Omnidirectional scanner using a time of flight sensor

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by
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Electronic Systems Engineering

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Abstract

This project analyzes which are the main technologies used for robot vision and explores the advantages and disadvantages of using a time-of-flight sensor for creating an omnidirectional scanner similar to one that is already on the market.

First of all, there is a research about the methods used to compute distances and the different hardware available nowadays. After that, there is the experimental part where two sensors are tested and compared.

At the end, the results show that the sensor that uses the TOF technology provides accurate results but it can only measure short distances.

Resum

Aquest projecte analitza quines són les tecnologies que es fan servir més en la visió de robots i explora els avantatges i desavantatges d'utilitzar un sensor *time-of-flight* per crear un escàner omnidireccional semblant a un que ja està disponible al mercat.

En primer lloc, s'ha fet una recerca dels mètodes més utilitzats en el càlcul de distàncies i del diferent hardware disponible. Tot seguit, hi ha la part experimental on s'han testejat i comparat dos sensors.

Finalment, els resultats mostren que el sensor que utilitza la tecnologia TOF proporciona resultats acurats però només serveix per mesurar distàncies curtes.

Resumen

Este proyecto analiza cuáles son las tecnologías más empleadas en la visión de robots y explora las ventajas y desventajas de utilizar un sensor *time-of-flight* para crear un escáner omnidireccional parecido a uno que ya se encuentra en el mercado.

En primer lugar, se ha hecho una búsqueda de los métodos más utilizados para el cálculo de distancias y del diferente hardware disponible. Posteriormente, se encuentra la parte experimental donde se han testeado y comparado dos sensores.

Finalmente, los resultados muestran que el sensor que utiliza la tecnología TOF proporciona resultados acurados pero solo sirve para medir distancias cortas.

Acknowledgements

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Chapter 1

Introduction

Statement of purpose

Nowadays, robotics and automation are growing in popularity and they are becoming an essential part of our day-to-day. At first, they were mostly used in factories for making the work easier. Now, they can be used for helping with the housework, driving vehicles and also for recreational purposes.

One important thing that automats need is the ability of knowing what is surrounding them and what does the environment look like. For example, manipulator robots should be able to model the objects that they need to grasp, and mobile robots should be able to avoid the obstacles that they can find while moving through the spaces.

There are different methods for achieving this. The robot can perceive what is near it with physical contact or remotely. Depending on the application we want to give to our robot, we will use a different kind of sensors.

This thesis explores the main technologies for measuring distances and the possibilities that can offer a low-cost TOF distance sensor compared to the expensive ones that are available in the market.

Requirements and specifications

The main goal of this thesis is do research about the TOF principle and see how can be used for robot vision. The main requirements of the project are:

- Create a distance sensor similar to *RPLIDAR A2*, explained in section 2.2.1.
- Use a TOF sensor for the omnidirectional scanner.
- Explore the capabilities of using this technology.
- Study the applications that has the sensor when it comes to robot vision.

Methods and procedures

For the theoretical part, some distance measurement methods and sensors have been studied and their principles and specifications have been compared.

For the practical part, two of the sensors studied were tested and the results were analyzed with the main goal of knowing which applications can have each scanner if it is used on a robot.

Work plan

The thesis consists on four work packages and each of them is divided into several internal tasks.

Work packages

WP1:

- Distance measurement methods
- TOF principle
- Distance sensors
- TOF distance sensors

WP2:

- Arduino and Processing coding
- Static measurements
- Moving measurements
- Repeat measurements

