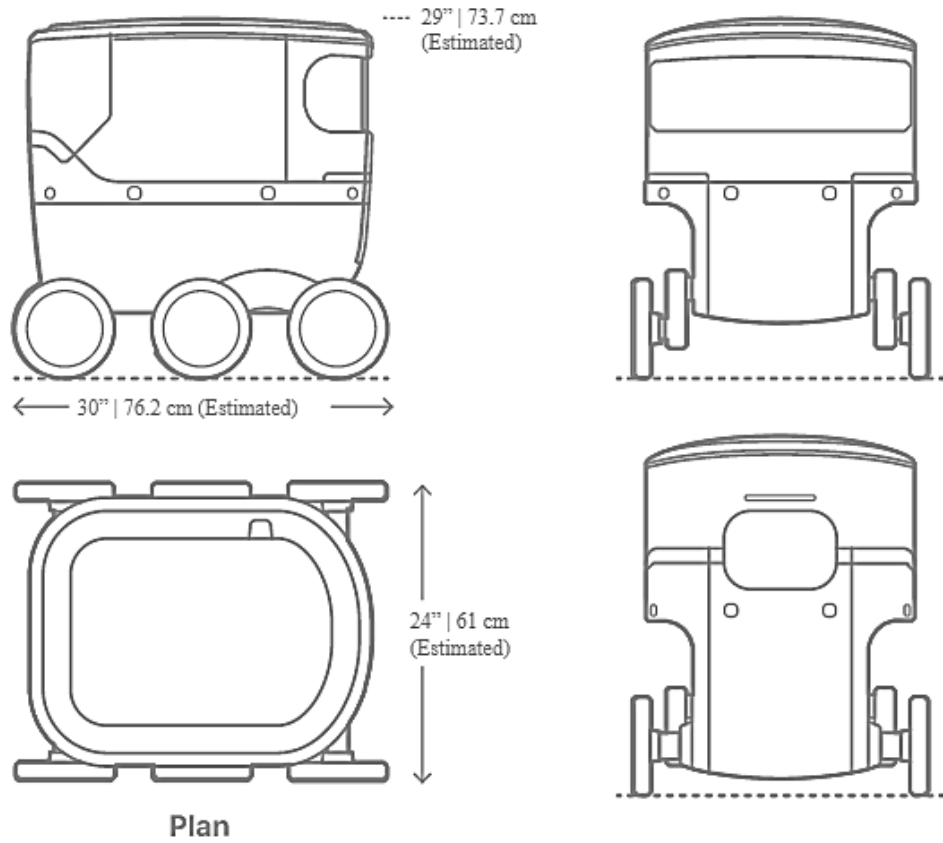


Fig. II.22: Amazon Scout Delivery Robot's Outer Dimensions (Martinez, 2020a)

2.4.7 FedEx Roxo Delivery Robot



Fig. II.23: FedEx Same Day Delivery Robot (FedEx, n.d.-a)

Another test-stage delivery robot is FedEx Roxo. Although FedEx Roxo has six wheels like many other delivery robots, its mechanism is different compared to the others. Four of the six wheels are driven by the motor, while the front two wheels are freewheels. This robot actually uses the iBot electric wheelchair base designed by the Deka company to provide mobility and dignity to paraplegic veterans (FedEx, n.d.-b, n.d.-a). The original seat was removed, and the cargo compartment was placed there. The robot easily climbs up and down the curbs.

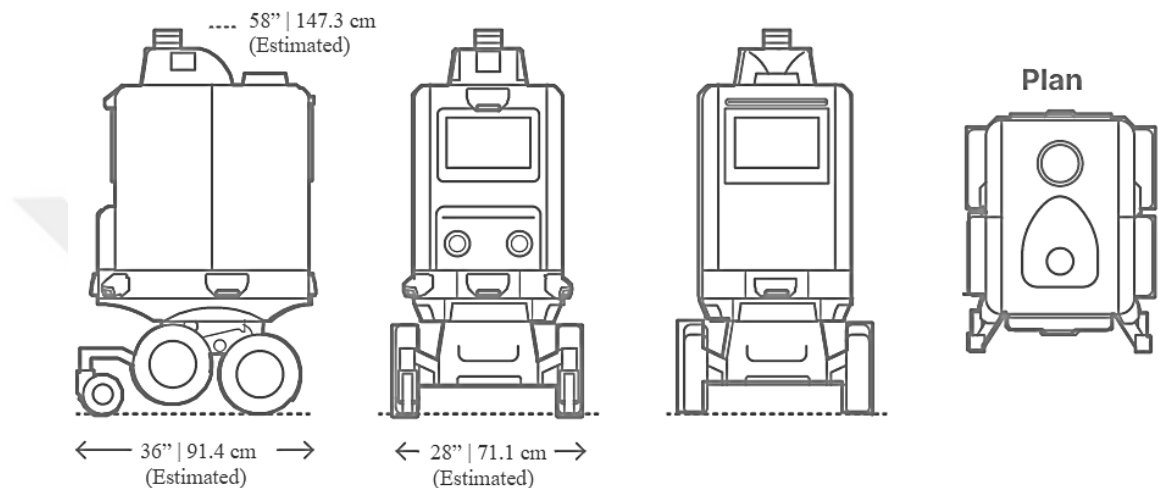


Fig. II.24: FedEx Roxo Delivery Robot’s Outer Dimensions (Martinez, 2020b)

Detailed technical specifications of the robot, whose external dimensions are presented in Fig. 2.24, can be observed in Table 2.2.

The most distinctive feature that distinguishes FedEx Roxo from other robots is that it is a very high robot. He is almost as tall as a young man. Its height allows it to detect people and other high objects more easily. Autonomy studies of the robot continue (FedEx, n.d.-a).

The specifications of all mentioned mobile delivery robots until this point were presented in Table 2.2 in detail.

Table II.2: The Specifications of All Mentioned Mobile Delivery Robots (FedEx, n.d.-a; Korosec, 2020; Mendez, 2021; Scott, 2019; “Serve (Serve Robotics) Dimensions & Drawings | Dimensions.Com,” 2022; Sodexo, n.d.; Swiss Post, 2017; Yandex, 2015a, 2015b; Yandex Self-Driving Team, 2021; Yandex Self-Driving Team & Alexey, 2021)

Delivery Robot	Starship	KiwiBot	Postmates Serve	CocoBot	Yandex Rover	Amazon Scout	FedEx Roxo
Weight	23 kg	20.5 kg	73 kg	23 kg	70 kg	Unknown	204 kg
Battery Life	2 h	Unknown	Unknown	Unknown	10 h	Unknown	Unknown
Max. Speed	6 km/h	3.9 km/h	10 km/h	Unknown	5-8 km/h	Unknown	Unknown
Average Speed	3 km/h	Unknown	Unknown	Unknown	3-5 km/h	Unknown	Unknown
Cargo Space	402x344x330 mm	Unknown	790x640x1050 mm	Unknown	420x420x250 mm	Unknown	Unknown
Max. Cargo Weight	10 kg	4 kg	23 kg	Unknown	20 kg	Unknown	45 kg
Snow	Yes (Max. 2 cm snow tickness)	Unknown	Unknown	Unknown	Yes	Unknown	Unknown
Rain	Yes	Unknown	Unknown	Unknown	Yes	Unknown	Unknown
Darkness	Not yet	Yes	Yes	Unknown	Yes	Unknown	Unknown
Temperature	-5C° to +40C°	Unknown	Unknown	-20C° to 60C°	Unknown	Unknown	Unknown
Camera	Yes (3 front, 4 sides, 2 rear)	Yes (3 front, 1 innerbag)	Yes	Yes	Yes (5)	Unknown	Yes (2)
Ultrasonic Sensor	Yes (8)	Unknown	Yes	Unknown	Yes (7)	Unknown	Yes
RADAR	Yes	No	No	No	Yes (2)	Unknown	Yes
LIDAR	No	Yes (5 front, 1 rear, 2 rear wide angle)	Yes	No	Yes	Unknown	Yes
IMU	Yes (2)	Yes	Unknown	Unknown	Yes	Unknown	Yes
GPS	Yes	Yes	Unknown	Yes	Yes	Unknown	Unknown
Motors	Yes (Brushless DC Motors)	Yes	Yes	Yes	Yes	Yes	Yes
Battery	8000 mAh	15.6 V	Yes	Yes	Yes	Yes	Yes

	18.5 V						
	Lithium						
	Polymer						
Charger							
Input	100-240 V	Detachable Battery	Unknown	Unknown	Unknown	Unknown	Unknown
Voltage							
Charge							
Consumption	Up to 250 W	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

2.4.8 Other Delivery Robots

To solve the last-mile delivery problem, many delivery robot startups have started to emerge worldwide in recent years. The most known and common ones are examined. As a result of an in-depth survey or review, in addition to the above robots, Switzerland-based TeleRetail (German Design Council, n.d.; TeleRetail, 2022), Canada-based TinyMile (Lightfoot, 2020b; Tiny Mile, 2021), China-based RoboPony (Singh, Dalla, & Shrivastava, 2021; Zhen Robotics, 2016), etc. delivery robots can also be found. These robots also work with differential drive or Skid-Steer driving systems. These are presented in Fig. 2.25.



Fig. II.25: a) TeleRetail Delivery Robot (German Design Council, n.d.), b) TinyMile Delivery Robot (Lightfoot, 2020b), c) RoboPony Delivery Robot (Singh et al., 2021)

CHAPTER III METHODOLOGY

This chapter presents the hardware and software of the designed eight-wheeled semi-autonomous delivery robot. Firstly, the general structure of the robot is outlined. Then, the robot is divided into three sub-categories and explained in detail in these categories.

3.1 The General Structure of the Robot

The robot's final design is shown in Fig 3.1, and the prototype of the design is displayed in Fig 3.2. On the other hand, the robot's electrical & electronics general diagram is presented in Fig. 3.3. The robot has eight wheels with two separate bogie systems.



Fig. III.1: The Final Design of Proposed Robot

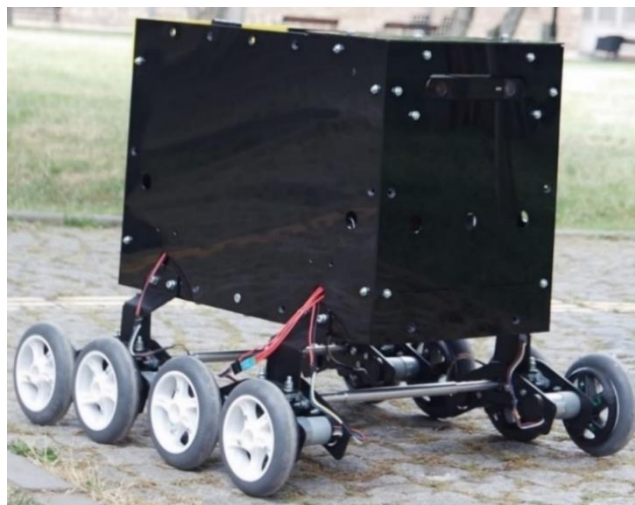


Fig. III.2: The Prototype of the Final Design

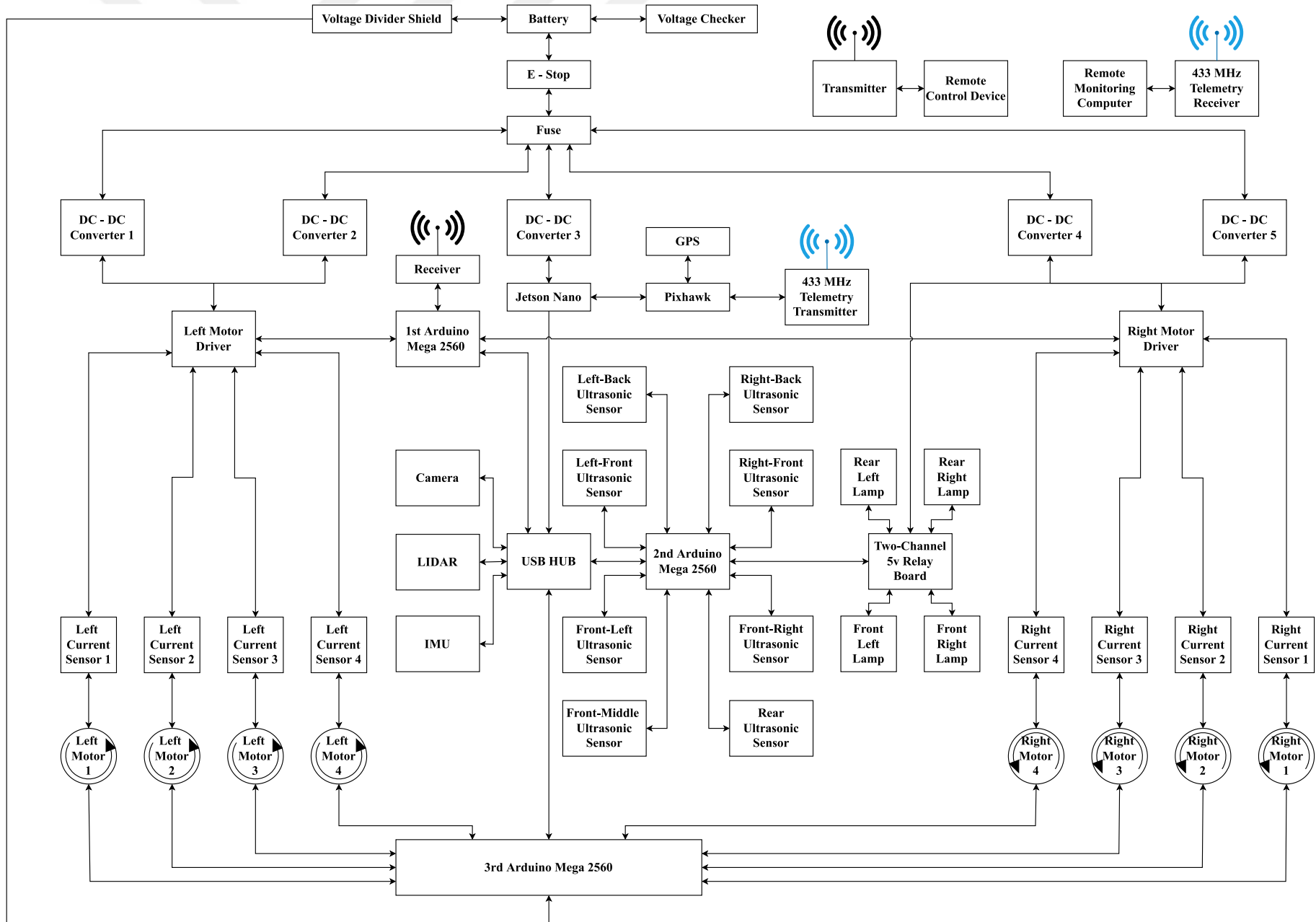


Fig. III.3: General Electrical & Electronics Diagram of the Proposed Eight-Wheeled Semi-Autonomous Delivery Robot

The components shown in Fig 3.3 are expressed in detail in section 3.3. However, those components are roughly mentioned in Table 3.1.

Table III.1: Quick Facts of the Electronic Components (Handson Technology, n.d.; NVIDIA Corporation, 2022; oyuncakhobi.com, n.d.; Pololu Corporation, 2022a; robolinkmarket, n.d.-a, n.d.-b; Shanghai Slamtec Co., 2022; Siemens, 2022)

Quick Facts of the Electronic Components	
Battery	It is the whole robot's energy source. Its specifications are 22000 mAh, 14.8 V 25 C. It has four cells.
Fuse	A 32A monophas fuse was used for power on and off.
E-Stop	A standard emergency stop button was used on top of the robot for any dangerous situation. E-Stop button was placed right after 32A-Fuse. It cuts the power immediately when the button is pressed.
DC-DC Converters	In order to convert the battery voltage to the required voltage level, DC-DC Converters were used. The robot has eight wheels and a couple of electronic cards. Therefore, five 300W/20A DC-DC Buck Converter modules were employed.
Motor Drivers	Two 43A-Motor Drivers were used in the robot. One of them drives the left-side motors, and the other drives the right-side motors. Each motor's stall current is 5.5A. Four of them equals 22A. Because of the total stall currents of each-side motor, the 40A-motor drivers were chosen.
Current Sensors	Current sensors were exploited to measure the current that the motor draws. Because it was planned to limit the current below the stall current of the motor. The used current sensors are capable of handling bidirectional current from -30A to +30A.
Motors	In the designed robot, the torque was preferred rather than speed. Therefore, the motors which have 131:1 Metal Gearmotor, 760RPM no-load speed, and 45kg.cm extrapolated stall torque was selected.
2 Channel / 5V Relay Card	Two-channel relay card were had for the lamps on the front and back sides of the robot.
Lamps	Four lamps were planned to use on the robot. Two of them for front signals and the last two for the back signals.
Ultrasonic Sensors	Firstly, the eight ultrasonic sensors were planned. But, then four of them were decided on the proofing of the concept.
Jetson Nano	Jetson Nano is the main board of the robot. All other electronic components communicate with Jetson Nano. It has 4 GB RAM.
USB Hubs	In the system, two UBS hubs were used to gather the data and distribute the main power for other electronic cards.
IMU	To precisely determine the heading of the robot, the IMU was employed.
GPS	GPS sensor is a crucial part of the autonomous driving of the robot. Because, other than the odometer, GPS data is quite beneficial for detecting the robot's current location. Then the robot goes to the target point by waypoints according to the GPS data that shows the current location.

