Autonomous delivery robots

Author:	Marianna Oleotti
Module:	Intelligent Systems and Robotics
Supervisor:	Dr. Abiodun Yusuf
Faculty:	School of Built Environment, Engineering, and Computing
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Abstract

In the era of e-commerce and food delivery the traditional supply chain has been profoundly modified. Not only is it now fundamental to keep track of every stage of the process, but also is important to plan the chain from the warehouse down to the customer's doorstep with the so-called last-mile phase.

From the challenges that this difficult phase has always raised, many solutions have been developed and deployed as alternatives to the traditional deliveries through couriers, postmen, and riders.

With COVID-19 pandemic, the evolution of the autonomous systems took a leap forward, as it became the perfect mean to avoid social interaction. Along with the always current sustainability issue, this paper analyzes the structure of the state-of-the art delivery robots, its limits, its possible improvements and future works.

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Chapter 1

Introduction

1.1 Background

In logistics, last-mile delivery is intended as the set of activities performed to ship a product from the hub of the distribution to the client's private houses in urban areas (Boysen et al. 2021). This constitutes the last ring of the supply chain and its planning has been facing increasing challenges in the last three decades due to the advent and rapid paced growth of the online shopping.

Since the first glimpse of e-commerce opened by Jeff Bezos in 1995, the e-commerce has become a trillion-dollar worth retail market sales, forecasted by Statista to build up the 25% of the total global retail sales by 2025.

Costumers require last-mile delivery to be fast, precise, secure, product-specific and convenient at the same time. On the opposite companies have to face with damaged or returned goods, unexpected delays, tracking, transparency, and geographic congestion. So far the goods are delivered mainly through vans. Vans are costly, subject to time pressure and have a significant impact on the environment.

This brings the necessity to find alternatives solution to deliver the purchases that has to consider the three perspectives of environmental sustainability, quality effectiveness and cost efficiency (Mangiaracina et al. 2019). Different last-mile solution exist nowadays. Along with the traditional single-van delivery, the following approaches have been implemented: the multiple transport vehicles (e.g., a delivery van and/or a drone), storage facilities (e.g., a central depot and/or a postal locker), and handover options (e.g., attended home delivery or self-service by customers) (Boysen et al. 2021).

After the recent pandemic of COVID-19, more and more people shifted towards online purchase or increased their tendencies, limiting the amount of social interaction and contact. This happened in countries where the population density is higher, such as India or China, where more than the 50% of customers ended up changing their purchasing habits into online e-commerce (Statista 2021).

As a consequence the study of last-mile delivery approaches that involved human presence was abandoned in favour of the development of automatized contact-less solutions, such as the autonomous delivery robots, which, as their name says, are robots that can deliver good in an autonomous way, without the supervision – or with a minimum level of supervision – of a human.

1.2 Aim and Objectives

The aim of this research is to provide an extensive analysis of an outdoor autonomous delivery robot, through case studies of deployed proprietary robots, and to propose improvements and advancements in the identified limitations of the system, by answering the following Research Questions (RQ):

1. What are the physical components (including sensors) and non physical components (task and mechanisms) that define the robot?
2. What is the process of getting a robot ready to operate?
3. To which extent is the human present in the autonomous system, if present?
4. What are the ethical implications of the robot and the social responses to the robot?
5. What are the limitations of the robot?
6. What is the future work that can be done to improve the robot?

1.3 Rationale

Delivery robots, such as the Starship Technologies systems, are the state of the art of sustainability in the last-mile of the supply chain. As pointed out in the 1.1, the diffusion of the delivery robots is increasing exponentially, especially after COVID-19 pandemic. Therefore, it's important to understand how these innovative systems work and what are the challenges that we still have to face before delivery robots can be fully integrated into society.

1.4 Scope

The scope of this report is limited to the analysis of the technical structure of an outdoor autonomous delivery robot from an engineering point of view. Both the hardware and the software components involved in the in the system will be inquired.

Furthermore, the ethical implications of the presence of the autonomous delivery system in the sidewalks of the towns and cities will be considered. Improvements and future developments will be also included at the end of the report.

1.5 Contribution

Thanks to the in-depth analysis of the structure and the behavior of last-mile delivery robots carried out in this study, solutions and improvements to the current intelligent system are proposed. These recommendations could raise the awareness of the companies on their own systems.