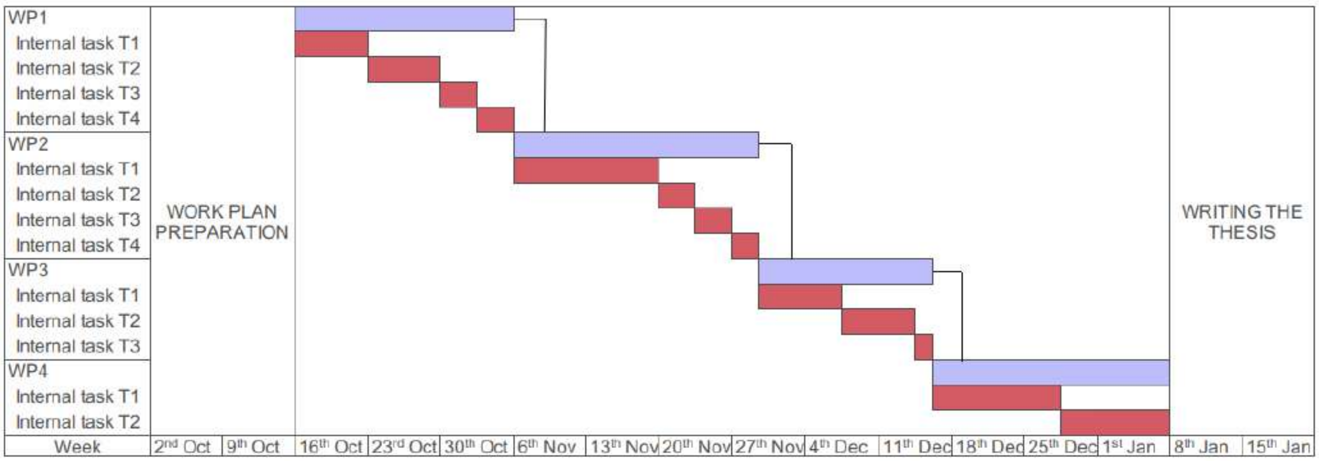
WP3:

- Setting up ROS
- Learning about ROS
- Testing with ROS

WP4:

- Comparison of results
- Advantages and disadvantages

Gantt diagram



Deviations and incidences

The final work plan of this project is almost the same than the original one. The main differences are the dates of every package. Most of them lasted longer than expected and, as a consequence, others were delayed.

The other modification was that the test with the robot was not possible because of the limited time. Instead of this, the possible applications of the sensor are explained theoretically.

The main incidences, or events that occurred that delayed the work packages, started with the tests. The first one, after deciding which TOF sensor to use, it was necessary to wait for a while before receiving the sensor and other materials used in the experimental part.

The second one happened when setting up the ROS environment: it was not compatible with the operating system so it was necessary to install it in a virtual machine. Once it was installed, the extension necessary for the sensor was not compatible with the new operating system so another version had to be installed.

Chapter 2

State of the art

The idea of this project, is to build an omnidirectional distance sensor that offers accurate results using cheap components. Also, it is interesting to explore the advantages and disadvantages that would offer a TOF sensor in comparison to others.

Robot vision

One important thing that most automats need is the ability to see their surroundings. Either if it is a mobile robot or a fixed one, it should be able to map the environment. In a factory, for example, there can be grasping arms, inspector robots controlling the dimensions and the quality of the materials and pieces, and also surveillance robots keeping an eye on the safety area.

Depending on the task that the robot has to do, the best sensor to use will be a different one. If the goal is detecting the presence of an object or tracking it, there is no need to use an image sensor such a webcam, a simple proximity sensor like the one used in this thesis would be enough. On the other hand, if we want to detect a face, it is better to use the image sensor. For some applications it is also possible to use a touch sensor, which can be included in the proximity sensors' group.

Despite this, no matter which is the technology used, acquiring an image of the surroundings is still an expensive and difficult task when it comes to the design of the robot.

Range finder sensors

The most common way of measuring distances is by using active sensors. They use an emitter that illuminates the target with a light pulse and then, analyze the reflected signal that arrives at the receiver. Some of these methods will be analyzed in section 3.1.

Another range finding technique would be using passive ranging. For this method, there is not a need for emitting a light pulse because they use the one provided by the Sun.

RPLIDAR A2

This LIDAR uses the laser triangulation principle for measuring distances up to 8m. It provides 4000 data samples every second that can be used for mapping and locating applications.

As it has a high-speed rotative engine, it can perform 360º scans really fast with a resolution of less than ±1%. It is only 4cm thin and it costs around €400. It is mostly used in robot applications such as 3D environment analysis, obstacle avoidance, cleaning or industrial services.

Figure 2.1: RPLIDAR A2. Source: sgbotic.

Hokuyo URG-04LX

The URG-04LX sensor from *Hokuyo* measures distances from 20mm to 5.6m that are located in the detection area of 240º and it is said to be one of the most famous sensors for people involved in robotics.

It is way more expensive than the other ones (around €1000) but its accuracy of ±3% in the worst case scenario makes it a great sensor for being the eye for a robot even though the price. It provides distance and angle data with an angular resolution of 0.352º. It communicates via USB, which also powers it and its dimensions are 50x50x70mm.

The technology that uses this sensor is the phase shift method with an IR laser of wavelength 758nm. That makes possible to obtain stable measurements without mattering the color and the reflectance of the target.

Figure 2.2: URG-04LX. Source: Robotshop.