Arduino – 1	The First Arduino Mega 2560 card is used to control the motors. It also calculates the odometer data and sends it to the Jetson Nano via serial port.
Arduino – 2	In the second Arduino Mega 2560 card, the ultrasonic sensor data were processed and transmitted. On the other hand, the front and rear lamps of the robot were controlled.
Arduino – 3	It is aimed to measure the battery charge level in this Arduino Mega 2560 card. Therefore, a voltage divider shield was designed and put on the third Arduino Mega 2560 card.
Camera	In the first place, the camera is aimed to stream live video wirelessly. Then it is planned to use some artificial intelligence algorithms via the camera for autonomous driving.
LIDAR Sensor	The robot perceives the environment only by ultrasonic sensors and the camera. This may not be enough in some cases. Therefore, the LIDAR was decided to use. The LIDAR perceives the 360°-area.

The robot is divided into two main parts, which are the electronic units and the cargo compartment. The aim of the division is safety and modularity. The safety for the sellers and customers who interact daily with the robot. The modularity for the technical crew who interfere the electronic components, changing or charging the battery, and carry out the maintenance periodically.

3.2 The Mechanical Structure of the Robot

The mechanical structure of the robot was first designed in 3D CAD software. Then, the designed robot was implemented by ordering or producing the necessary parts. The mechanical design process of the robot took longer than expected due to the problems in the supply of the necessary materials. In addition, different parts had to be chosen instead of the parts that were determined in the first design but could not be supplied. This situation caused the design of the robot to change. In the Design Process Section, all design versions and processes of the robot, from the initial design to the final design, are explained. In the Chassis & Body section, the chassis and body of the robot in its final design are discussed in detail. The motors and wheels used in the robot are mentioned in the Motors & Wheels section. Finally, the proposed suspension system for the designed eight-wheeled semi-autonomous delivery robot is explained in the double bogie suspension system section.

3.2.1 Design Process

At the beginning of the design process, the main idea was to design a delivery robot that could climb up and down the pavements and ramps. Therefore, an eight-wheeled

structure was proposed. These eight wheels are grouped in pairs. Of these two groups, the ones that are opposite each other on the sides of the robot form a bogie system. The bogie system has several advantages. These are explained in detail in the relevant section. In order for the bogie system to be able to angle comfortably without causing the robot to tip over, the double groups must be on the side of the robot body, not under it. In this case, the entire weight of the robot falls on the shafts of the Bogie system. Therefore, the closer the double groups in the Bogie system are to the body of the robot, the better the load distribution. For this reason, hub motor wheels were preferred as the wheel in the first design. As a result of long searches, no company has been found that sells the desired hub motors in Türkiye. Manufacturers selling motors were found abroad. However, the inability to make international cargo deliveries due to the pandemic or the very late delivery has moved us away from the hub motor idea. We changed our policy to procure materials domestically. When hub motors were removed from the design, it was thought to replace them with external motors and wheels. There isn't much left of any choice. Building a hub motor from scratch didn't seem like an effective way to go. At this stage, the motors to be replaced by the hub motors would cause the wheel distance of the robot to expand from the body to the sides. This was an undesirable situation for the balanced distribution of the load. Therefore, we wanted to keep this expansion to a minimum. For this, we started the research of an L-shaped, geared, brushed DC motor. We found these motors, but this time none of the motors found had an encoder. We cared about calculating the odometry information of the robot with the data we would get from the encoders of the motors. This information would be used to calculate the robot's position, distance traveled, and remaining distance. The last motor type to go after L-shaped motors were motors with known external encoders. Since the length of these motors was 72,6 mm, they moved the wheels transversely from the main body. Before considering these motors, we considered attaching external encoders to L-shaped motors. Because L-shaped motors were 21 mm in length, the wheels would be closer to the body. This difference is observed in detail in Fig. 3.4.

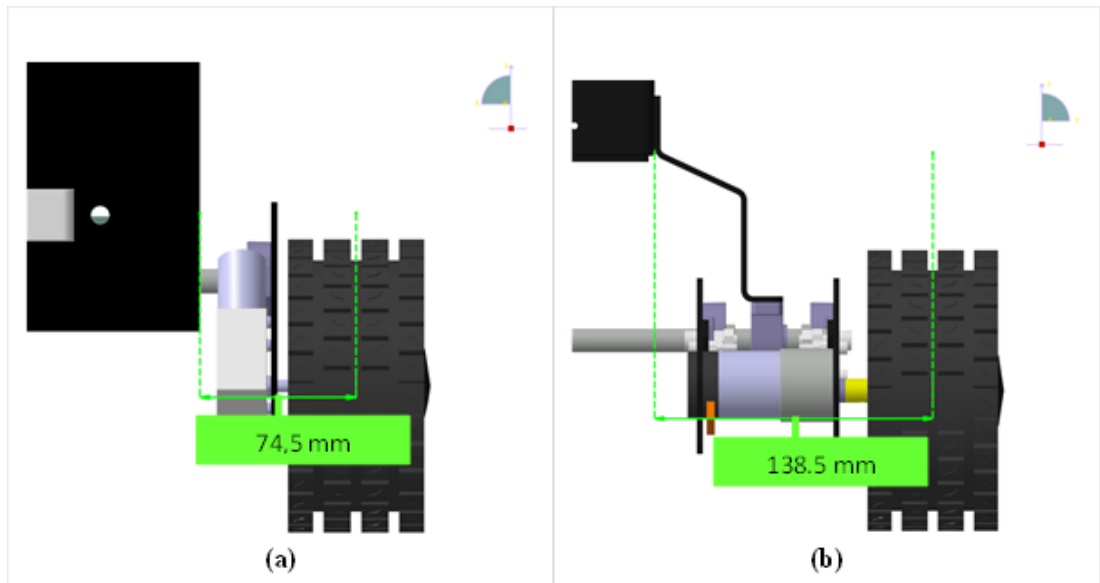


Fig. III.4: The Comparison of the L-Shaped and Encoder-Mounted DC Motor in the Context of the Distance from the Robot Body **a)** The L-Shaped DC Motor is mounted to the Robot, **b)** Encoder-Mounted DC Motor is mounted to the Robot

This time, it was understood that L-shaped motors are unsuitable for installing external encoders. This design was also abandoned.

Then using, standard-type motors with an encoder were determined. In the designs made after that, the existing motors were used. These motors cause to keep the wheels 137 mm away from the robot body.

Additionally, encountered another problem was the absence of the wheels that were equivalent to the wheels of the hub motors. As a result of long searches, 140 x 65 mm KKpit large terrain wheels were found. However, these wheels were weak in carrying loads compared to the hub motor wheels in the first design. Since the aim of the study is proof of the concept, this disadvantage was accepted and continued. Unfortunately, the disadvantage could not allow for any acceptable test. Therefore, both making the robot lighter and distributing the total weight of the robot as close to the wheels as possible were decided. The number of aluminum parts in the robot were reduced. The thickness of the base plate was reduced from 5 mm to 3 mm. As a result of this lightening work, the robot weights 3.563 kg. In addition, two different plans were considered to distribute the robot's load close to the wheels:

1. To distribute the load with fixed parts,
2. Using Shock Absorbers

While positive feedback was received from the first method, the desired feedback could

not be obtained from the second method except for the weight problem. The second method is slightly different, and the connection of the parts to which the shock absorbers are connected with the body has been changed. However, that didn't work either. Finally, a second lightening operation was performed on the robot, and it was decided to use the 1st method.

Although all the lightening operations, the wheels could not carry the robot body. Even the wheels were left from the motor shafts during the field tests. Therefore, the new thermoplastic polyurethane wheels, which are explained in the Motors And Wheels Section, were utilized. These wheels easily carried the robot without any problem. In Fig. 3.5, the design stages of the robot are displayed in order from the first version to the last version.





Fig. III.5: The Design Process of the Proposed Robot

3.2.2 Chassis And Body

The robot chassis is made up of a base plate, profiles, two bogie systems, and eight rubber wheels. The base plate is a 6000 series aluminum alloy component whose

dimensions are 300x550x3 mm. It weighs about 1.311 kg. There are two 30x30x490 mm super light sigma profiles on the top sides of the base plate. The bogie systems are mounted on these sigma profiles. Each bogie system has a shaft, six cast ball bearings, four 3 mm mounted plates, four motors, four wheels, some screws, and nuts. Fig 3.6 displays the pure chassis, and Fig 3.7 shows the one Bogie system.



Fig. III.6: The the Pure Chassis of the proposed Robot



Fig. III.7: A Bogie System of the proposed Robot

On top of the chassis, the essential electronic components, cards, battery, sensors, and the cargo compartment are situated. These components constitute the body. On the front side of the robot, there is a camera, ultrasonic sensors, and front lamps. There are ultrasonic sensors on both sides of the robot. Lastly, there are rear lamps and a rear ultrasonic sensor on the back side of the robot. The cargo compartment's dimensions are 295x365x185 mm, and the volume is ~20 lt. The robot body is shown in Fig 3.8.

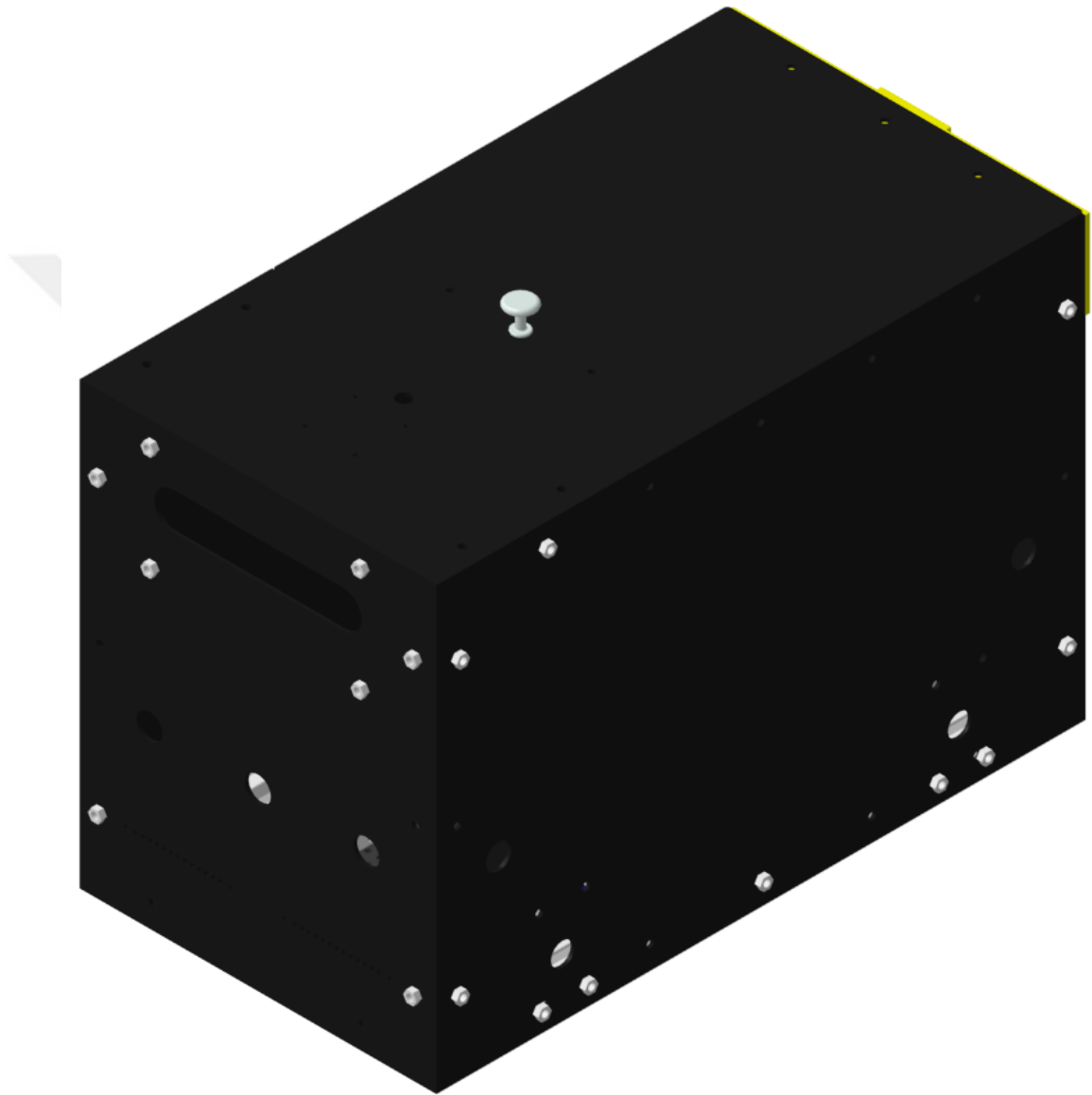


Fig. III.8: The Robot Body

The outer dimensions of the whole robot are 640x610x613 mm, and the different-angle views of its final design are shown in Fig. 3.9.

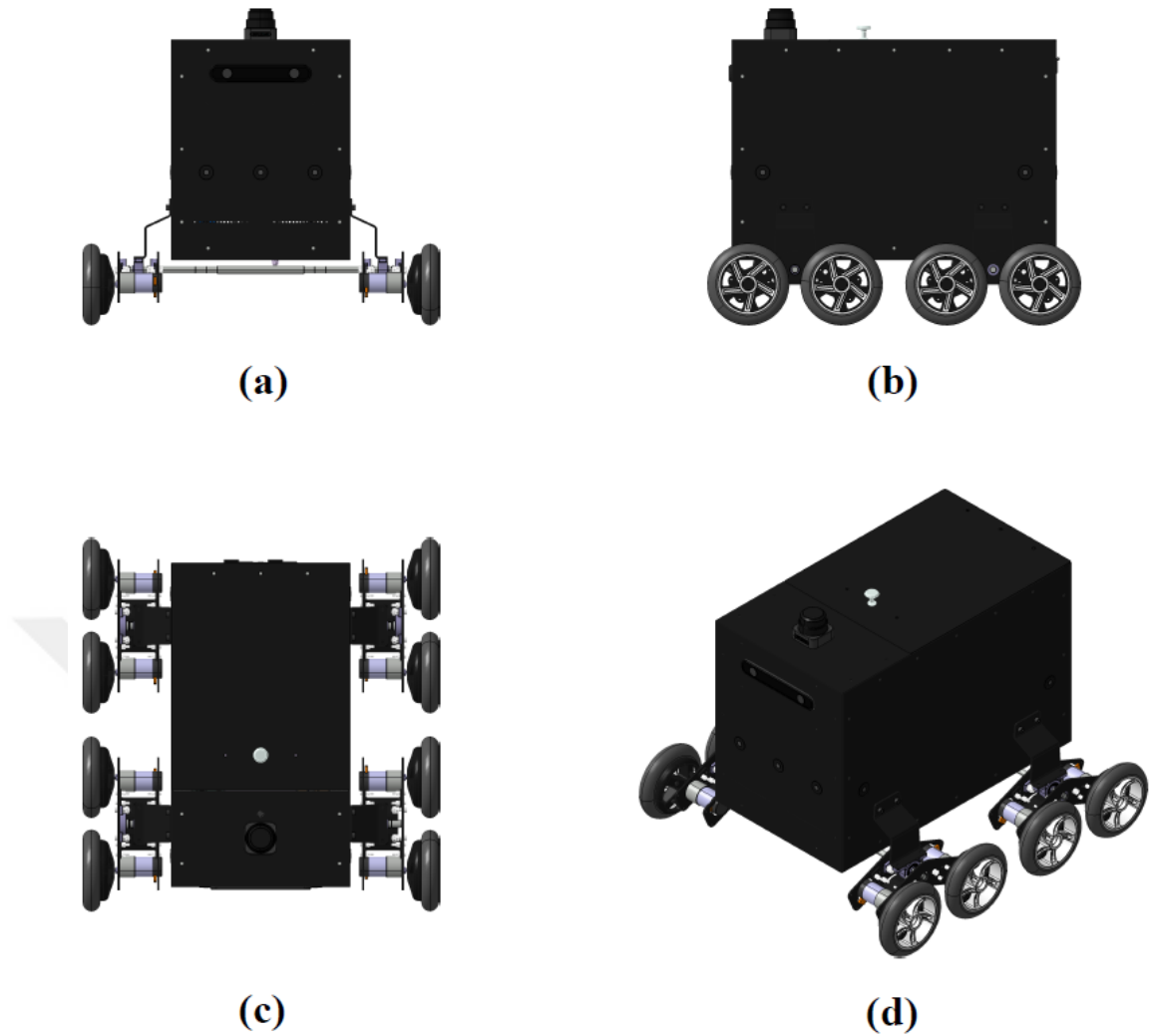


Fig. III.9: The views of the designed Eight-Wheeled Semi-Autonomous Delivery Robot; **a)** Front-View, **b)** Side-View, **c)** Top-View, and **d)** Isometric-View

3.2.3 Motors And Wheels

On the robot, eight brushed DC motors and rubber wheels are used. In the delivery robot field, the desired points are low speed as well as the pedestrians and high torque for climbing up and down the curbs. Therefore, high gear-ratio-motors are preferred. The brushed motors do not turn backward or forward without digital commands, according to the brushless motors. Additionally, brushless motors are generally used for high-speed applications like drones. In our case, brushed DC motors perfectly fit. The specifications of used motors are listed in Table 3.1 below.