Moreover, the study conducted aligns with the 17 Sustainable Development Goals (SDGs), established by the 2030 Agenda for Sustainable Development of the United Nations. In particular, it aligns with the ninth goal: *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*; and eleventh goal: *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation* (United Nations 2015).

1.6 Outline

This section provides an overview of the organisation of this report. After presenting the problem of the sustainability and efficiency of last-mile in logistics and stating the aim and objectives of this study in Chapter 1; a review of the deployed autonomous delivery robots is carried out in Chapter 2. Chapter 3 describes the fundamental hardware and software components of such a system. An evaluation of the robot is given in 4, along with an overview of the ethical implications of it. Finally, directives for future developments and improvements of the system are proposed in Chapter 5.

Chapter 2

Literature Review

To address the main challenges of last-mile delivery, multiple solution have been implemented and are currently on the market, competing to optimize the supply chain.

The robotics and automated solutions can be divided into four categories:

1. Autonomous delivery drones (Amazon Prime Air, UPS' Flight Forward, Wing)
2. Autonomous trucks (Gatik, Tusimple, Waymo Via)
3. Autonomous delivery cars or vans (Nuro, Udelv, Robomart)
4. Autonomous delivery robots – the focus of this Chapter (Starship Technologies, Kiwibot, Lmad, TwinswHeel, Eliport, Scout by Amazon)

2.1 Starship Robot®

The Starship Robot® by the company Starship Technologies was first introduced to the world in the United States in 2018. The autonomous system can drive both in streets and sidewalks. Nowadays it is present in the United States, the United Kingdom, Germany and Estonia, operating mainly in college campuses. In Figure 1, is possible to see a Starship Robot® in action.

Starship's robots [1] are food delivery robots, therefore the base structure is the one of a generic deliver robot, but the box is built to carry orders made from restaurants and fast food. The robot can be personalised, as the company offers the option to add insulating insert for eventual chemicals or other good delivery. So far, the robot can travel only within a 6km radius, at a maximum speed of 6km/h. The robot is

[1] https://starshipdeliveries.com/industry

Figure 1: Starship Robot in Milton Keynes, UK

autonomous but at any time human can intervene to take control of the system and help the robot carry out the task. It is equipped with six wheels so that it can climb over sidewalks and small obstacles.

The specification of the sizes of the robot can be seen in Figure 2. In total, the robot weights 35kg and can carry a maximum of 10kg.

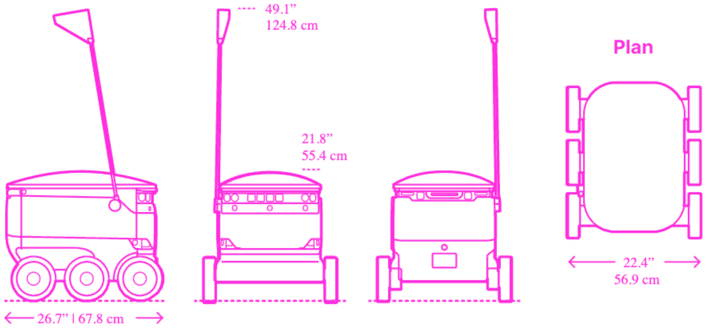

Figure 2: Starship Robot® specifications

The hardware includes ultrasonic sensors, 12 cameras, radar, GPS, alarm system, reflectors, signal flag, TOF cameras. The recipient box includes a security mechanism that allows the box to be open only be the person who placed the order through the ad-hoc developed mobile app. It has a 1260 Wh battery, that allows the robot to drive for over 12 hours. The robot is cO2 neutral, as it is emission-free and does not generate any noise.

2.2 Kiwibot®

Kiwi Campus[2] is a Colombian company that provides food delivery services through autonomous robots called Kiwibots®. The robot was first deployed in the campus of Berkley University to deliver food to hungry students. Nowadays it is successfully deploys in New Mexico State University, Loyola Marymount University, and Gonzaga University.

The systems are also autonomous, but human operators supervise the progress of the deliveries. The main feature of the robot is the 10” LED screen that displays a face with simulated emotions: the eyes of the robot can turn angry, sad, happy, or in love (see Figure 3. The specification of the sizes of the robot can be seen in Figure 4.

Figure 3: Kiwibot® multiple faces

Kiwibot 4.0® has a recipient box that can host up to two food orders at the same time; it includes 3 frontal cameras, a 180-degree camera, HD internal camera, 4G, GPS, and a 512-Core GPU with Tensor Cores.