SICK Distance sensors

SICK is a manufacturer of factory, logistics and automation technology and some of their products are specialized on vision and industrial sensors.

They have a wide range of distance sensors that mostly use laser triangulation but also TOF techniques. They provide highly precise results and they can measure long and short distances.

Their distance sensors are divided into seven categories depending on their function: displacement measurement sensors, mid range sensors, long range distance sensors, linear measurement sensors, ultrasonic sensors, optical data transmission and position finders. Their prices are around €600.

Figure 2.3: Dx100 Long range distance sensor from SICK. Source: SICK.

Chapter 3

Methodology / project development

The first research done in this thesis is about the technologies that are most commonly used for obtaining distance measurements. Apart of TOF, two other measurement methods are mainly used for this purpose: phase shift and laser triangulation. The three principles have been studied, compared and explained in the following sections.

For the practical part, two distance sensors were used to make range measurements and compared. They use different technologies, hardware and software but the procedures and the testing conditions for the experiments were the same for both of them.

Distance measurement technologies

TOF

The time of flight is an accurate and easy to understand technology used for measuring distances. Its principle is based on computing the time it takes for a light pulse to go from the sensor to the target and back.

The process starts when the emitter sends a pulsed light to the object and observes the reflected light. The time of flight is the time that it takes for this pulse to travel from the emitter to the object and then back to the receiver.

The following formula is needed for computing the distance: $d = \frac{1}{2}c\tau$, where τ is the time of flight and c is the speed of light.

The main advantages of using a TOF sensor are:

- The reflectance of the object does not affect the measurement.
- It can work with low light conditions.
- The system is compact.
- The technology is really easy to use.
- It provides accurate results.

- It offers real time capabilities.

There are also some limitations when using this technology:

- Hard to use outdoors because high intensity light can saturate the sensor.
- If light is reflected multiple times (on corners), it can alter the measurement.
- The glass covering the sensor distorts the reflected signal

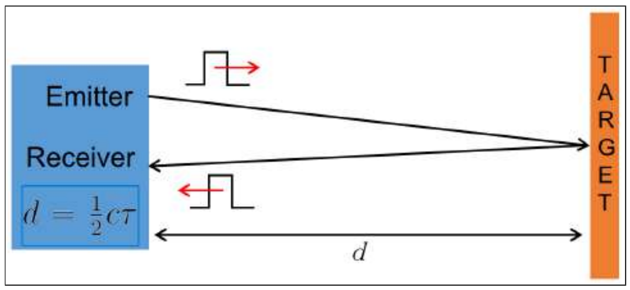


Figure 3.1: Representation of the TOF principle.

Flightsense

This technology was patented by the semiconductor company *ST* and solves some of the issues that have the TOF sensors.

First of all, there is the compensation algorithm for correcting the distortion produced by the cover glass. As the cover glass is always located on the same place, it has fixed optical characteristics that are used to correct the measurement.

Another system improvement is about the performance outdoors. The technology keeps ambient photons out with an optical filtering and also rejects the remaining ones (lower wavelengths) thanks to a time-domain rejection.

Phase shift

This technology uses a similar method than TOF for computing the distance to a target but, as it does not obtain the time of flight directly from the signal received, it is not considered the same measuring technology.

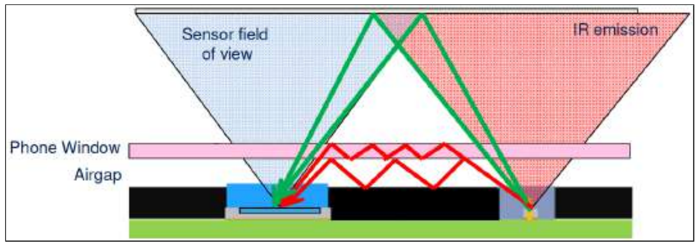


Figure 3.2: Unwanted reflections caused by the cover glass. Source: ST Microelectronics.

In this case, the emitter sends a sinusoidally modulated signal to the target, a continuous wave. The time of flight is computed by knowing the modulation frequency and comparing the phase of the received signal with the phase of the one emitted.