Table III.2: Technical Specifications of the Used Pololu DC Motors (Pololu Corporation, 2022a)

Parameter	Specification
Type	Brushed DC Motor
Rated Voltage	12 V
Stall Current	5.5 A
No-Load Current	0.2 A
Gear Ratio	131.25:1
No-Load Speed	76 RPM
Extrapolated Stall Torque	45 kg - cm
Encoder	2 Channel Hall Effect Sensor

The motors have integrated quadrature encoders on their backs. The encoders play a crucial role in estimating the odometer information. The integrated encoders procure a resolution of 64 counts per revolution of the motor shaft, which corresponds to the 8400 counts per revolution of the gearbox’s output shaft.

The Hall Sensor needs an input voltage, V_{cc} , in the range from 3.5 V to 20 V. The sensor also draws the 10 mA current. The output A and B are square waves between the 0 V and V_{cc} about 90° out of phase. The frequency of the transitions indicates the motor speed, and their order points to the motor direction. In Fig. 3.10, the encoder output A and B (yellow and blue) using 12 V motor voltage and 5 V of V_{cc} for Hall Sensor are displayed.



Fig. III.10: Encoder A and B Outputs at the Rated Voltage of the Preferred DC Motors (Pololu Corporation, 2022b)

When rising and falling edges of both output A and B are counted, the 64 counts per revolution of the motor shaft are reached with a high degree of probability. If only a single edge of one channel is utilized, the 16 counts per revolution of the motor shaft are achieved. In the study, the only rising edge of channel A was counted.

On the other hand, thermoplastic polyurethane wheels are employed in order to move the robot. The dimensions of these wheels are 140 x 30 mm. The wheels carriage capacity is up to 50 kg (burakteker.com, 2020).

The motors and wheels are shown in Fig 3.11.

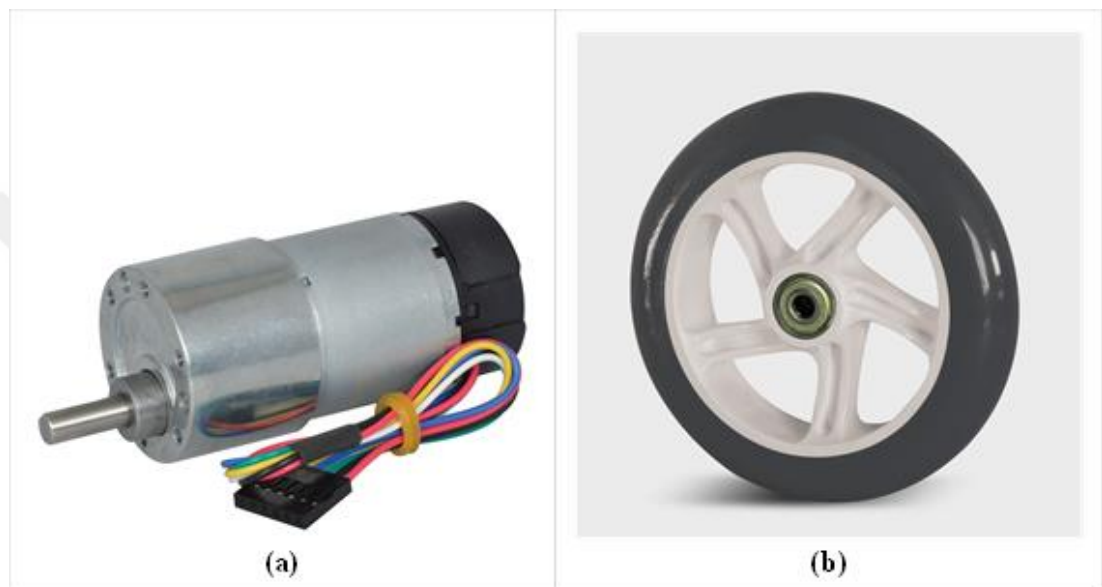


Fig. III.11: a) One of the Employed DC Motors (Pololu Corporation, 2022a), b) One of the Wheels Attached to the Motors (burakteker.com, 2020)

3.2.4 Double Bogie Suspension Systems

A simple railroad bogie system roughly consists of three main parts: Two-wheel axles and a bogie frame. The wheels are designed to roll on the rails. The bogie frame is connected to the vehicle body with springs and dampers (Cooperrider, 1972).

Bogies serve a couple of purposes :

- Strut of the vehicle body
- Equilibrium on various track types such as straight and curved.
- Enhance the ride comfort by absorbing vibration and reducing the centrifugal force effects
- Tolerate the track irregularities and rail abrasion

Fig 3.12 shows the simple bogie systems.

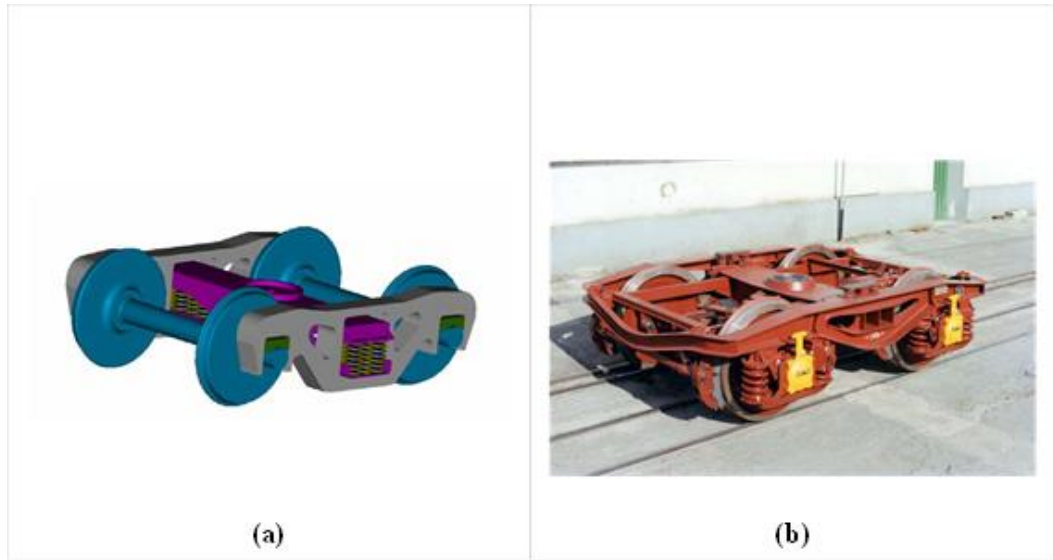


Fig. III.12: a) A Simple Bogie Design (Iwnicki, Grassie, & Kik, 2000), b) An Assembled Real Bogie System (Desarrolla Soc. Coop. And. Jándalo, n.d.)

The bogie systems used in robotic vehicles are not identical to the railroad bogie systems but quite similar. In robotic vehicles, the Sojourner Mars Exploration Rover used the bogie system with a rocker (Harrington & Voorhees, 2004). But the Sojourner's bogie system has no wheel axle between the right and left sides of the robot. Therefore, the bogie systems may have few differences from each other. In our robot, while there is no wheel axle, there is an axle between two side frames of the bogie system. The proposed robot's bogie system is shown in detail in Fig 3.13.

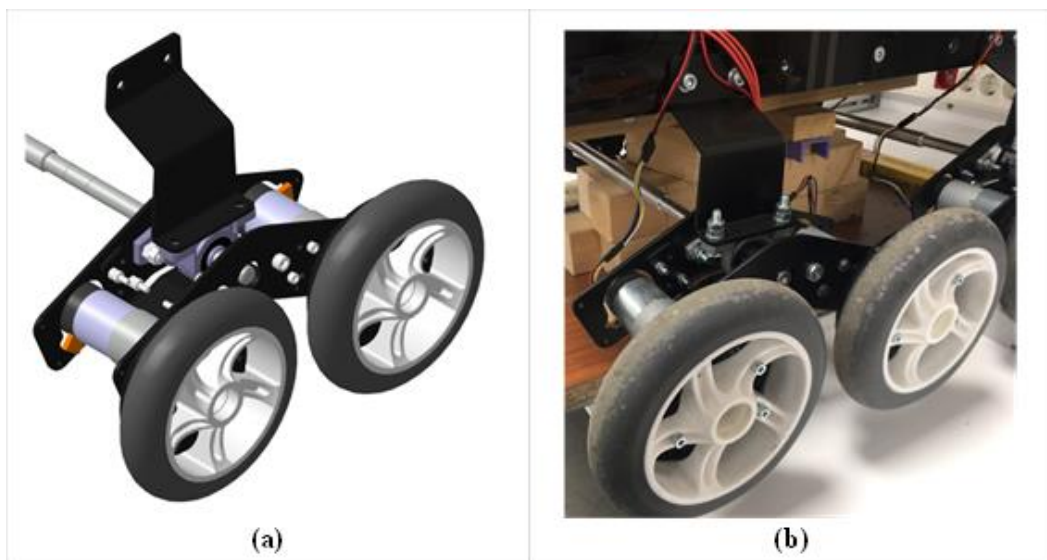


Fig. III.13: a) The Design of the Bogie System of the Robot, b) The Prototype of the Designed Bogie System

We increased the ground contact by using eight wheels and double bogie mechanisms.

3.3 The Electrical and Electronic Structure of the Robot

The robot's electrical and electronics structure is designed to properly drive the robot by providing maximum safety for customers and the technical crew. The system has a fuse and e-stop for any dangerous situation. Besides, the cables and connectors were specified according to the working safely up to the maximum current rate. The specified cables are listed in Table 3.3.

Table III.3: The Used Cables and Their Specifications

Parameter	Specification
Battery Connection Cables	10 AWG
Power Distribution Cables	12 AWG
DC-DC Converter - Motor Driver Wiring	16 AWG
Rest of the Wiring	20 AWG

The cables are completely isolated as a precaution for short circuits and leakage. The robot's electrical and electronic structure provides scalability for the robot's development.

3.3.1 Battery

The battery used in the robot was determined according to the criteria given below :

- Type
- Robot's power consumption
- High capacity
- Battery voltage
- Maximum safe continuous discharge rate
- Cost

After the determination of the equipment of the robot, their power consumption was estimated. The estimated current draws are listed in Table 3.4.

Table III.4: The Estimated Current Draws of Important Electronic Components of the Robot

Component	Min. Current Draw	Max. Current Draw	Avg. Current Draw	Number	Total of the Min. Current Draws	Total of the Max. Current Draws	Total of the Avg. Current Draws
DC Motors	200 mA	5500 mA	2500 mA	8	1600 mA	44000 mA	20000 mA
Jetson Nano	2000 mA	4000 mA	3000 mA	1	2000 mA	4000 mA	3000 mA
Arduino Mega 2560	850 mA	1000 mA	900 mA	2	1700 mA	2000 mA	1800 mA
JSN-SR04T							
Ultrasonic Sensors	5 mA	30 mA	25 mA	8	40 mA	240 mA	200 mA
RPLIDAR S1	300 mA	500 mA	350 mA	1	300 mA	500 mA	350 mA
Zed 2i Camera	300 mA	500 mA	380 mA	1	300 mA	500 mA	380 mA
SparkFun IMU	400 mA	600 mA	450 mA	1	400 mA	600 mA	450 mA
Neon Lem Lamps	100 mA	150 mA	120 mA	4	400 mA	600 mA	480 mA
Pixhawk	200 mA	500 mA	350 mA	1	200 mA	500 mA	350 mA
u-blox GPS	10 mA	100 mA	50 mA	1	10 mA	100 mA	50 mA
Total					6950 mA	53040 mA	27060 mA

The battery type was chosen as a lithium polymer. Because, in most cases, lithium-ion and lithium-polymer battery technology are superior to lead-acid due to its reliability and efficiency, among other attributes. The key difference between lead-acid and lithium batteries is charging. Charging a lead-acid battery can, for instance, take more than 10 hours, whereas lithium polymer or ion batteries can take from about 3 hours to as little as a few minutes to charge, depending on the size of the battery. The capacity of the battery is 22000mAh which means the battery provides 22000mA continuously for an hour. The battery voltage level is higher than the nominal voltages of the motors. Because of the four cells, the nominal battery voltage is 14.8V. But the motor's nominal voltage level is 12V. Therefore, the DC-DC buck converters were employed to reduce the voltage level. On the other hand, the battery's maximum safe continuous discharge rate is 550000mA, according to the formula (3.1). That means the battery safely and

continuously discharges the 550000mA for roughly 2.4 minutes. The estimation may be calculated by using the formula (3.2).

$$\text{Maximum safe continuous discharge rate} = \text{nominal discharge rate} \times C \text{ Value} \quad (3.1)$$

$$\text{Battery discharge time} = (\text{nominal discharge rate} \times 60) / \text{max. safe continuous discharge rate} \quad (3.2)$$

The cost is also a significant part of the determination of the battery. The used battery is cheaper than the other counterparts.

The battery given specifications in Table 3.5 was selected out of consideration of the criteria.

Table III.5: The Selected Battery Specifications (oyuncakhobi.com, n.d.)

Parameter	Specification
Type	Lithium – Polymer
Cell Number	4
Nominal Voltage	14.8 V
Minimum Capacity	22000 mAh
Charge Rate	1-2 C (Max. 5C)
Continuous Discharge Current	25 C (500 A)
Burst Discharge Current (10 sec)	50 C (1000 A)
Pack Weight	1747 gr

3.3.2 Fuse And E-Stop

A fuse was used in order to power on and off the system. It is a 32A-monophase fuse. When the system attempts to draw more than 32A current, the fuse blows. It is connected between the battery and the e-stop button. Right after the fuse, the e-stop button is wired to the system. It is planned to place on the most viewable point of the robot. Because people around the robot must reach the button in any dangerous situation. When the button is pressed in case of emergency, the power is cut immediately.

3.3.3 DC-DC Converters

There are voltage level differences between the battery and other electronic components in the system. DC-DC converter requirements have emerged. Therefore, 300W/20A DC-DC buck converters were employed. The robot has eight motors, a Jetson Nano, Arduino boards, motor drivers, ultrasonic sensors, a camera, etc. Most of them are working under different DC voltage levels. While the motors need 12V, the Jetson Nano and Arduino boards operate with 5V. The used DC-DC converters are current-adjustable and voltage-adjustable. There, firstly the current and voltage limits were adjusted and tested. The performed tests and adjustments are presented in Fig. 3.14 and Fig. 3.15 below.

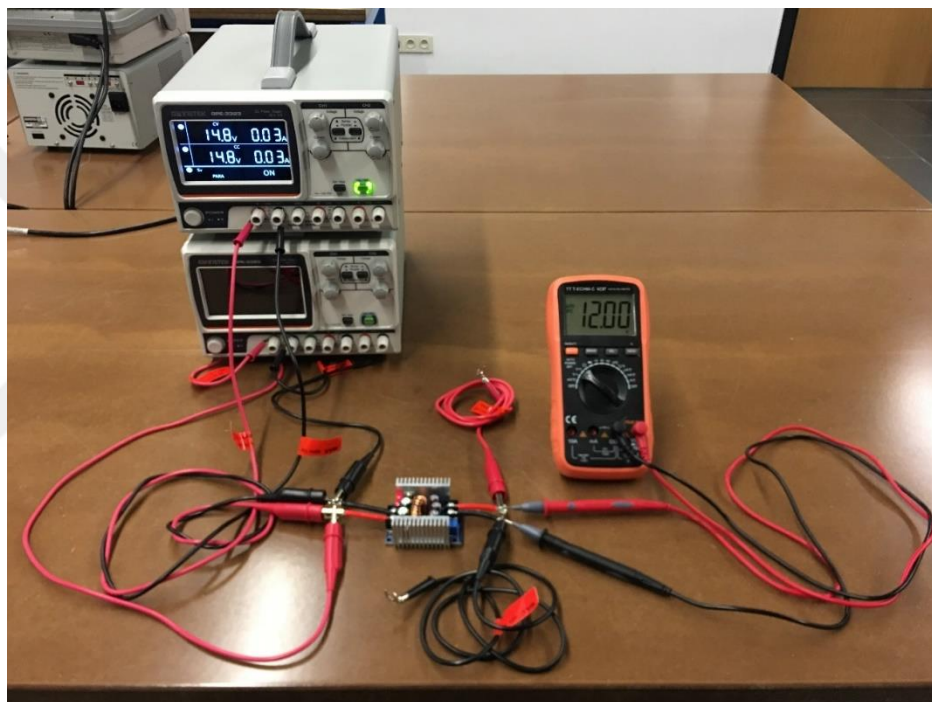


Fig. III.14: One of the Voltage Tests and Adjustments of the DC-DC Converters

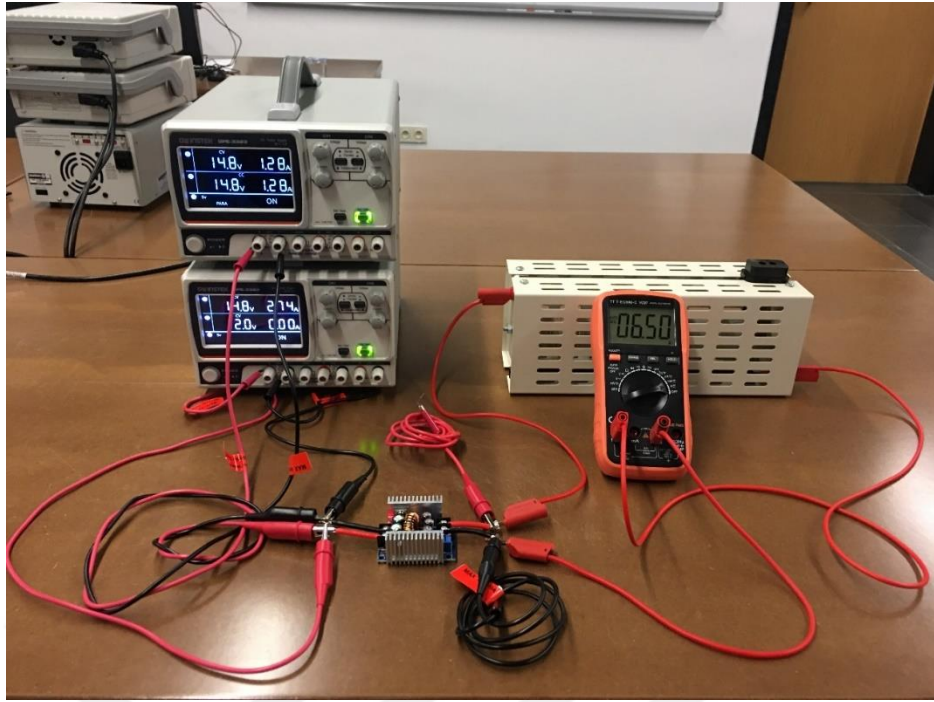


Fig. III.15: One of the Current Tests and Adjustments of the DC-DC Converters

3.3.4 Main Controller

As the main controller, the Jetson Nano is determined and used. The Jetson Nano is a small, low-price computer that allows accelerating robotic and artificial intelligence applications.