2.3 LMAD®

Last Mile Autonomous Delivery (LMAD)[3] is a startup company that developed an autonomous delivery locker system. It combines the concept of autonomous delivery and lockers as a last-mile solutions in a state-of-the-art and unique delivery system.

The robot was developed in Aalto University Campus, Finland, supported EID Digital and manufactured by GiM Robotics®. The robot, which can be seen in Figure 5,

[2]https://www.kiwibot.com/
[3]https://www.lmad.eu/

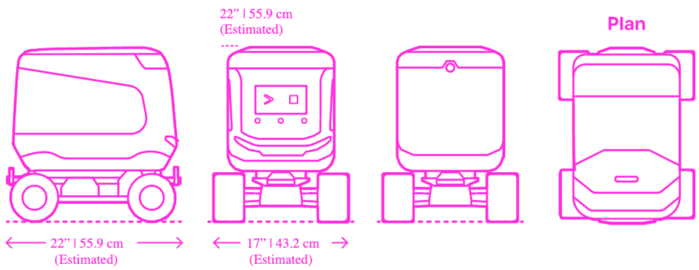

Figure 4: Kiwibot® specifications

has 360° LiDARs, a high-accuracy GPS system and an obstacle-detection feature. So far, the robot is only able to stop in case of obstacle, but advances in this direction are currently under development.

All the possible trajectories in the campus are pre-mapped so that the robot only needs to focus on the choice and movement. In the campus, 15 pickup points have been selected. The robot is destined to streets and not sidewalks.

Figure 5: Lmad® robot

Chapter 3

Methodology

In this section the system will be described, from an overview of the whole system, the main modules will be described.

The main components of an autonomous delivery robots are summarised in Figure 6.

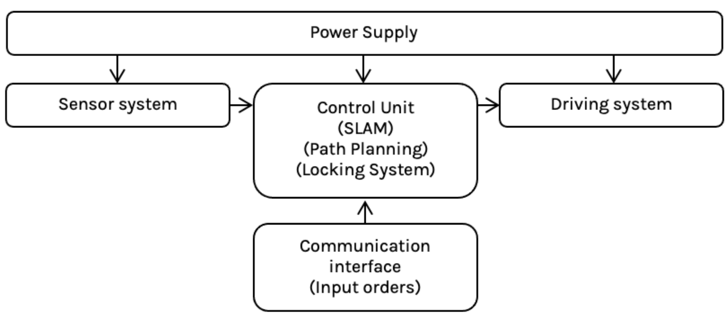

Figure 6: Diagram of the robot components

3.1 Sensors

To detect the surroundings the robot are equipped with cameras, LiDAR sensors, IMUs, and ultrasonic (proximity) sensor.

3.1.1 Light Detection and Ranging sensors

Light Detection and Ranging (LiDAR) sensors are believed to be the key sensors that an autonomous system should have. This sensors dynamically measure distances through a modulated laser carrier and reconstruct the environment that lies in its field of view (FoV) as a high-density 3D or 2D point cloud thanks to the measured time of flight (ToF) of the signal (Wang et al. 2020).

LiDAR are classified as mechanical or solid-state, based on their capabilities of scanning or non-scanning the environment to acquire data.

1. Mechanical LiDAR. This technology include a rotatory mechanisms that enables the system to have a 360° FoV Van Nam & Gon-Woo (2021),

2. Solid-state LiDAR. This technology does not include any spinning component, therefore it has a reduced FoV – which also makes the sensor cheaper compared to a Mechanical LiDAR. To obtain a wider range different channels of emissions can be used (Khader & Cherian 2020).

Figure 7: Example of 3D reconstruction of the world through LiDAR

3.1.2 Inertial Measurement Unit

Inertial Measurement Unit (IMU) is a set of sensors that are used in several fields to assess the velocity, gravitational force and orientation of an object in the space. Older IMUs only include accelerometers and gyroscopes, while later IMUs also include the use of a third sensor, the magnetometer, commonly known as compass (Ahmad et al. 2013). In Figure 8 it is possible to see the appearances of the sensors.

Together the three sensors are able to detect with high accuracy the pitch, roll and yaw of an object.

Figure 8: Accelerometer, gyroscope and magnetometer.

3.1.3 Ultrasonic sensor

An ultrasonic sensor is a technology that transmit ultrasonic sound waves and then receive them into an electrical signal. By measuring the delta of time between the moment the signal is emitted and the moment the signal is received, it is possible to estimate the distance from a point precisely (ESPHome 2017). An ultrasonic sensor can be seen in Figure 9.