The following formula is used to calculate it and then it will be possible to obtain the distance: $d = \frac{1}{2}c\frac{\Phi}{2\pi}f$, where Φ is the difference between the phases, f is the modulation frequency and c is the speed of light. It can be seen that the time of flight τ is directly proportional to the modulation frequency f: $\tau = \frac{\Phi}{2\pi}f$

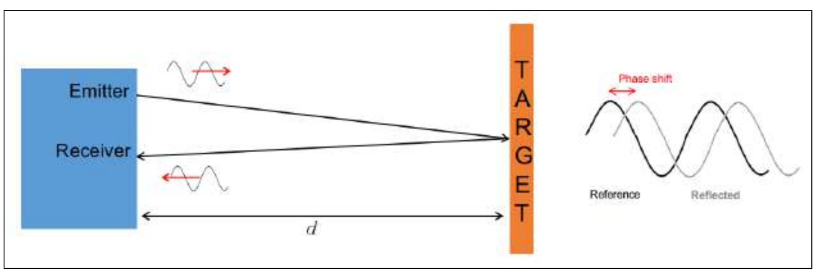


Figure 3.3: Distance measurement with phase shift method.

Laser triangulation

Laser triangulation consists on an emitter sending a laser light that will hit the target and reflect to a CCD or a PSD sensor. These kind of sensors convert the received light into a digital signal that is going to be processed.

During this procedure, the laser light will hit the object with an incident angle and form a triangle with a vertex on the emitter, another one on the target and the last one on the sensor. Depending on the distance where the targeted object is, the position of the received light will change and also the final digital signal. This is how the distance is measured.

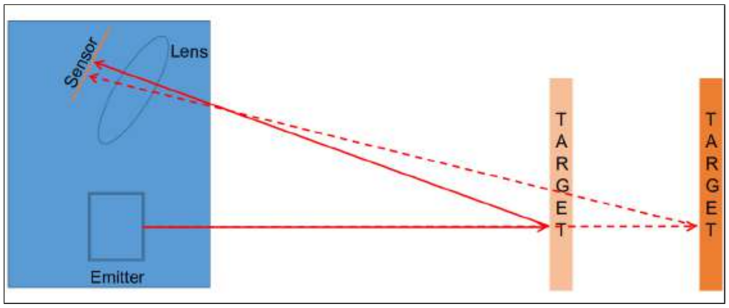


Figure 3.4: Laser triangulation principle.

Proximity sensors based on TOF.

VL6180X

VL6180X is a proximity sensor from *ST*, the same company that patented the *FlightSense* technology. It provides rigorous distance measurements from 0 to 10cm and it incorporates an accurate ambient light sensor that works properly even with ultra-low light.

This sensor is low-power, low-cost (around €8) and really easy to integrate and use. It is controlled using the I2C communication protocol, also used for sending the data to the master device. That offers the possibility of connecting it alongside other slave devices.

The API provided by the manufacturer allows 2 different ranging modes: single shot and continuous. With these 2 ranging modes it is possible to use 3 different operating modes: with the single shot it can operate in polling or asynchronous mode and with the continuous it can work with interrupts. With polling, the master device asks for a single measurement and waits for the slave to send the result. On the other hand, with asynchronous, the host does not wait for the result; it can check it later or it can wait for an interrupt. In the mode that works with interrupts, the sensor is continuously sending data to the master device, which is waiting for the interrupts with the results of the measurements.

The total range time is the addition of the pre-calibration time (3.2ms), the range convergence time (it can go from 0.18ms to 10.73ms depending on the distance between the sensor and the targeted object and its reflectance), and the readout averaging period (4.3ms is the value that the manufacturer recommends).

It has a SPAD array, which detects single photons with very high time-of-arrival (picoseconds) resolution, and that is used for measuring the distance to close targets.

It also incorporates a 850nm VCSEL for emitting the light pulse with a stable wavelength and with a focused direction. Other advantages of using a VCSEL are that can be mounted on printed circuit boards and integrated in packages with other light sources such as lasers.

Nowadays, this sensor can be found in smartphones, tablets and laptops. It is being used in applications where the device and the user are really close: turning off the screen when the user is talking through the phone, lock the device when the user is going away, decrease the light intensity depending on the user proximity so it won't hurt user's eyes and also depending on the ambient light.

Figure 3.5: VL6180X. Source: Robotshop.

VL53L0X

VL53L0X is said to be the smallest distance sensor available in the market that uses the TOF technology and it is also created by *ST*. It provides accurate measurements (up to ±3%) without mattering the reflectance of the targeted object for distances between 50mm and 1200mm.

It has some similarities with the sensor explained before. VL53L0X is also low-power and low-cost (around €8 too) and uses the I2C communication protocol for sending the data to the master device, which makes the sensor easy to integrate to other projects. The VCSEL that incorporates produces beams of light with a wavelength of 940nm, which makes possible to measure farther distances and provides more protection to ambient light.