Its technical specifications are listed in Table 3.6.

Table III.6: The Technical Specifications of Employed Jetson Nano (NVIDIA Corporation, 2022)

Key Feature	Value
GPU	NVIDIA Maxwell architecture with 128 NVIDIA CUDA® cores
CPU	Quad-core ARM Cortex-A57 MPCore processor
Memory	4 GB 64-bit LPDDR4, 1600MHz 25.6 GB/s
Storage	16 GB eMMC 5.1
Video Encode	250MP/sec 1x 4K @ 30 (HEVC) 2x 1080p @ 60 (HEVC) 4x 1080p @ 30 (HEVC) 4x 720p @ 60 (HEVC) 9x 720p @ 30 (HEVC)
Video Decode	500MP/sec 1x 4K @ 60 (HEVC) 2x 4K @ 30 (HEVC) 4x 1080p @ 60 (HEVC) 8x 1080p @ 30 (HEVC) 9x 720p @ 60 (HEVC)

Camera	12 lanes (3x4 or 4x2) MIPI CSI-2 D-PHY 1.1 (1.5 Gb/s per pair)
Connectivity	Gigabit Ethernet, M.2 Key E
Display	HDMI 2.0 and eDP 1.4
USB	4x USB 3.0, USB 2.0 Micro-B
Others	GPIO, I ² C, I ² S, SPI, UART
Mechanical	69.6 mm x 45 mm 260-pin edge connector

All the low-level systems in the robot, such as the motor control system, sensor system, IMU system, GPS system, battery checker, and camera, are planned to connect to the Jetson Nano over external USB hubs.

The Jetson Nano works under 5V and draws the maximum 4A. But the 5V is the nominal voltage level. The minimum voltage level of the board is 4.75V. During the test and development process, a voltage drop below 4.75V was experienced. When the voltage drops under 4.75V, the Jetson Nano shuts down immediately. This is the brownout problem. When the brownout happened, a monitor, two USB hubs, and 3 Arduino boards were connected to the Jetson Nano. Then, the monitor pulled out the Jetson Nano, and the brownout problem went away.

3.3.5 Motor Controller

An Arduino Mega 2560 board is used to control the motors. It is an Atmega2560-based microcontroller board. The reasons to select the Arduino Mega 2560 as a motor controller are its easy usage, the numerousness of the IO pins, the low-power consumption, and the cheapness. The Arduino Mega 2560 is easy to code, and it has 54 digital IO pins. 15 of the digital IO pins can be utilized as PWM outputs. There are 16 analog inputs, 4 UARTs, and 16 MHz crystal oscillators.

The board connects to the Jetson Nano via USB cable. Two different scripts were uploaded into the Arduino Mega 2560 motor controller board. One is for speed controller via PID. The other one is for remote control operation. The algorithm of remote manual control is shown in Fig. 3.29.

3.3.6 Motor Driver

In order to drive the brushed DC motors bidirectionally, the H-Bridge circuit is employed. The elemental circuit diagram of the H-Bridge can be shown in Fig. 3.16 below. While the M symbolizes the motor, S1, S2, S3, and S4 symbolize the switches. The S1 and S4 switches are off to rotate the motor clockwise. For counter-clockwise,

the S2 and S3 switches must be off. In this way, the rotating direction of the motor is controlled.

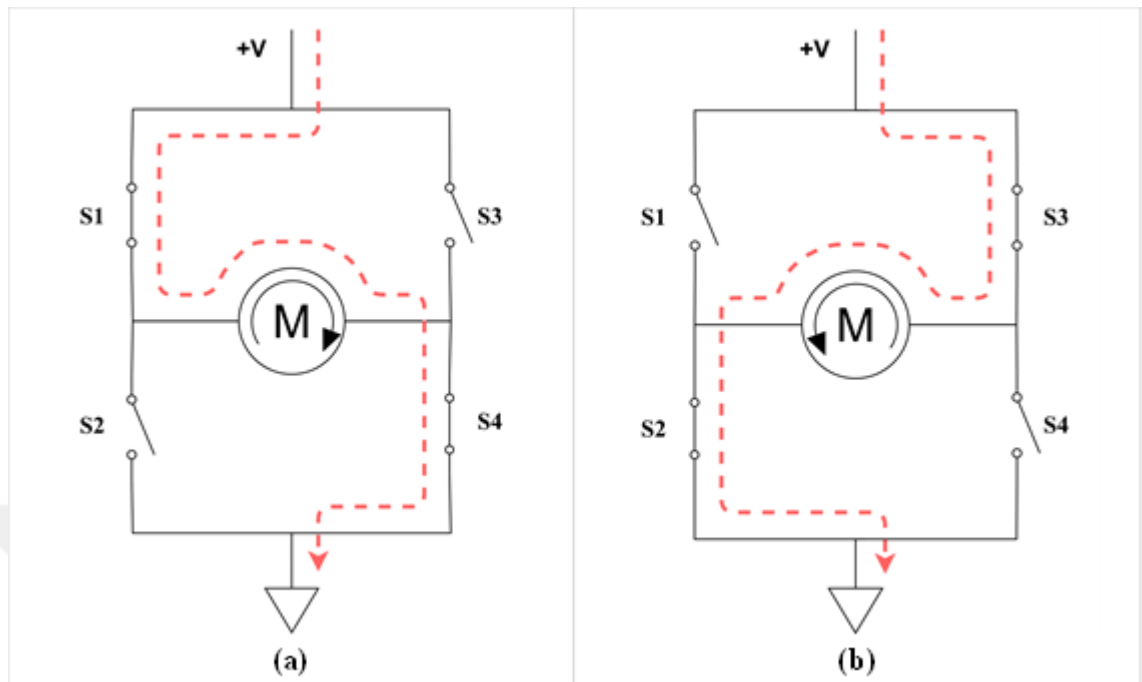


Fig. III.16: a) Driving the Motor Clockwise, b) Driving the Motor Counter-Clockwise

On the other hand, in order to control the speed of the motor, the PWM must be applied to input signals coming to the switches. PWM is a method that changes the time of logic-1-state of the square wave signal. By doing this, the average value of the signal is manipulated. Therefore, the average motor voltage changes and the speed of the motor is controlled. In Fig. 3.16, there are manual switches, but undoubtedly that the aim is to control the motor automatically. Therefore, transistors are used.

In the study, we wanted a motor driver board that drives all the motors on one side. Because our robot is a Skid-Steering mobile delivery robot. Therefore, two motor driver boards were employed for each side-motors. Due to the high current tolerance, the BTS7960 H-bridge motor driver modules were selected and used. Its specifications are listed in Table 3.7.

Table III.7: The Specifications of Utilized BTS7960 H-Bridge Motor Driver (Handson Technology, n.d.)

Key Feature	Value
Driver	Dual BTS7960B
Input Voltage	6 ~ 27 V DC
Peak Current	43 A
PWM Capability	Up to 25 kHz
Control Mode	PWM or Level
Control Input Level	3.3 ~ 5 V
Over-Voltage	Lock Out
Under-Voltage	Shut Down

3.3.7 Sensor Controller

For controlling the ultrasonic sensors, one more Arduino Mega 2560 microcontroller board was added to the system. The reason the first Arduino Mega 2560 board was not used as both a sensor controller and a motor controller is to not slow it down. Because the PID algorithm was used in addition to encoder delays in the first Arduino Mega 2560 board. That means faster cycle time and more precise controlling the motors. There the second Arduino Mega 2560 board was utilized for ultrasonic sensor control. In the first plan, there are eight ultrasonic sensors. However, only four ultrasonic sensors were decided to use in the beginning. Then, we can scale up the system up to eight ultrasonic sensors. The aim of using ultrasonic sensors is both to detect the obstacles in the dangerous area of the robot and to measure the distance between the obstacle and the robot. When the sensors detect the obstacles in the dangerous area, the robot stops. Additionally, the sensors can be used to support the LIDAR for measuring the obstacle distance according to the robot.

3.3.8 Led Lamps And 2 Channel - 5v Relay Board

The robot was designed to be used both in daylight and at night. Therefore, we put the lamps on the robot. There are two front and two rear lamps. The front lamps flash out the white light, and the rear lamps flash out the red light. These lamps work under 12V. In order to control the flashing of the lamps, the 2-channel 5V relay card was utilized. The planned operation is to use the lamps when the sun sets. In the daylight, the robot

turns off the lamps.

The connection diagram can be seen in Fig. 3.17.

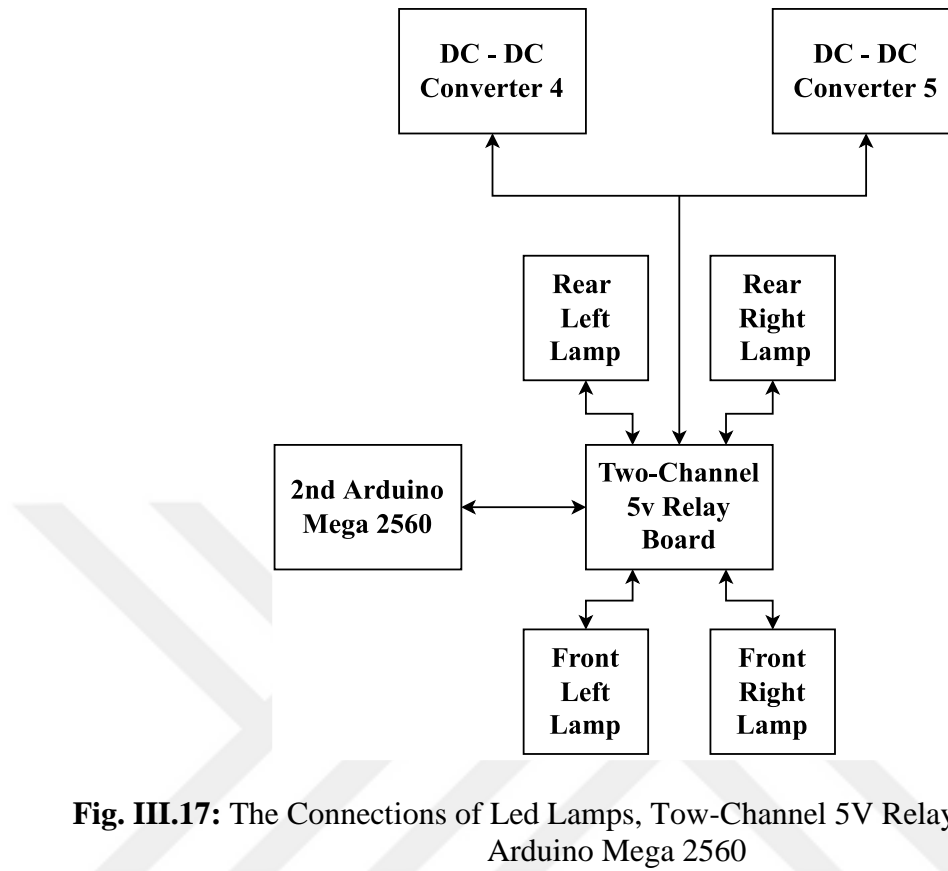


Fig. III.17: The Connections of Led Lamps, Tow-Channel 5V Relay Board, and 2nd Arduino Mega 2560

3.3.9 Ultrasonic Sensors and Sensor Shield

In order to detect the obstacles in the dangerous area and measure the obstacle's distances, the JSN-SR04T ultrasonic sensors were selected. They are easy to use, low-cost, and low power consumption sensors. They work under 5V nominal DC voltage. Their sensing range is between 250 mm and 4500 mm. Their precision is roughly 50 mm, which is an acceptable distance. The dangerous area and the ranges of the ultrasonic sensors can be seen in Fig. 3.19. In addition, these are waterproof sensors that can work under rain and wet conditions. This is also a beneficial point for the robot in the context of working under rainy weather.

As mentioned before there are eight ultrasonic sensors were used. We determined the second Arduino Mega 2560 as a sensor controller and made a sensor shield card to place on top of the second Arduino board. The printed circuit of the designed sensor shield can be seen in Fig 3.18.

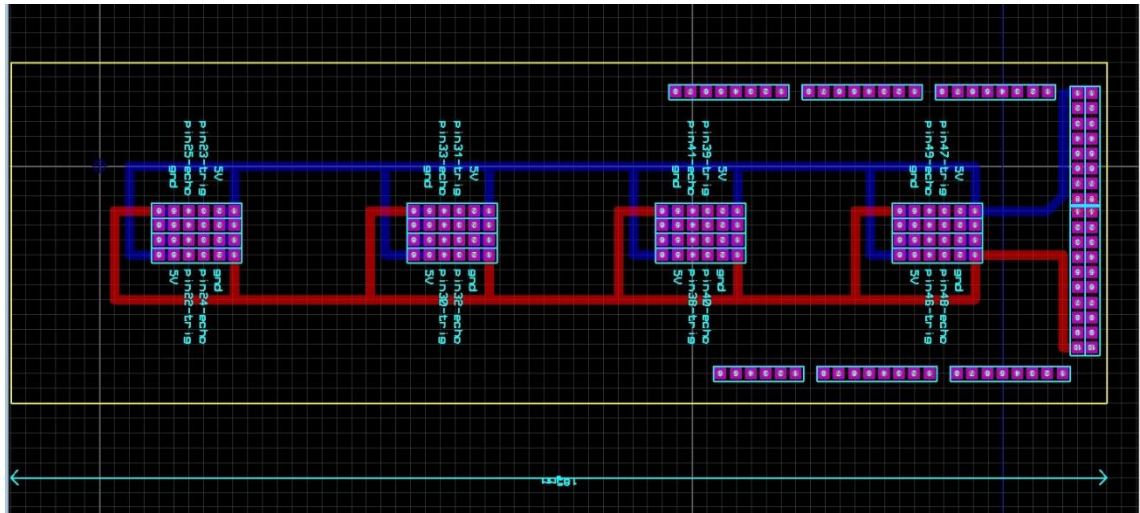


Fig. III.18: The Ultrasonic Sensor Shield

3.3.10 Camera

The robot is planned to sense the environment via ultrasonic sensors and LIDAR. But none of them substitute for the camera. The aim was to build a robot that could work on both sunny and rainy days. Therefore, like the other components, a waterproof camera, Stereolabs Zed2i, was selected. The camera can both send the data and get the power via the Type C USB cable. It is connected to the Jetson Nano as in the wiring diagram. The specifications of the camera are listed in Table 3.8.

Table III.8: The Specifications of Utilized Stereolabs Zed 2i Camera (Stereolabs Inc., 2022)

Parameter	Specification
Field of View	120
Protection for Environmental Effects	IP66 (Resistant to dust, water and humidity)
Sensors	Gyroscope, Accelerometer, Magnetometer, Barometer,
Operating Temperature	-10C to +45C
Output Resolution	Side by Side 2x (2208x1242) @15fps 2x (1920x1080) @30fps 2x (1280x720) @60fps 2x (662x376) @100fps
Mounting	Multiple Mounting Options (Backside & Bottomside)

3.3.11 Navigation Board - Pixhawk

As a navigation board, two options were evaluated. One of them is using a second Arduino Mega 2560 board. The first option loads on the second Arduino Mega 2560 board. Because the second Arduino Mega 2560 board is used as the sensor controller. The eight ultrasonic sensors send the immediate distance data to the board in order robot to check the safety of its environment. Therefore, the second Arduino Mega 2560 board was left as the only sensor controller.

The other option is using the Pixhawk controller board, which is perfectly suitable for unmanned low-scale vehicles such as drones, boats and mobile robots. In this option, the Pixhawk is connected to the Jetson Nano only to receive its power. After that, the u-blox NEO M8N GPS Module, which is mentioned in the following section, is connected to the Pixhawk board. After a couple of minutes from its connection to the Pixhawk, the GPS module searches and connects to the satellites. Thereafter, it sends the received immediate location data packages to the Pixhawk. At this point, these location data must be received wirelessly by the remote control station. This communication is made with 433 MHz Telemetry Radio modules.

These modules have a Micro-USB port, a DF13 six-position port, and an antenna. They

are small, light, and cheap radio modules that allow communication in about 300m range. They have open-source firmware and easy usage with Mission Planner software and Pixhawk board (ArduPilot Dev Team., 2021).

In the study, two 433 MHz Telemetry Radio modules were used. One is with Pixhawk, and the other is with the remote control computer.

On the remote control station side, the Mission Planner Software was installed on a Windows PC. The connection was established via the telemetry modules. Thereafter, the remote controller can monitor the location of the robot on the map.