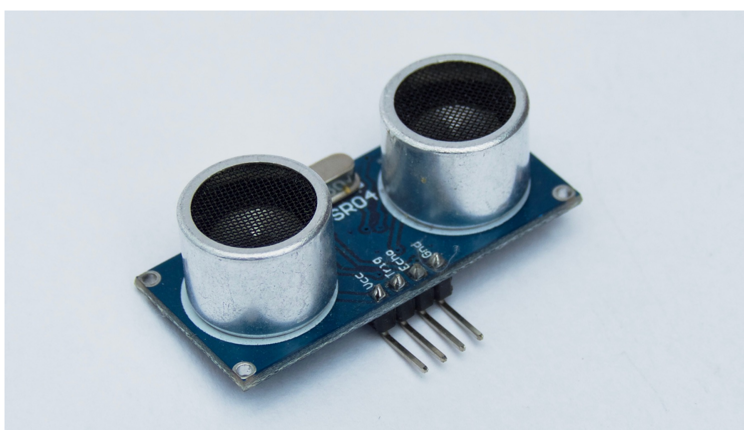

Figure 9: Ultrasonic sensor

3.2 Navigation and path planning

One of the crucial problems of autonomous driving for robots is to be able to have a semantic understanding of the environment, meaning where they are located, what are the obstacles to their driving and which routes are possible (Panigrahi & Bisoy 2021). The phases that a robot undertakes to accomplish the task of navigation are:

1. Perception (or initialization): gathering data from the surroundings through sensors

2. Localization and mapping: estimating the current orientation, position and location on the map (based on the collected data)

3. Cognition: planning the path

4. Motion control: modifying accordingly the motor outputs

3.2.1 Simultaneous Localization and Mapping

Simultaneous localization and mapping (SLAM) is the problem of building and updating in real-time the map of the surroundings of the robot, for it to be able to localize itself and therefore take the next step towards its goal, while updating at the same time its position (Durrant-Whyte & Bailey 2006).

The flow is summarized in Figure 10, where the process is divided into two phases: the processing phase that is dependent from sensors and the processing phase that focuses on optimization.

This problem can be divided in three different sub-problems according to the initial information available to the robot about its state:

1. Tracking. The robot's initial location is known (in probabilistic it is denoted with a Gaussian distribution)

2. Global positioning. The robot's initial location is not known and therefore need to be estimated, knowing the surroundings.

3. Kidnapped robot problem. The robot's initial location is not known and therefore need to be estimated, without knowing the surroundings.

SLAM techniques have been classified according to the hardware used to collect data:

1. LiDAR SLAM, processing data collected only through LiDAR sensors. The estimation of the movement is obtained by a continuous matching of the point clouds as they are acquired by the LiDAR sensors and then converted into grid maps or voxel maps (MathWorks 2021). As LiDAR lacks in semantic informations, it is mostly used in indoor environments, but can be included in outdoor systems along with IMU or cameras.

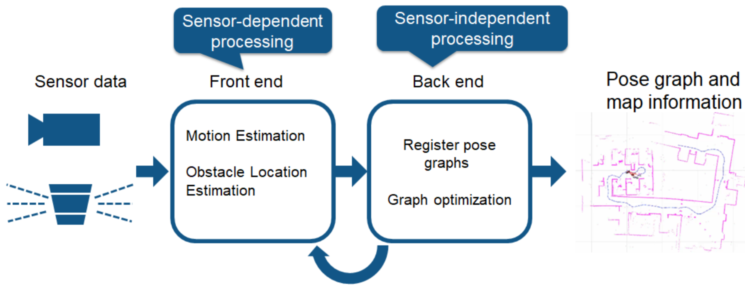

Figure 10: SLAM processing flow (MathWorks 2021)

2. Visual SLAM, processing images captured by cameras or visual sensors. Visual SLAM algorithms are computational more complex, but the the equipment is relatively cheaper (Macario Barros et al. 2022).

   (a) Visual-only SLAM. A monocular or stereo camera capture the surroundings.

   (b) Visual-inertial (VI) SLAM. The system is integrated with an IMU. Faisal et al. (2019)

   (c) RGB-D SLAM. The system is integrated with a depth sensor, so that the data captured is a RGB-D image. This type of sensors are based on LiDAR [Shaikh, 2021].