For this sensor, the API also provides 3 different operating modes: single ranging, where ranging is only performed once, continuous ranging, where measurements are done one after the other without stopping, and timed ranging, which works like continuous ranging with the difference that after a measurement, the sensor waits for the delay before doing the next one.

It is also possible to change the way of measuring distances thanks to the different ranging profiles available. For each of them, the timing and the maximum measurable distance will vary.

This sensor is useful in applications where the user and the device are not that close, like smarthomes for detecting the presence of people or in laptops, for saving energy if the user is gone. In smartphones, for example, the sensor can be used alongside the camera for focusing the image. It is also perfect for obstacle avoidance in robots and drones.

If we compare the specifications of both TOF sensors we see that VL53L0X is smaller, faster, better in accuracy and, even though it does not have an ambient light sensor, it has a better performance when working with sunlight. Also, VL6180X offers accurate short distance measurements (from 0 to 10 cm) and if we need our robot to do a mapping of the environment with objects not so close to it, it won't be able to do it. On the other hand, VL53L0X provides rigorous results for farther distances and that means that it can be used in a larger range of applications: obstacle avoidance, object grasping and even for machine vision. . Having said that, I decided that there are more reasons for choosing VL53L0X for the practical part.

Software

Arduino

For this project I have used *Arduino*, an open source platform that people use for electronic projects related to research, development and leisure. It has the hardware part, a variety of microcontroller boards that are suitable for different kind of

Figure 3.6: VL53L0X. Source: Cetronic.

projects, and the software, an IDE that you can install on your computer where you can write the code using C++ language, verify it and upload it to the board.

The main reason for using this platform is that it offers the possibility of communicating with devices using I2C protocol, the one that VL53L0X uses. It provides one pin (SDA) for the data transfer and another one (SCL) for the clock.

What is also useful about *Arduino* is the big community that exists behind it. There is a large number of users that provide examples, share their code and also help others by answering questions in the forums.

Processing

Processing is also an open source platform but this one only contains the software part. Its purpose is to provide an easy way to program visual projects with its own simplified programming language.

I used the *Programming* environment on this project alongside *Arduino* because it can read the data that is being printed on the serial port, which are the measurement results acquired from the sensor. It is also helpful the huge community that exists online providing codes, examples and references.

ROS

*R*OS is a software platform for robot development. Its goal is to make as simple as possible the process of creating powerful and complex robot conducts using different robotic platforms. At first, it was mostly used in research laboratories but it gained popularity and it's increasing its use in the commercial sector for industrial and service robotics.

In this project, *ROS* was necessary for testing the URG-04LX sensor. It provides tutorials and examples that help with the installation of the environment, the extensions and the nodes for the sensor.

Experimental part

VL53L0X without movement

The first test done with VL53L0X was with an Arduino code based on the examples from the VL53L0X libraries provided by *Adafruit*[1] and *Pololu*[2]. This was the simplest one. The sensor was located in one fixed place and the object was moving back and forward while the results where printed on the serial monitor. The light of the room and the color of the target changed during the experiment in order to study different results and also some parameters such as the operating modes and the raging profiles were modified to obtain measurements as accurate as possible.

VL53L0X with movement

After obtaining the first measurements, I wanted to check how fast could the sensor move while still obtaining accurate results. In order to do it, VL53L0X was located on a servo motor and then, both devices (sensor and servo) were connected to an Arduino UNO board. The measurements obtained were printed in the Serial Monitor of the Arduino IDE and then sent to Processing, the software that drew the results in a scanner screen.

Hokuyo

The experiment with HOKUYO was done using an example provided by ROS. Before running the test, it was only necessary to set up the ROS environment and install the Hokuyo node, which was required for displaying the data from the sensor.

The test was also changing the color of the target but could not be done outdoors because the sensor is not designed for that so I did the test with the artificial lights from the laboratory and then I turned them off and repeated the test.