3.3.12 GPS

In semi-autonomous mode, there is a critical requirement which is to know the location of the robot in the world. To meet the requirement, a GPS sensor was employed. In this process, several GPS brands and models were tested. While Quectel GPSs were connecting fewer satellites, Ublox and Radiolink's GPSs were connecting approximately 12 satellites which are almost two times more than Quectel's GPSs. The crucial data are the latitude and longitude in this robotic delivery application. These are the world coordinates.

The specifications of the preferred u-blox NEO M8N GPS Module are displayed in Table 3.9.

Table III.9: Specifications of Used GPS Module (u-blox, n.d.)

Parameter	Specification				
Receiver Type	72-Channel u-blox M8 Engine				
Operational Limit of Altitude	50,000 m				
Operational Limit of Velocity	500 m/s				
Velocity Accuracy	0.005 m/s				
Heading Accuracy	0.3 degrees				
GNSS	GPS & GLONASS	GPS	GLONASS	BeiDou	Galileo
Horizontal Position Accuracy	2.5 m	2.5 m	4 m	3 m	3 m
Max. Navigation Update Rate	5 Hz	10 Hz	10 Hz	10 Hz	10 Hz

3.3.13 IMU

The purpose of employing the IMU is to estimate the robot's orientation and relative changes in its velocity and position. As an IMU, the SparkFun 9DoF Razor IMU M0 was selected. It has an SAMD21 microprocessor with an MPU-9250 9DoF sensor. These equipments make the IMU board re-programmable. In this context, the board can be programmed to monitor and log the motion data of the robot, such as accelerations and Euler angles. The 9DoF MPU-9250 sensor on top of the board includes three 3-axis sensors, which are an accelerometer, gyroscope, and magnetometer. These interior sensors provide to sense linear acceleration, angular rotation velocity, and magnetic field vector's. On the other hand, Atmel's SAMD21 is an Arduino-compatible microprocessor. Also, there is a USB socket on the board. Therefore, the 9 DoF Razor IMU M0 can be both powered and programmed via a USB socket and Arduino IDE.

In the study, the IMU board was used during all tests. The IMU data were logged into the MicroSD card at the end of every test. The data were shown in the graphs in Chapter IV.

3.3.14 LIDAR Sensor

LIDAR is the acronym of words that are Light Detection And Ranging. LIDAR sensor is used to detect the obstacles within its range. The LIDAR sensor emits the pulsed light waves into the environment. These pulses return to the sensor by bouncing off surrounding the objects. Then the sensor utilizes the time and calculates the distance light traveled. The LIDAR sensors are very precious. On the other hand, they are too expensive. In our case, we need a LIDAR sensor that is usable in outdoor applications. Both outdoor usage and the cost of the RPLIDAR S1 LIDAR sensor were determined and planned to put on top of the robot.

The specifications of RPLIDAR S1 are given in Table 3.10.

Table III.10: The Specifications of Used RPLIDAR S1 (Shanghai Slamtec Co., 2022)

Parameter	Specification
Type	Portable TOF Laser Range Scanner
Range	On White Objects: 40m (White light-diffused surface)
	On Black Objects: 10m
Blind Range	0.1 m
Scanning Angle	0.2 A
Sample Rate	9200 times per second
Sample Frequency	10 Hz
Angular Resolution	0.391°
Communication Interface	TTL, UART (3.3V)
Band Rate	256000 bps
Distance Resolution	3 cm
Accuracy	± 5 cm

The ranges of the camera, LIDAR and ultrasonic sensors can be seen in Fig. 3.19.

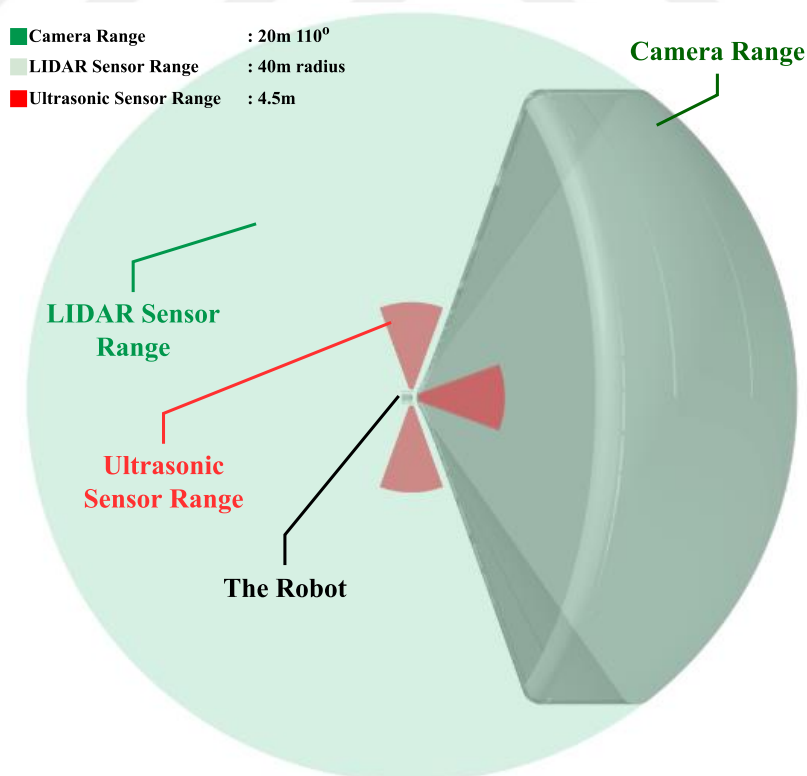


Fig. III.19: The LIDAR, Camera, and Ultrasonic Sensors Detection Ranges

3.3.15 Wireless Controller

As mentioned before, the robot's wireless remote control is one of the two robot control modes. As a remote controller, the Turnigy 9XR PRO was utilized, and the V8FR-II module was used as a receiver. It has eight channels. The connections are seen in Fig 3.3.

According to the FrSky's website operating range of the remote controller is more than 1.5 km. We specified the channels as in Fig 3.20.



Fig. III.20: The Specified Channels of the Turnigy 9XR PRO Remote Controller

- **Channel 1:** By moving the stick up and down, the robot moves to forward and backward directions
- **Channel 2:** By moving the stick between right and left, the robot turns right or left directions
- **Channel 3:** The left stick is only used for accelerating the robot. If the stick goes up, the robot moves faster. Otherwise, the robot moves slower and may be stopped.
- **Channel 4:** This channel is not used.
- **Channel 5:** The purpose of this switch is to change the manual robot driving mode. If it is low, the robot is in manual ordinary driving mode. If the switch is

high, the robot is in manual whirlygig mode. These modes are explained in detail in the Manual Robot Control section.

- **Channel 6:** This is the potentiometer. It controls the spin and the spinning direction of the robot.
- **Channel 7:** This is the activation switch for all the sticks, switches, and potentiometers on the remote controller. After turning on the remote controller, these sticks, switches, and potentiometers can not be used immediately. They need to be activated. Therefore, this switch provides activation. When the switch is low, the robot can not be controlled remotely, and it is only monitored by the remote controller.

3.3.16 Voltage Checker

The most important topic related to the safety of the robot is monitoring the battery charge level. The used battery in the robot is a lithium-ion technology battery that has a polymer electrolyte. The robot's lithium-ion polymer battery, or shortly the Li-Po battery, is susceptible to overcharge and over-discharge. Both situations can result in thermal runaway and calamitous failure leading to explosion and fire. Therefore, the battery must be monitored. At this point, we planned to use double voltage checkers; one is an off-the-shelf product, and the other one is our designed voltage divider circuit. Our designed voltage divider circuit is a shield that is compatible with Arduino Mega 2560. There is one more Arduino Mega 2560 board to run the battery charge level detection code embedded in the third Arduino Mega 2560. Both voltage checkers were tested simultaneously. No error has been faced. In the outdoor tests, the only off-the-shelf voltage checker was used. Because the robot's mechanical problems impeded the making clear data transferring between the third Arduino Mega 2560 board with the designed voltage divider shield and the main controller. Solving mechanical problems took too much time.

The off-the-shelf voltage checker allows for adjusting the voltage level; the people around the battery or robot will be warned by raising the alarm.

3.3.17 Current Sensors

The robot has eight wheels, and the aim is to drive the robot outdoor. The robot is also planned to climb the curbs and inclines. Therefore its motors often draw a high current.

But when the motors draw too much high current and continue working, their lifetimes reduce. In order not to reduce the motors' lifetimes, the current sensors were put right before the motors. The sensors measure the currents and inform the robot. When the limit current exceeds, the robot stops. The employed current sensors are ACS712 current sensors. With this sensor, up to 30A current can be measured. It was designed for bidirectional input current from -30A to +30A. For each wheel, a current sensor was used. The sensors are first tested and calibrated. But due to the same reason as the voltage divider shield, the current sensors were not used in the robot's outdoor tests.

3.4 The Software and Control Structure of the Robot

In this subsection, the software and control structures of the robot are explained.

3.4.1 Manuel Robot Control

The developed delivery robot is an eight-wheeled, two-bogie system skid-steering mobile robot. The robot's each-side wheels are driven at the same speed. There are four wheels on both the right and left sides of the robot. In order to control the robot manually, a program was developed and embedded into the first Arduino Mega 2560 according to the algorithm shown in Fig. 3.21.

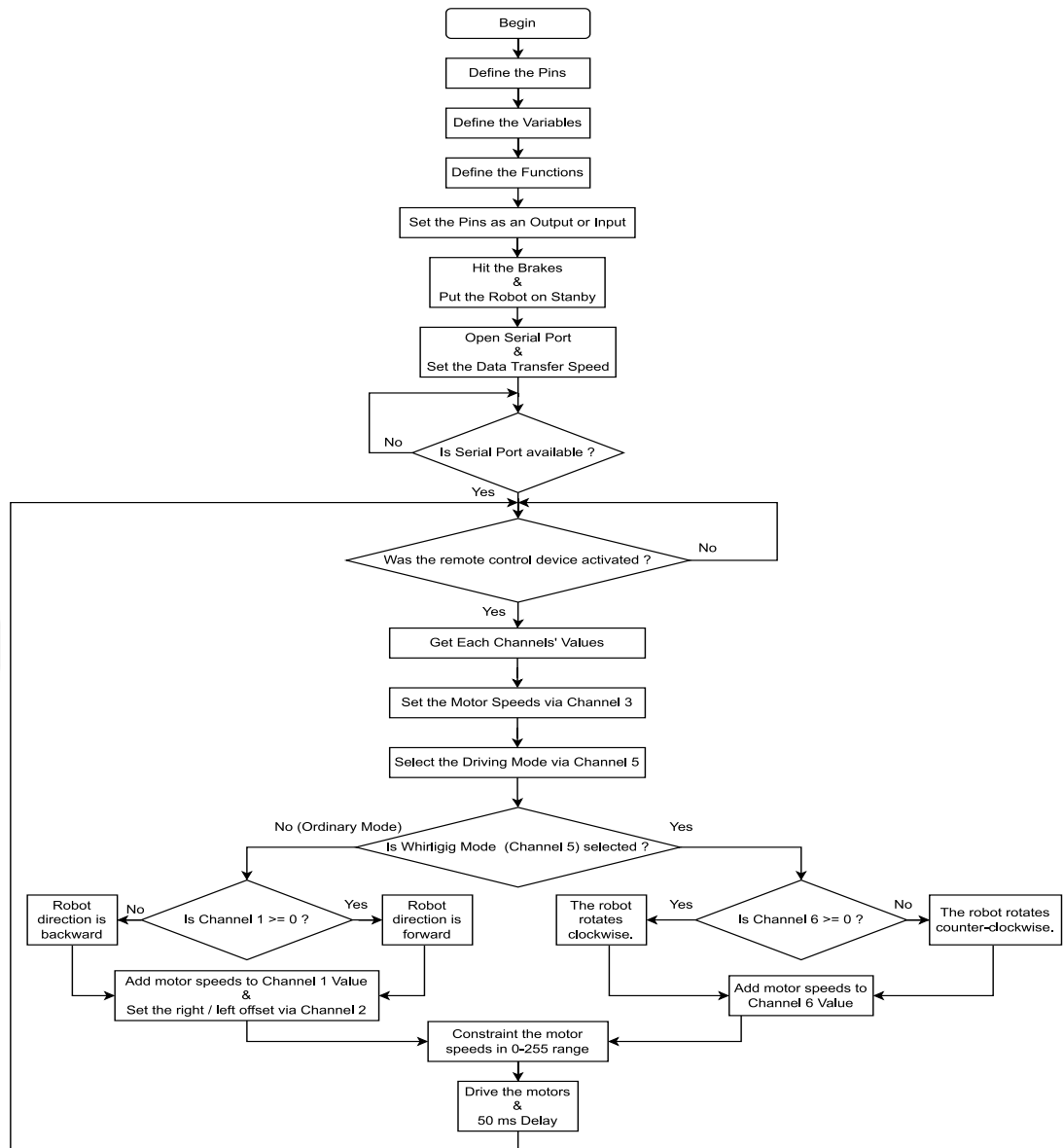


Fig. III.21: The Manual Control Algorithm of the Robot

In the beginning, the input and output connections of the right and left motors and motor drivers were begun to define. Defining these connections was followed by six input connections from the V8FR-II eight-channel receiver. After that, four integer variables were determined to represent the analog signals coming from the receiver channels. The employed switches matched with channels 5 and 7 were represented with boolean data types. The essential variable defining process was completed by defining the motors' speed and direction variables. In the next step, the six functions were produced. Three of them are related to the motors' motion; one is a robot stopping and standby function, and the rest are left and right motors' driving functions, respectively. The other three functions were created for reading the channels' and switches' data. While the channels' read integer data are transformed into a specified lower range which is -100 to 100 in

the study, the switches' read boolean data are converted into 1 or 0.

In Arduino's Setup Section, the modes of all pins were set as input or output. Then the brakes were hit, and the robot was put on the standby. The serial port was open, and the data transferring speed was set to 115200 baud.

In Arduino's Loop Section, the remote control operator has to activate the remote control device. Otherwise, the program in the Arduino does not continue. When the remote control operator changes the state of the switch, channel 7 is assigned, and the remote control device is activated. Therefore, the program in the Arduino continues. If the remote control device is deactivated later, the robot stops immediately and puts itself on standby mode.

After the activation, each channel's values were taken. The right stick mapped to channels 1 and 2 controls the direction and, to some extent, speed by returning the value between -100 and 100. The left stick manipulates the motor speed via channel 3. The values coming from the left stick are mapped from 0 to 155. This value is summed up with the value coming from channel 1, and then it is assigned to two motor speed variables. In the next step, the robot's manual control mode is selected. There are two manual driving modes for remotely controlling the robot:

1. Ordinary Mode
2. Whirligig Mode

On the one hand, the robot's speed and direction are controlled using the joysticks in Ordinary Mode. On the other hand, the robot is spun on a point as a whirligig in the second mode. Hence, the name of the second mode was given as the Whirligig Mode. In order to change the driving mode, the switch matched to channel 5, ELE D/R, is manipulated towards the reverse direction.

While the remote control device's right stick is utilized to control the robot's steering and orientation, the left stick is used for acceleration in the Ordinary Mode. In the Whirligig Mode, the potentiometer mapped to channel 6, PIT.TRIM, controls the rotation direction of the robot. If the values coming from channel 6 are positive, the robot rotates clockwise. If the values are negative, the robot rotates the counterclockwise. The left stick is used for the robot's spin speed.

In order to be sure that the algorithm works as explained above, firstly, a relatively small two-wheeled mobile robot was built. Then the accuracy of the channel mapping and the

algorithm were tested. When the small robot worked well, the algorithm was tested on the proposed eight-wheeled mobile delivery robot. The algorithm also performed well on the proposed robot. The small and the proposed eight-wheeled robots are shown in Fig 3.22.

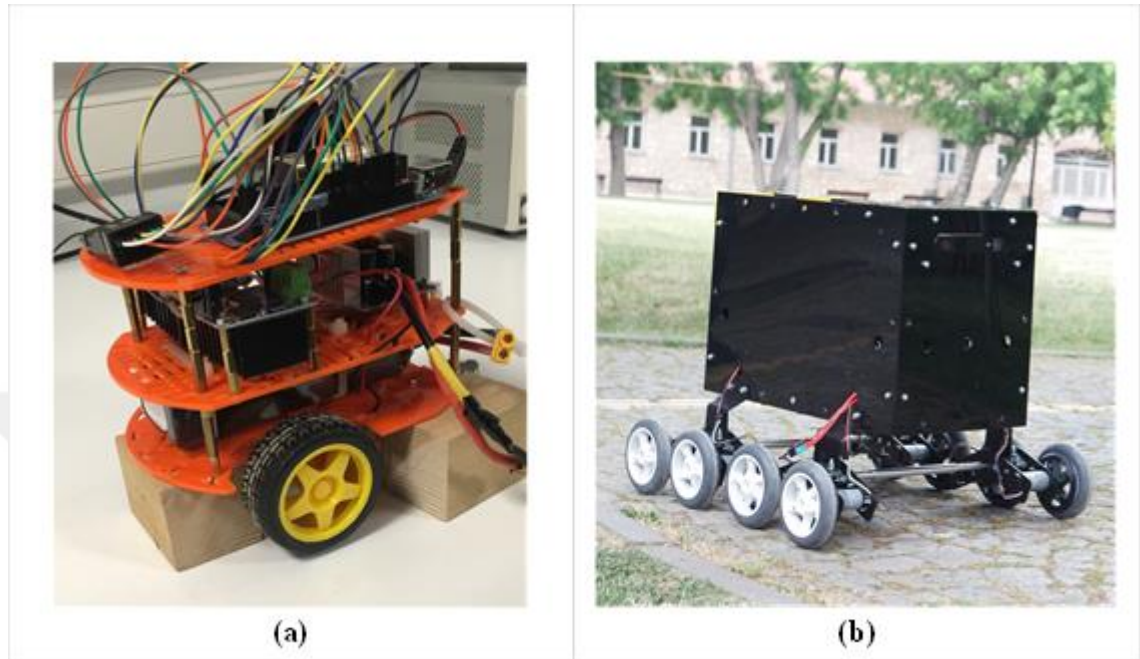


Fig. III.22: a) The Small Two-Wheeled Mobile Robot, b) The Proposed Eight-Wheeled Semi-Autonomous Delivery Robot

3.4.2 Live Video Stream

The essential point here is to see what the camera sees remotely. This was realized with a less than 1 s delay. The connection was established over the internet. Therefore, internet speed certainly affects the connection quality. On the other hand, the good point is that; both the remote control station and the robot are not need to be connected to the same local network. Before going on duty, the remote camera connection is established. Afterward, the robot sends to the delivery point.