   The algorithms mainly used in autonomous driving are based on the Bayesian Filter (such as Kalman Filters or Particle Filters). The main challenge of this algorithm is to keep the computational complexity to its minimun, with a minimized delay so that the robot can perceive and process in almost real-time.

In the case of robots as Starship Technologies, a 2D graph-map is created in advance from satellite images, and the made available to the robot for it to improve it. With the human supervision the robot is first introduced to the new space to collect all the data to form a 3D offline map. The information can be collected by different robots and then merged together on the server. The map is robust against small and medium changes, such as a tree being cut, but it needs to be updated in case of major changes, such as a new sidewalk. The main algorithms used are based on CNN and to reduce computational complexity, they adopt a multitraining technique, sharing the same backbone for object detection and segmentation.

3.2.2 Path planning

The problem of navigation – to go from a point A to a point B – is often decomposed into the problem of path planning and trajectory planning.

1. Path planning. This is the task of planning an optimized and collision free path. The main challenge of path planning is to deal with the uncertainty of the environment, as it may change over time (Sariff & Buniyamin 2006).

2. Trajectory planning. This is the task of scheduling the next step that a system has to take along the previously planned path

If the path is planned in advance it is said to be off-line, otherwise, if the path is updated real time and adapted to the new information available at *t+1*, the algorithm is said to be on-line (Hachour 2008). The algorithm used by all the autonomous delivery robots are on-line, as they need to change their path as they proceed and encounter obstacles. Generally the algorithms used for path planning are the Dijkstra or A*.

As soon as an order is placed through the mobile app, and the user has selected the pick-up location, the robot computes the path and the travels to the destination.

3.3 Security and parchel management

To keep the robot safe during its journey, different methods have been implemented. First, all the robots are tracked with GPS sensors, and therefore their location is always available at any time, for the operator to check where the robot is located or if it got stuck. The robot is also featured with an alarm, that signals in case of ’emergency’, such as the robot being kidnapped.

To maintain the parcel or the order safe, the recipient box of the robot can only be opened by the app through which the order was placed. For the whole path the good is stored inside the robot safely.

In addition, most of the robot have a limited travel speed, so that limited impact accident can happen.

Chapter 4

Evaluation

The autonomous delivery robot is an intelligent system, that proved its efficiency and effectiveness in a non-controlled environment. The robot proposed in Chapter 2 have been able to place the majority of the orders without facing any issue.

The human presence is still fundamental to this robots to be fully operational, as there is the need to intervene in case of emergency situations.

4.1 Ethical implications

Several tests and surveys have been conducted in order to assess the social acceptance of the robot on the sidewalks, walking next to humans. LMAD's company conducted a survey in the city of deployment (Helsinki, Finland).

The results showed that the majority of the people (69%) where interested in trying the new service and they had a positive welcoming approach. The most important finding is that the robot did not interfered with the traffic or the pedestrians (LMAD 2021).

In addition to the fact that the presence of robots walking alongside people can annoy many, the workforce factor must be considered. At this time, the development of robots has not yet reached a level that can be considered a threat to people working in the logistics sector; but a lot of workers already see these robots as entities who will take their place sooner or later. It is therefore important to evaluate the impact autonomous robots can have on jobs at each step of the evolution of these systems.

4.2 Legal issues

Some legal steps need to be taken in order to regularise the presence of the robots in the environment, to define responsibilities and duties of the system.

So far, in Europe, non legislation exists for autonomous delivery robots, as each Member State is making its own laws to support the development, test and deployment of such systems.

Chapter 5

Summary and Outlook

The main characteristics of an autonomous delivery robot where presented, based on the feature of the operating robots on the market. The robot has an extremely intelligent behavior that can still be improved in the near future.

5.1 Future Work

Improvements in the intelligence of the robot will occur as the SLAM and path planning technique improve, so that in the future the human intervention would be limited to the supervision of this robots and not included in the pre-planning of the map.

The first improvement that is proposed to this system is the integration of solar panels, in order to be 100% autonomous and independent, with a reduced need to recharge in charging stations.

The second improvement proposed is the adaptation of this robot to the kind of parcel that is delivered: if it is food, to include the possibility to refrigerate or heat the content.

5.2 Challenges

Many challenges remain open:

- The social acceptance
- The navigation of the robot in crowded environment (dealing with animals, bicycles, obstacles)

- The ability of the robot to adapt to big changes in the map (such as new construction sites)

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