[1] https://github.com/adafruit/Adafruit_VL53L0X
[2] https://github.com/pololu/vl53l0x-arduino

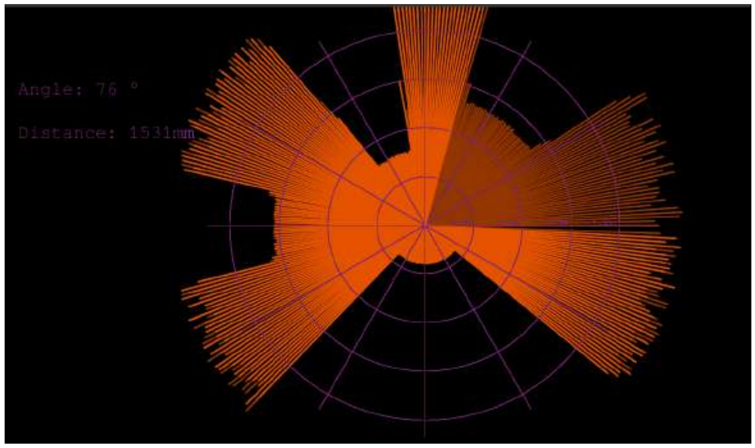
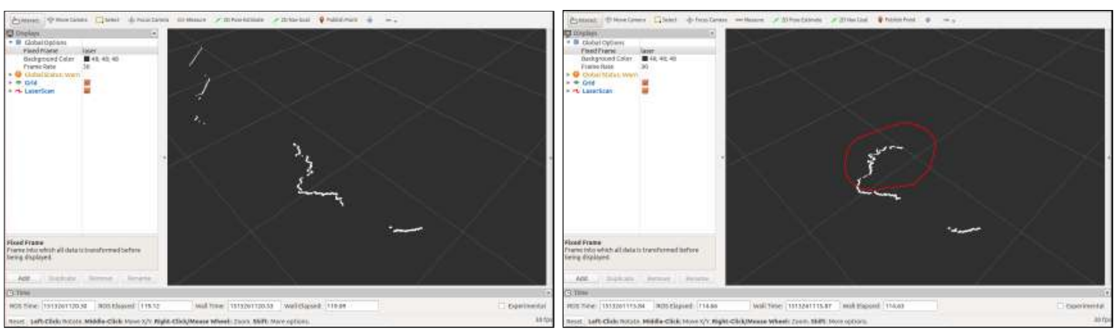


Figure 3.7: In this picture there is the radar screen programmed with processing showing the distances measured by VL53L0X.



Screenshot A *Screenshot B*

Figure 3.8: These pictures show the screen during the test with the sensor from Hokuyo. Screenshot B shows how the sensor detects an object that was not there when the screenshot A was taken.

Chapter 4

Results

The measurements for the thesis took place in a room from the TU Wien. The parameter studied is the accuracy and, as it can be affected by target reflectance and ambient light, the test was done several times changing them.

Three objects with different reflectance were used: pink, with a reflectance of 56% approximately, black, with 6%, and white, with 85%.

To make sure that the results obtained were correct, the datasheet of each sensor was checked before the experiment so it was possible to compare the values and see if they were as expected.

VL53L0X

VL53L0X is the TOF sensor chosen for the experiment, as it was said in section 3.2.2. In order to obtain the best results, the ranging profiles were set to high accuracy and long range.

Artificial light

Distance	Pink	Black	White
100mm	±3%	±3%	±3%
500mm	±3%	±3.6%	±1.8%
800mm	±0.6%	±1.25%	±0.8%
1000mm	±2.6%	±3.7%	±2.2%
1200mm	±2.8%	±5.6%	±3.4%
1400mm	±4.5%	±12.1%	±3.1%
1500mm	±3.8%	±11.5%	±4.1%

Table 4.1: Artificial light. Accuracy of the sensor VL53L0X depending on the reflectance of the target using artificial light.

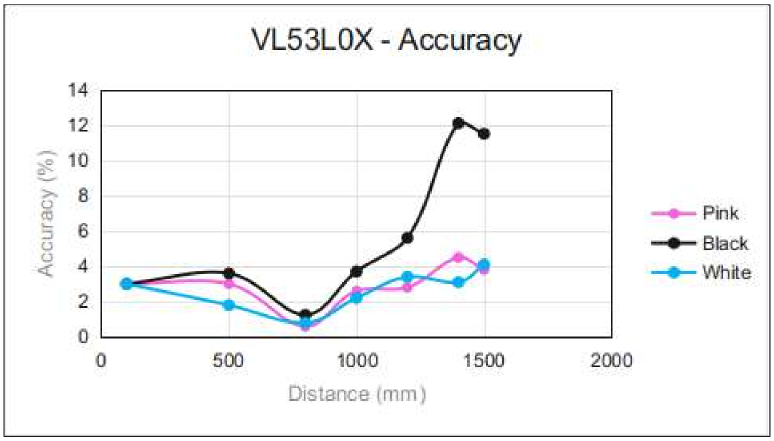


Figure 4.1: Artificial light. Graphical representation of the accuracy depending on the reflectance with artificial light.