3.4.3 The Ultrasonic Sensors and Distance Measurement

The ultrasonic sensors do not sense the distance. As the name refers, ultrasonic sensors measure the duration of traveling ultrasonic waves. The sensors first emit an ultrasonic wave and receive the wave reflected back from the object. There is a time difference between emission and reception times. The difference measured by an ultrasonic sensor is the traveled ultrasonic wave. By using this time difference, the distance between the sensor and the object is found. This can be found in two ways.

In the first way, the distance is calculated by employing the formula X. The speed of sound is roughly 343 m/s in air at 20°C.

$$Distance = (duration / 2) * 0.343 \quad (3.3)$$

The formula gives the distance in mm. Because the sensors measure the time difference in ms.

In the second way, which is preferred in the study, Arduino's map function is used. The Arduino's map function re-maps a numerical value from one range to another. The minimum value in the one range matches the minimum value in the other range. The same method is applied for the maximum values and the rest of the values between maximum and minimum values. While the function does not constrain the values within the range, it works for the out-of-range values, as well. Its syntax can be seen below :

$$y = map(x, 1000, 5000, 10, 50); \quad (3.4)$$

The x is a number between 1000 and 5000. By using the map function, it is mapped to the available number between 10 and 50. After that, it is assigned to the y. In the study, while x symbolizes the duration, y represents the distance.

The second way is to calibrate the sensors while measuring the distances. Because in the same distance, all ultrasonic sensors gave different outputs. Therefore, a test bench was set up. All ultrasonic sensors were tested and calibrated respectively on the same test bench. In the beginning, the Front-Left ultrasonic sensor of the robot was fixed on a constant point, and then, put the ruler under it. After that, an object was placed in front of the sensor and on the 25 cm level of the ruler. The output was recorded. Then the object was slid on the 30 cm until the 45 cm. On every level, the sensor output was recorded. If the outputs overlap with the linear increase of the object's real distance, the sensor is meant to be tested and calibrated. The test bench and the graphs of the calibrated sensors are shown in Fig 3.23 and Fig 3.24, respectively.

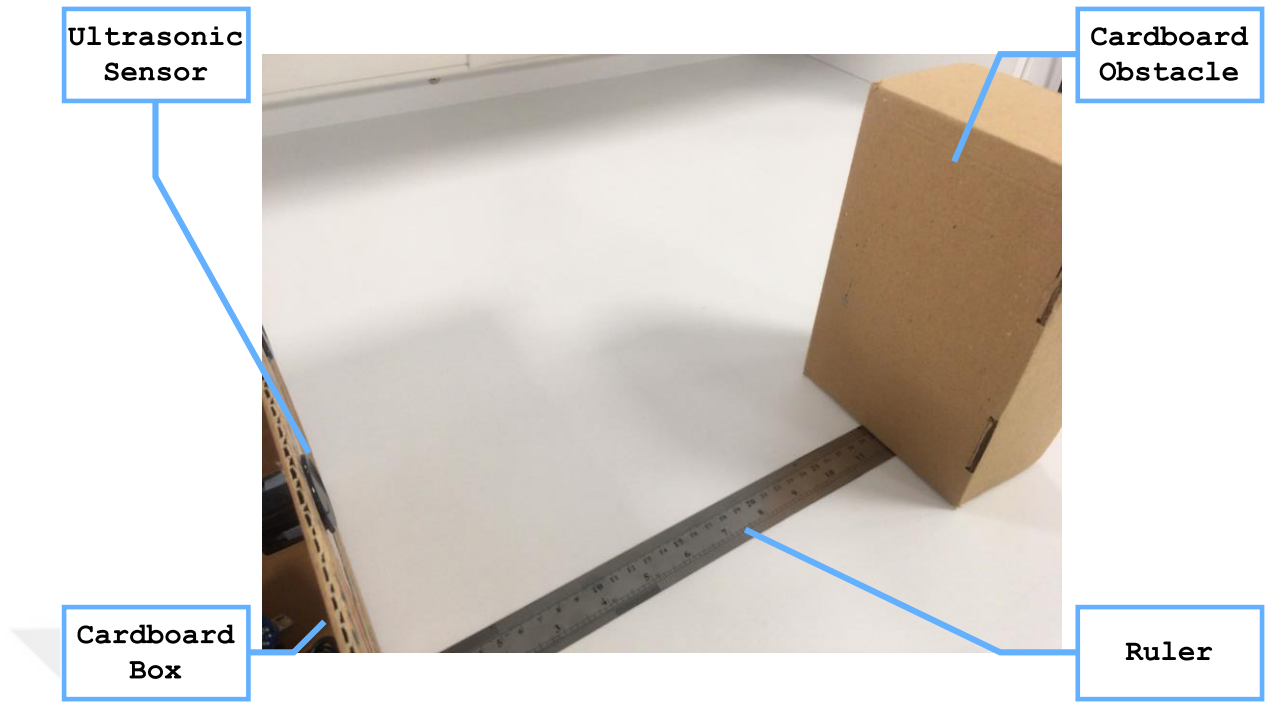


Fig. III.23: The Ultrasonic Sensor Test Setup

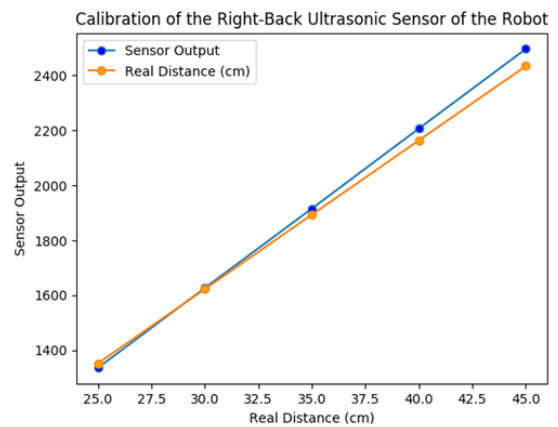
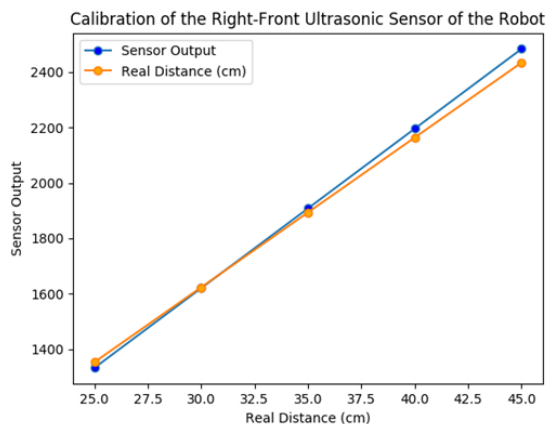
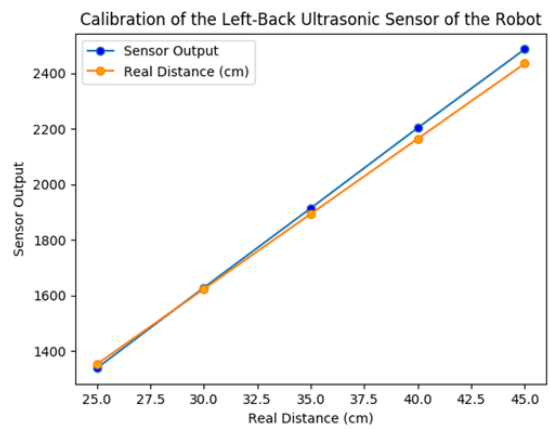
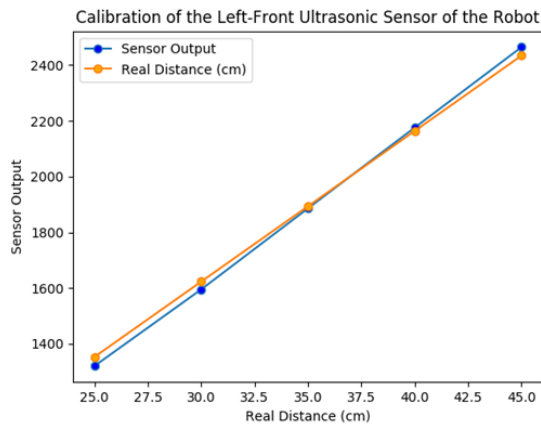
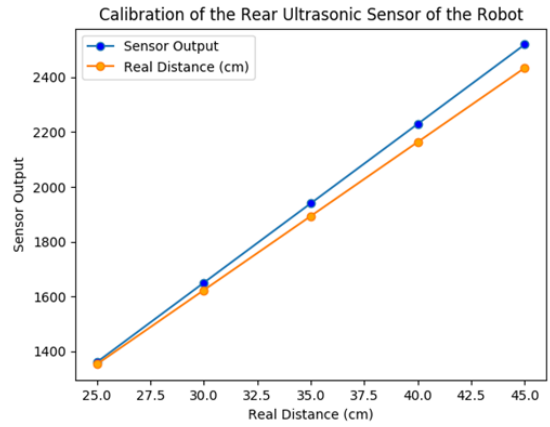
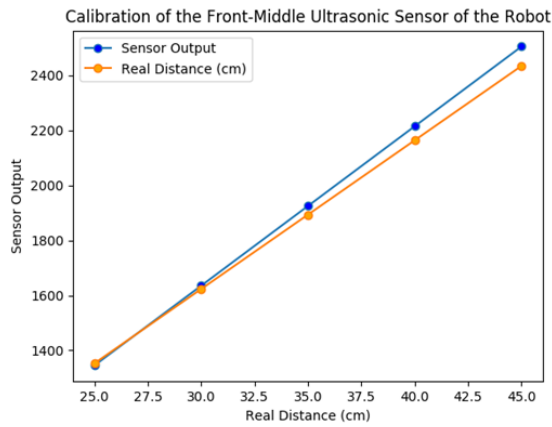
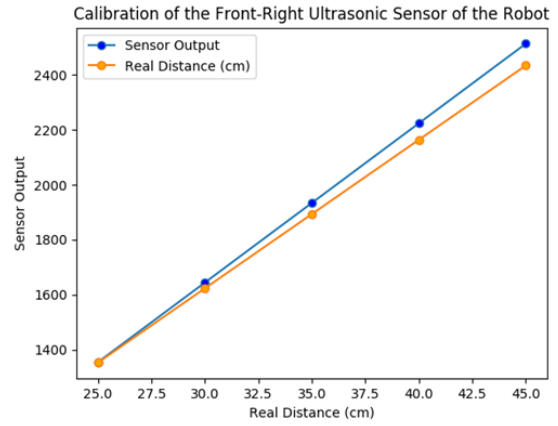
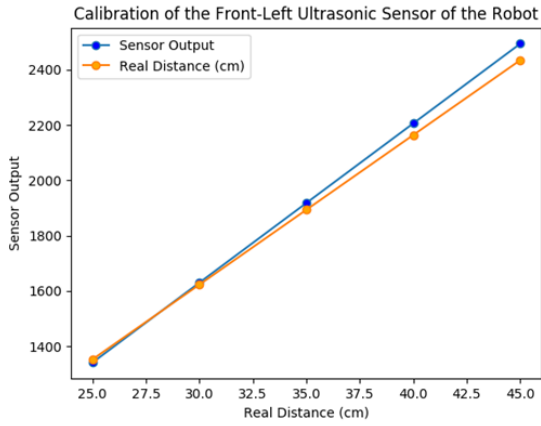


Fig. III.24: The Graphs of the Calibrated Sensors

All the calibrated sensors were connected to the ultrasonic sensor shield on top of the second Arduino Mega 2560. The distance measuring program was coded according to the algorithm displayed in Fig 3.25.

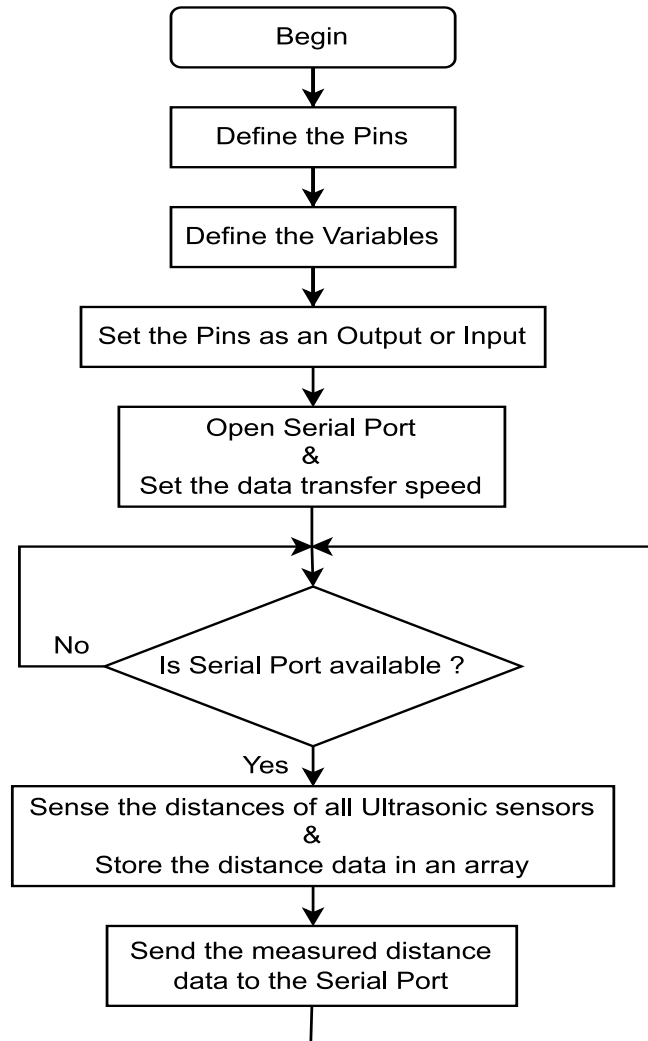


Fig. III.25: The Distance Measuring Algorithm

3.4.4 Semi-Autonomous Robot Control

In semi-autonomous robot control mode, we planned to make the robot autonomously realizes a big part of the delivery process. When the robot only faces a crucial, unpredictable situation, then it must send a signal to the remote control operator to take the robot's control. These situations can be crossing over, climbing the curbs and ramps, or getting stuck in very crowded areas. But due to the mechanical problems, the semi-autonomous robot control mode could not be accomplished. The solutions to the mechanical problems caused delays and took too much time. In this subchapter, the

point arrived at the semi-autonomous robot control is explained in detail.

The proposed eight-wheeled delivery robot's free-body diagram shown in Fig 3.26 is created. In order to control the robot's movement, linear and angular velocities are required. Because in the upper-level development environment, only linear and angular velocities are planned to use for driving the robot. The upper-level controller, the Jetson Nano, sends the velocity data to the lower-level controller, the first Arduino Mega 2560. The lower level controller converts the velocity data into the PWM signals for the robot's motors. The lower level controller also employs a PID algorithm to drive the robot in the desired direction with the determined speed according to both sent and actual velocity data.

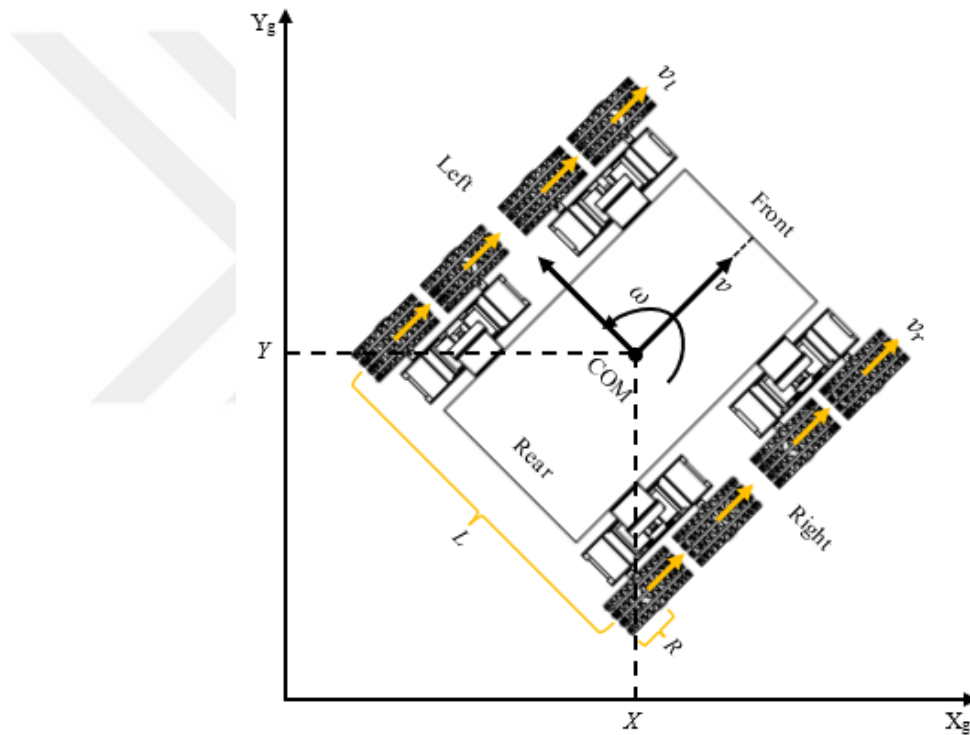


Fig. III.26: Proposed robot's free-body diagram

The control of the robot is provided by linear and angular velocity. The linear velocity (v) of the robot seen in Fig 3.26 is found by the formula (3.5) below.

$$v = \frac{v_r + v_l}{2} \quad (3.5)$$

In the above equation, v_r represents the linear velocity of the right wheels and v_l represents the linear velocity of the left wheels.

The angular velocity (ω) of the robot is found by formula (3.6).

$$\omega = \frac{v_r - v_l}{L} \quad (3.6)$$

L: It is the width between the wheel centers on the sides of the robot.

The linear velocities of the robot's wheels are found with the help of the formulas (3.7) and (3.8) below.

$$v_r = \omega_r \times R \quad (3.7)$$

$$v_l = \omega_l \times R \quad (3.8)$$

v_r represents the linear velocity of the right wheel, and v_l represents the linear velocity of the left wheel. ω_r represents the angular velocity of the right wheel while ω_l represents the angular velocity of the left wheel.

R: It is the radius of the wheels.

By combining the formulas (3.5), (3.6), (3.7), and (3.8), the angular velocities of the right and left wheels are obtained as in the following formulas (3.9), (3.10).

$$\omega_r = \frac{2v + \omega \times L}{2R} \quad (3.9)$$

$$\omega_l = \frac{2v - \omega \times L}{2R} \quad (3.10)$$

The obtained velocities are the target velocities and are converted from rad/s to RPM units by employing the formulas (3.11) and (3.12).

$$\text{Right Wheel's Target Velocity} = \omega_r \times 9.5493 \quad (3.11)$$

$$\text{Left Wheel's Target Velocity} = \omega_l \times 9.5493 \quad (3.12)$$

On the other hand, there are the feedback data coming from the motors' encoders. The feedback data are the counted ticks that represent the motors' rotation rates. By using encoder data, motors' actual velocities are calculated in terms of RPM, too. In the

calculation, the formulas (3.13) and (3.14) given below were utilized.

$$\text{Right Wheel's Actual Velocity} = ((\Delta pos_r \div 2100) \times 60) \div \Delta t \quad (3.13)$$

$$\text{Left Wheel's Actual Velocity} = ((\Delta pos_l \div 2100) \times 60) \div \Delta t \quad (3.14)$$

While the transformed wheels' angular velocity data, which are the target velocities, are the inputs for the PID control program, the calculated encoder data, which are the actual velocities, are the feedbacks. The block diagram of the PID controller is displayed in Fig. 3.27.

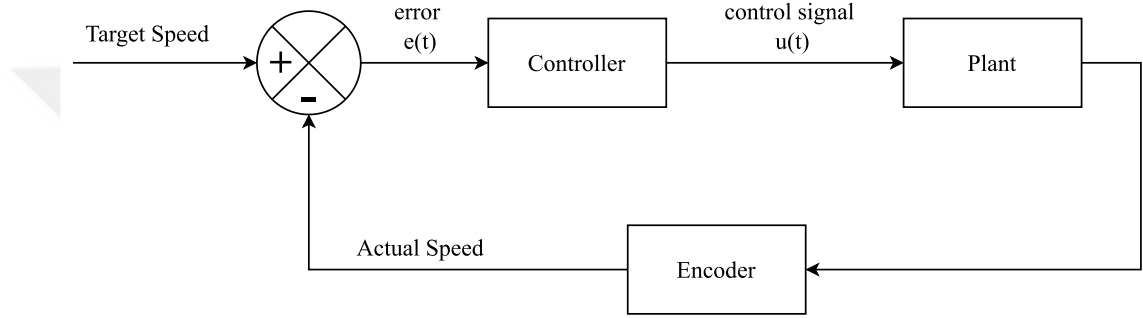


Fig. III.27: The Block Diagram of the PID Controller

The error is computed by taking the difference between the target velocities and the actual velocities as in the formula (3.15) and (3.16).

$$e_r(t) = \text{Right Wheel's Target Velocity} - \text{Right Wheel's Actual Velocity} \quad (3.15)$$

$$e_l(t) = \text{Left Wheel's Target Velocity} - \text{Left Wheel's Actual Velocity} \quad (3.16)$$

If the computed errors are equal to or less than 10 RPM, new control signals are not produced, and the motors are driven with the same previous PWM values. Otherwise, the derivative and the integral of the error signals are computed in the formulas (3.17) and (3.18), respectively.

$$\frac{de}{dt} = \frac{e - e_{prev}}{\Delta t} \quad (3.17)$$

$$\int e(t)dt = e_{int} + e \times \Delta t \quad (3.18)$$

By computing the proportional, derivative, and integral terms as in the formula (3.19), control signals are produced. The motors are driven by using the produced control signals.

$$u(t) = \left(k_p \times e(t)\right) + \left(k_i \times \int e(t)dt\right) + \left(k_d + \frac{de}{dt}\right) \quad (3.19)$$

If the control signals are higher than 255, the motors are driven with 255, which is the highest value for the PWM output.

Everything until this point arrived at was brought up to the desired mark. The planned but not completed steps are as given below :

- Estimating and sending the odometer data
- Employing the LIDAR sensor
- Realizing the sensor fusion process by using the odometer, LIDAR, IMU, ultrasonic sensors, GPS, and camera data
- Obstacle detection
- Sending the robot autonomously from one point to another along the predefined path on the earth by avoiding the possible collisions

CHAPTER IV FINDINGS AND DISCUSSION

The thesis aims to design an eight-wheeled semi-autonomous delivery robot and test the design by transferring it to real life. The design process of the robot took longer than planned due to the material supply problem brought by the pandemic environment, the failure of the materials received to show the expected effect, and some points that were overlooked. This caused the time allocated for the electronics and software of the robot to be shorter than expected. With this robot, solutions were sought for two fundamental problems of delivery robots used in the last step of the delivery. One of them is curb and ramp climbing. Here, it is aimed to solve this problem by creating two bogie systems on the front and back of the robot. Another problem is the autonomy of delivery robots. Here, too, the aim is to remove the robot from a completely remote-guided structure and enable it to perform specific tasks autonomously.

4.1 Eight-Wheeled Semi-Autonomous Delivery Robot And Ground Tests

The designed eight-wheeled structure of the robot was realized and tested. As mentioned in the Design Process section, the mechanical design and assembling of the robot took longer than planned because of mechanical problems. However, in the end, the final design of the robot was enough for the tests.

The mechanical structure of the robot has eight wheels actuating with eight motors and a double bogie system. On the other hand, its electrical and electronics structure has a 4S 22000 mAh lithium polymer battery, a 32 Amperes fuse, an E-Stop, DC-DC Converters, Jetson Nano, motor drivers, Arduino Mega 2560 boards, a specific shield, led lamps, a relay, eight ultrasonic sensors, camera, Pixhawk, telemetry modules, GPS module, IMU board, LIDAR Sensor, wireless control console, transmitter and receiver module for teleoperation, voltage checker, current sensors. On the software and control side, the successfully realized tests were teleoperation of the robot, monitoring the robot location remotely, live video streaming from the robot to the remote control station, remote steering robot from the remote control station, PID speed control of the wheels,

ultrasonic sensor calibration and distance measurements, current sensor calibration, and current measurements.

The field tests were explained in detail in the following sections.

4.2 Ground Tests

The very first tests of the robot were realized on different ground types such as epoxy, asphalt and grass. The ground types can be seen in Fig. 4.1.



Fig. IV.1: The ground types that the tests were realized, **a)** Epoxy Ground, **b)** Asphalt Ground, **c)** Grass Ground

While the robot was moving on these grounds, the IMU data were collected.

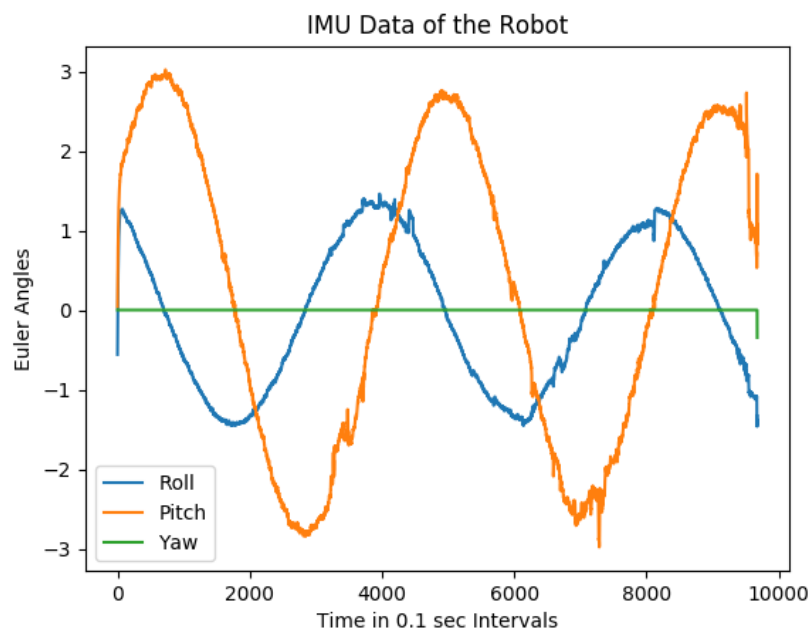


Fig. IV.2: The IMU data while the robot was moving on the Epoxy Ground

While the robot was moving on the epoxy ground, it had only small vibrations. The

reason of not changing the yaw is the straight movement of the robot.

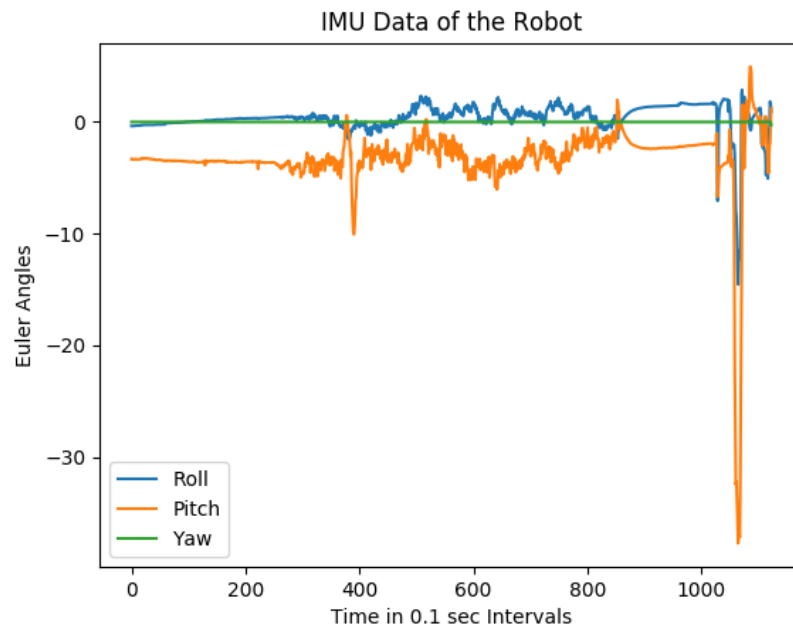


Fig. IV.3: The IMU data while the robot was moving on the Asphalt Ground

In this test, the frequency of the vibration is high. The reason of the highest peak on the Pitch is asphalt distortion, as can be seen in Fig. 4.1. The movement is still straight.

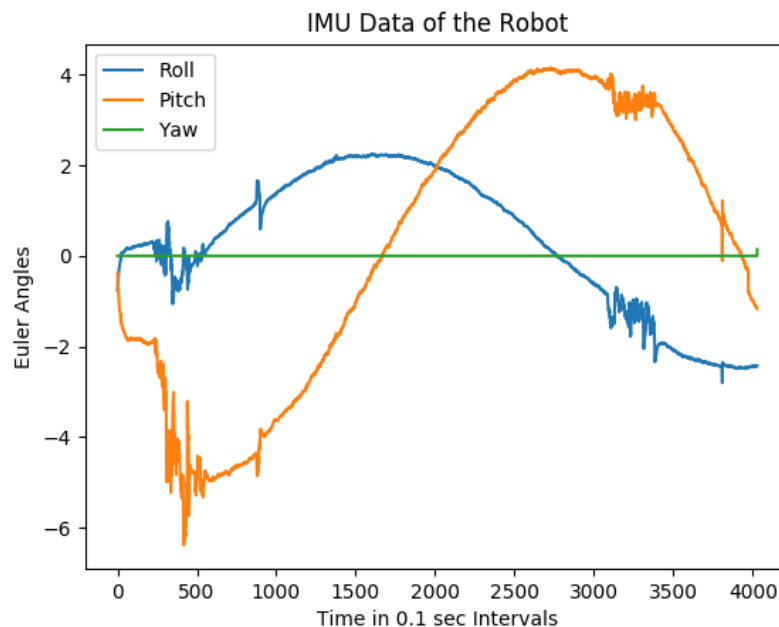


Fig. IV.4: The IMU data while the robot was moving on the Grass Ground

When the robot went on the grass ground, its roll and pitch angles increased because of

the small hills and descents. The robot went straight as in previous tests.

However, the robot smoothly moved on and tested three ground types. It has not stuck in any kind of tested ground.

4.3 Teleoperation, Climbing Up And Down Of The Curb And The Ramp Tests

On teleoperation tests, the FRSky transmitter and receiver modules with the Turnigy 9XPRO console were used. The receiver is connected to the Arduino Mega 2560, where the motor control is done. When the operator intervenes in the robot remotely, he/she takes control of the robot by using the AIL D/R switch on the console. The effective range of the used teleoperation modules has been tested first. The range is about 250 m. Beyond the tested maximum range, the connection between the robot and remote controller bumps off.

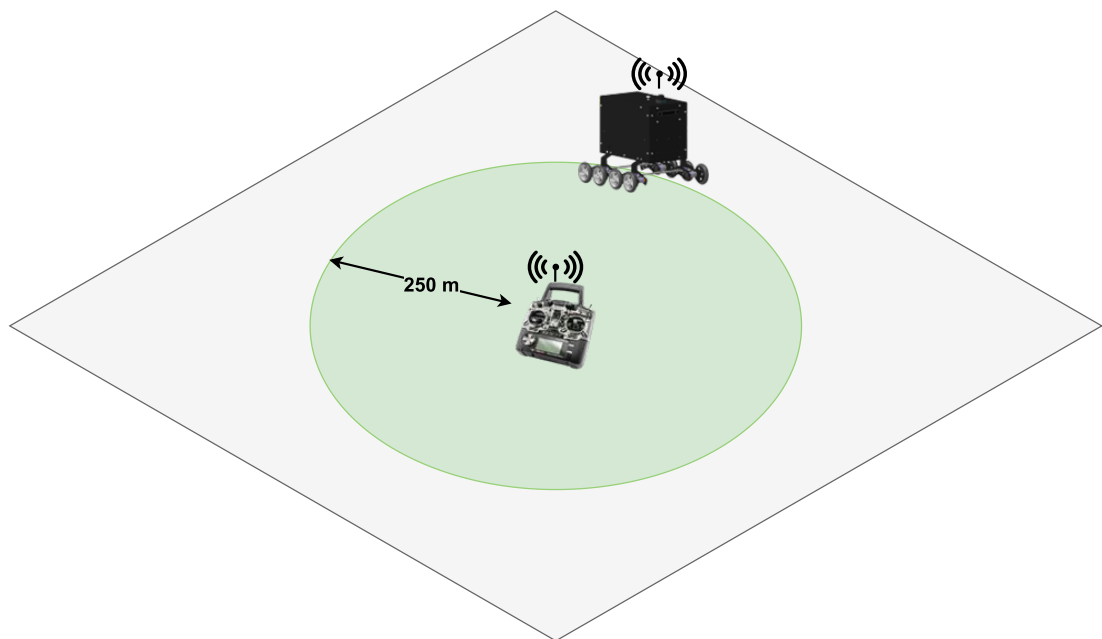


Fig. IV.5: The Range of the Remote Controller

Later, the remote steering of the robot was tested with the console. It has been observed that there is no obstacle in front of easily controlling of the robot.

Thereafter, the navigation and live video streaming tests were realized. In order to monitor the location of the robot, the Mission Planner Software was used. Because it is easy to integrate and use. Therefore, it has been utilized. When the GPS connects to the satellites, the location of the robot immediately appears on the map of the software GUI.

On the other hand, the camera connection can be established over the internet. It has

also been tested. On the remote control monitor, the remote control operator can monitor both the environment of the robot and its location at the same time.

In Fig. 4.6, a sample scenario can be seen: While the robot is out of the field of the operator's vision, the operator monitors on the remote control station what the robot sees and steers the robot towards the target point remotely.



Fig. IV.6: A Sample Scenario, **a)** The robot is on duty outside, **b)** The remote operator monitors on the remote-control station screen what the robot sees and steers the robot remotely.