Here we see that the worst results are the ones obtained with the target with a lower reflectance and that when using pink or white targets, the accuracy improves.

The best most accurate results are at 800mm and after this point, the accuracy starts getting worse.

Dark conditions

Distance	Pink	Black	White
100mm	±2%	±3%	±2%
500mm	±1.4%	±2.2%	±2%
800mm	±1.1%	±1.5%	±1.5%
1000mm	±1.4%	±1.4%	±1.5%
1200mm	±2.6%	±4.6%	±4%
1400mm	±5.6%	±10.6%	±9.6%
1500mm	±8.9%	±10.1%	±9.4%

Table 4.2: No light. Accuracy of the sensor VL53L0X depending on the reflectance of the target without light.

When the experiment is done in dark conditions, a black target obtains almost the same results as before but when it comes to pink and white targets, we can

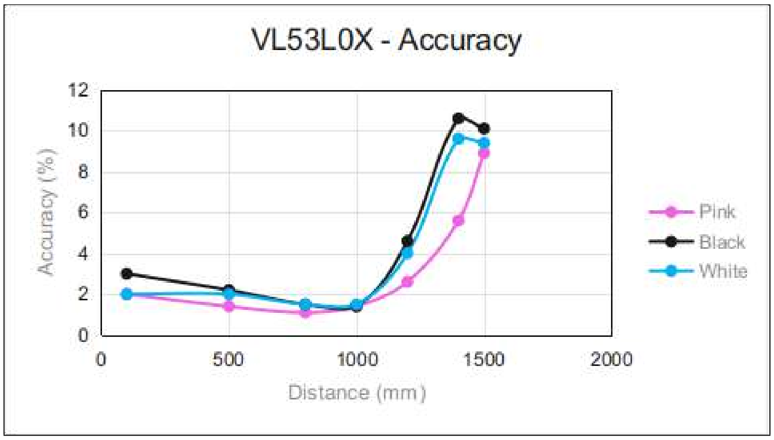


Figure 4.2: No light. Graphical representation of the accuracy depending on the reflectance with no light.

see that after 1200mm the results are not as accurate as they were while there was artificial light during the experiment.

In this case, the distance were the accuracy starts getting worse is 1000mm and the target with the most accurate results is the pink one.

Ambient light

As this sensor also works outdoors, it was interesting to explore its potential and see if the results are good enough, so there is also a test outdoors with ambient light. The accuracy could only be computed up to 1200mm because the sensor could not measure longer distances.

Distance	**Pink**	**Black**	**White**
100mm	±3%	±4%	±5%
500mm	±1.8%	±1.8%	±1.8%
800mm	±3.3%	±2.6%	±2.6%
1000mm	±3.5%	±2.9%	±3.3%
1200mm	±7.2%	±8%	±7.8%
1400mm	±13.6%	±17.4%	±13.2%

Table 4.3: Ambient light. Accuracy of the sensor VL53L0X depending on the reflectance of the target outdoors.

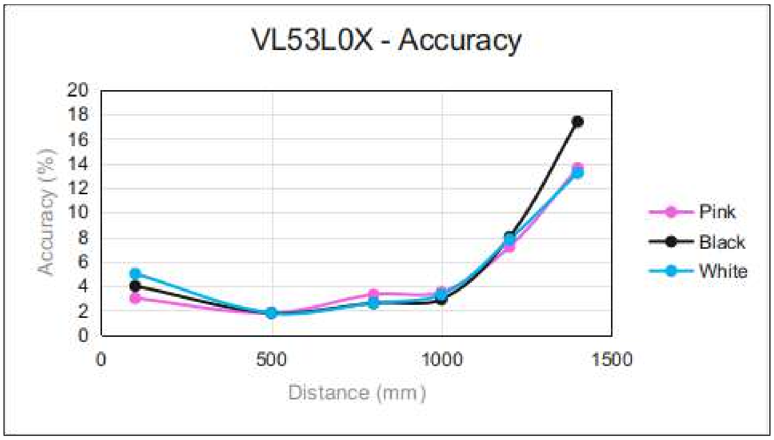


Figure 4.3: Ambient light. Graphical representation of the accuracy depending on the reflectance for artificial light.

As it was expected, the results outdoors were not as good as indoors. First of all, at 1000mm the sensor started with timeout errors and approximately 80% of the results were correct. At 1200mm, half of the results were wrong and at 1400mm less 20% of the results were acceptable.