4.3.1 The Robot Climbing Up And Down on 130 mm High Curb

At this point, the proposed idea was tested. Its simulation tests were realized in (Kaya & Erdemir, n.d.). As can be seen in Fig. 4.7, the robot easily climbed up on the 130mm-high curb and climbed down easily from the same curb from the same point. As proposed before, during all the tests, at least six wheels of the robot stayed touched with the ground. Therefore, the robot has not fallen or is stuck on the curb.

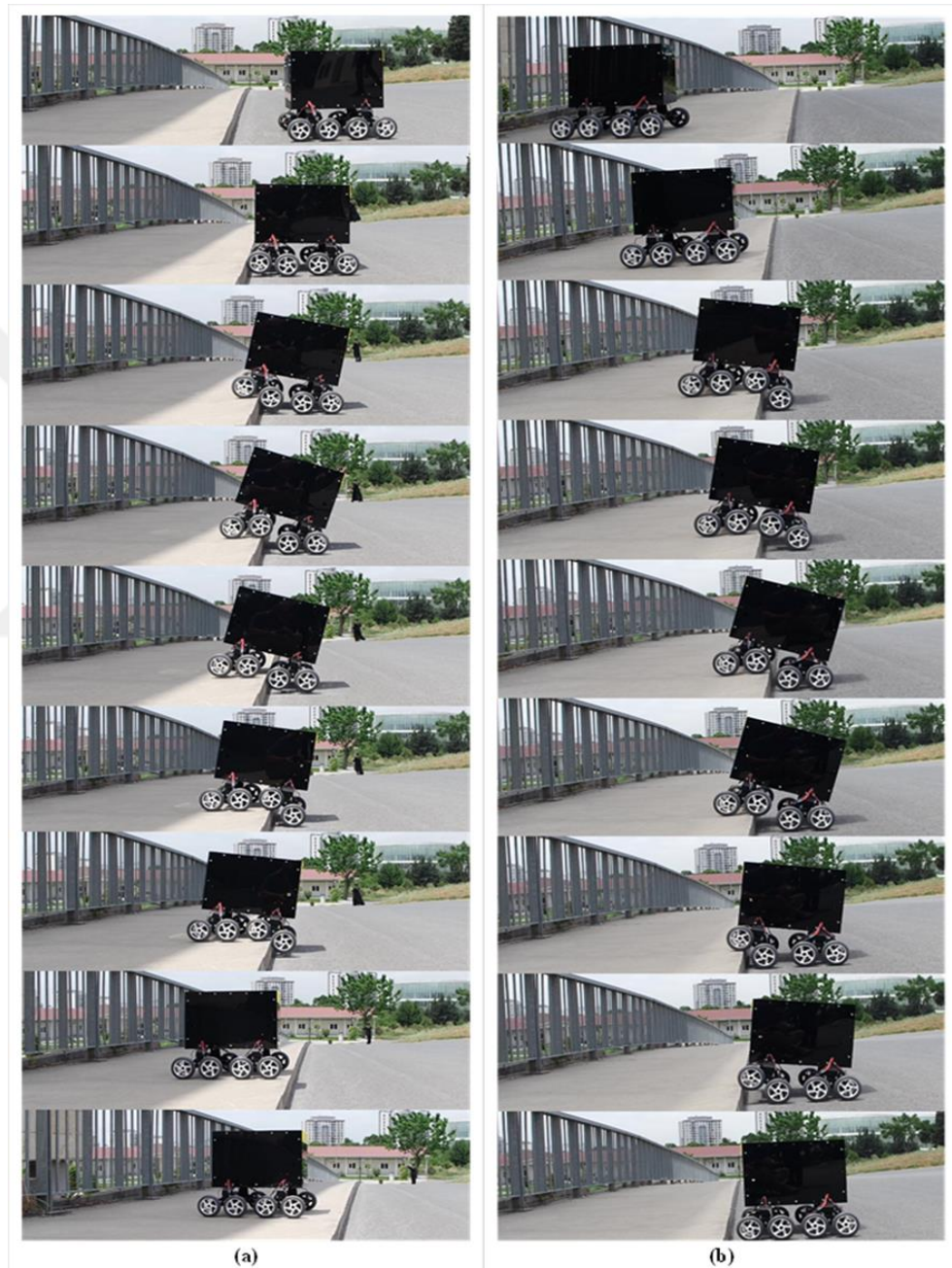


Fig. IV.7: The climbing up and down of the robot on 130mm-Height curb **a)** The climbing up test, **b)** The climbing down test

While the curb climbing tests, the IMU data of the robot were collected. As seen in the Fig. 4.8 below, the robot was making some peaks while climbing up.

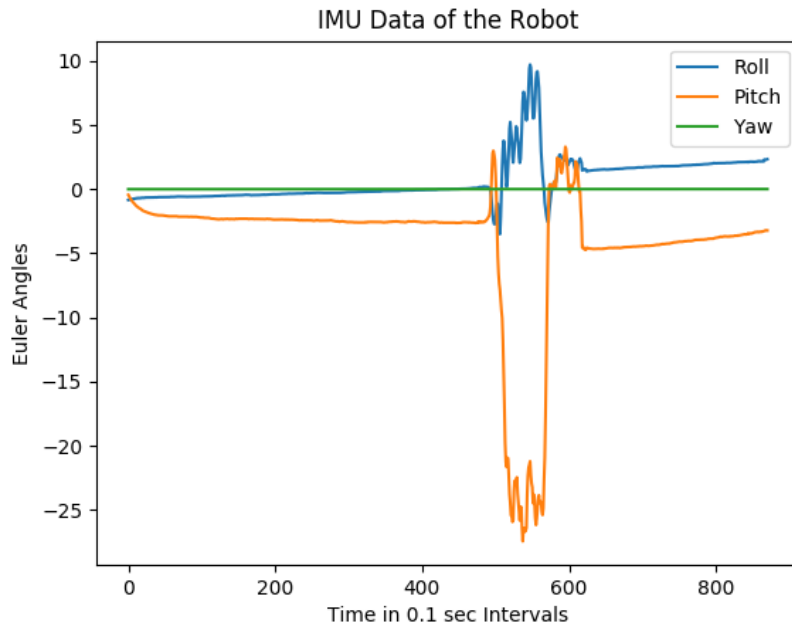


Fig. IV.8: The IMU data during the test of climbing up on the curb

Similar to the climbing up, the robot made a peak while climbing down from the curb. However, this peak is in the reverse direction. The movement can be observed in Fig. 4.9.

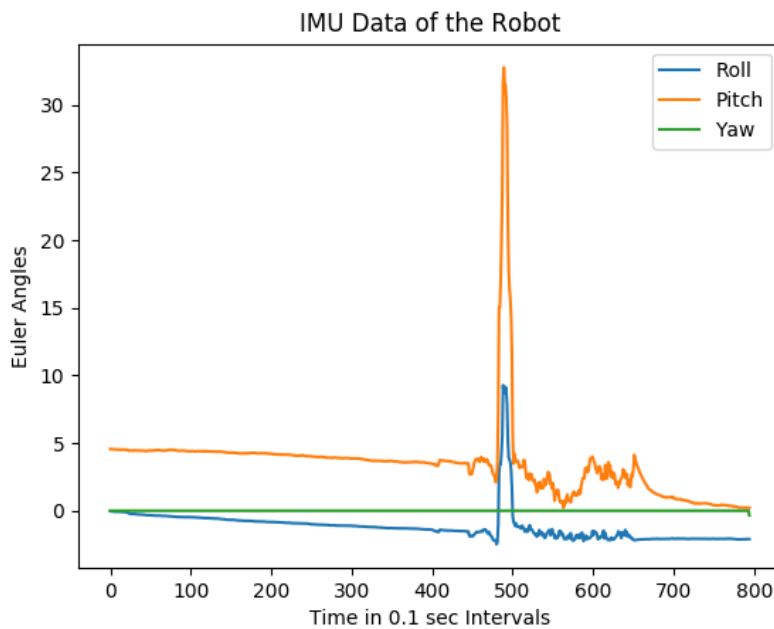


Fig. IV.9: The IMU data during the test of climbing down from the curb

4.3.2 The Robot Climbing Up And Down on 300mm-Height Ramp

In this test, the robot climbed up, on, and down from the 300mm-height ramp. The robot easily realized the tests. The figures below show the tests and the IMU data during the tests. On the reverse movements, the data plotted the reverse lines.

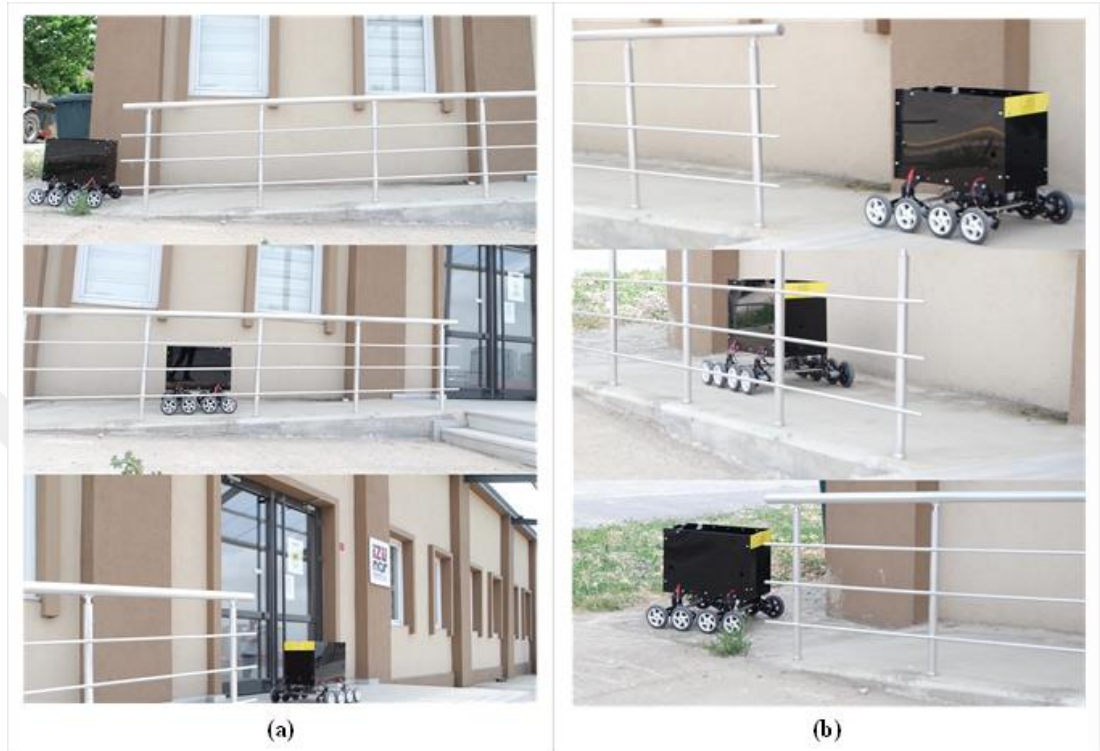


Fig. IV.10: The climbing up and down of the robot on 300mm-Height ramp **a)** The climbing up test, **b)** The climbing down test

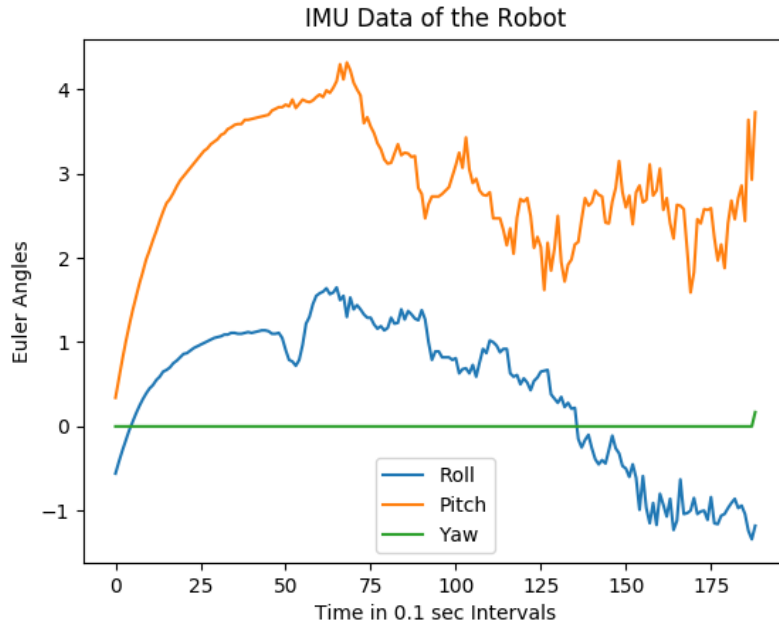


Fig. IV.11: The IMU data during the test of climbing up on the ramp

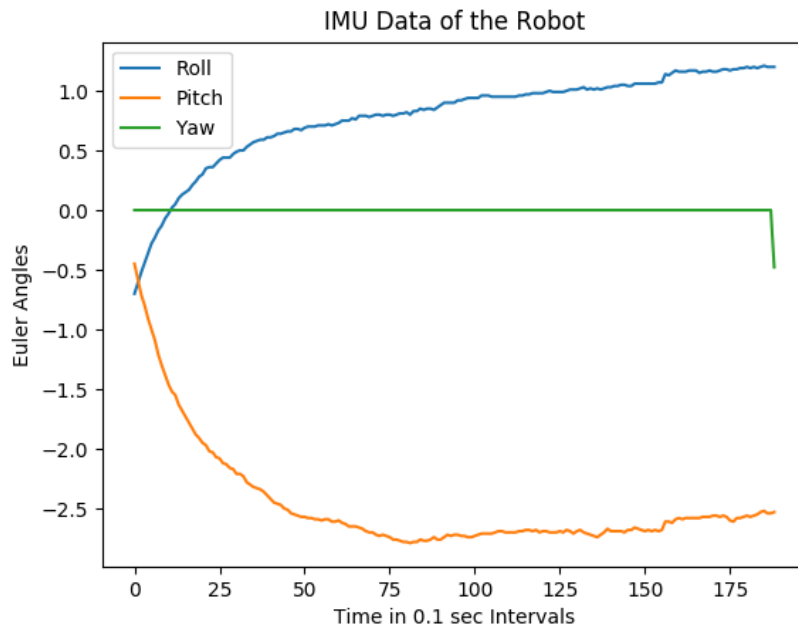


Fig. IV.12: The IMU data during the test of climbing down from the ramp

4.4 Semi-Autonomous Mode

The indispensable issue for the semi-autonomous steering mode has been GPS. Here, the basic approach is to go to the defined coordinate in the shortest way to the robot. On the other hand, the robot calculates its location using the information it receives from its encoders and GPS data. As a result, it moves by calculating the distance between its destination and its current location. The robot is not initially given only the final

destination point to go. A route is created with waypoints given at short intervals, and the destination point at the end of this route is given. After reaching the target point, the robot returns to the starting position by following the same route.

In addition, an obstacle avoidance algorithm is used for the robot to avoid the obstacles it encounters during its mission. At the software point, the basis of the robot's autonomy was aimed to lay by using 2 PID control programs, Trajectory Tracking and Collision Avoidance programs. However, the mechanical problems faced could not allow the autonomy studies.



CHAPTER V

CONCLUSION & FUTURE SCOPE

In this study, a semi-autonomous delivery robot with eight wheels was designed, developed, and realized to some extent. The realized robot is a prototype and also serves as a research platform for delivery robot studies. The robot was tested in the Istanbul Sabahattin Zaim University Halkali Campus. Its eight-wheeled double-bogie structure proved the proposed climbing up and down actions during the field tests. At least six wheels always stayed in touch with the ground in these tests.

The robot also showed durability during the tests on the different ground types. This allows for the robot to be used other than the pavements as well. The IMU data shows that the robot has only small vibrations.

On the one hand, the teleoperation of the robot was successfully tested. Although its effective range is relatively small for the delivery tasks, it can be enlarged with the long-range receiver and transmitter modules.

On the other hand, the monitoring robot location remotely was realized with the Pixhawk board and Mission Planner software. These tools are very handy.

Lastly, live video streaming was realized over the internet. The bad points here are the quality and the speed of the internet. However, the good point is that the robot and the remote-control station do not have to be connected to the same local network.

Although the thesis result is mostly satisfactory, not all of the sensors on the robot could be used actively. However, in future studies, it is planned to use all of the sensors on it simultaneously. In addition, the long duration of mechanical design and procurement of parts has caused a shortening of the time considered to be devoted to electronics and software. These also affected the autonomy studies. The autonomy studies and tests were not realized.

The planned other studies are improving the electronic connections of the robot, reducing wiring, and testing multiple algorithms. In addition, increasing the number of real-time tests is among the targets. It is aimed to increase the autonomy level of the

robot by improving the algorithms with the feedback to be obtained.

Several planned actions in the future scope are given below:

- Utilizing the odometer data
- Deploying all the sensors such as LIDAR sensor, ultrasonic sensors, GPS. and IMU
- Multi-sensor fusion operation
- Obstacle detection and collision avoidance
- Semi-autonomous movement tests



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CURRICULUM VITAE

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Papers

- Usage of Open-Source Mobile Robots in Engineering Education and a Sample Curriculum
 - Istanbul Sabahattin Zaim University Journal of the Institute of Science and Technology
 - <https://doi.org/10.47769/izufbed.866093>
- Design of An Eight-Wheeled Mobile Delivery Robot and Its Climbing Simulations
 - 2023 International Conference on Precision Engineering and Mechanical Manufacturing