HOKUYO

This sensor is for measuring longer distances than the ones that can be measured with VL53L0X. Despite this, the measurements were done with distances up to 1500mm for making easy the comparison of both sensors.

For this one, the test could not be done outdoors because the sensor it is not designed for this purpose and would not work.

Artificial light

If we see the graphical representation of the results obtained with this sensor it is interesting because, as it is a sensor for longer distances, the accuracy gets better when the target is farther and the results are not good enough when we work with close targets. In addition, we see more independence from the target reflectance.

Distance	Pink	Black	White
100mm	±43%	±35%	±38%
500mm	±7%	±6.2%	±8.2%
800mm	±4.4%	±3.9%	±4.4%
1000mm	±3.7%	±3.1%	±2.9%
1200mm	±1.9%	±1.9%	±2.5%
1400mm	±1.9%	±1.7%	±1.6%
1500mm	±2%	±1.8%	±2.2%

Table 4.4: Artificial light. Accuracy of the sensor from Hokuyo depending on the reflectance of the target using artificial light.

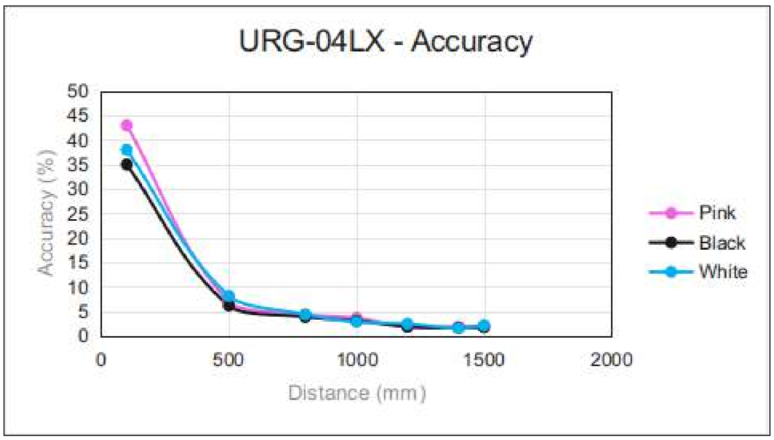


Figure 4.4: Artificial light. Graphical representation of the accuracy depending on the reflectance with artificial light.

Dark conditions

For this sensor, changing from artificial light to dark conditions does not make really important changes when it comes to accuracy. We see the similar behavior than before for each different target reflectance.

Distance	Pink	Black	White
100mm	±43%	±36%	±38%
500mm	±7%	±6.6%	±6.6%
800mm	±4.6%	±3.6%	±3.9%
1000mm	±3.6%	±2.3%	±2.9%
1200mm	±2.8%	±2%	±1.8%
1400mm	±1.6%	±1.5%	±1.3%
1500mm	±1.3%	±1.9%	±1.1%

Table 4.5: No light. Accuracy of the sensor from Hokuyo depending on the reflectance of the target without light.

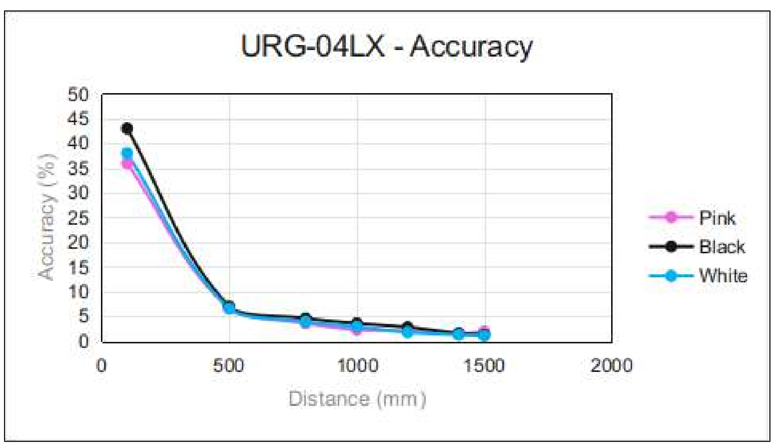


Figure 4.5: No light. Graphical representation of the accuracy depending on the reflectance with no light.

Chapter 5

Budget

This thesis has been a research and a comparative study. Its budget has two main parts: the hardware for the sensors tested and the salaries for the staff that participated on the project. As the software used is free, it won't add more expenses.

Hardware budget

The hardware parts that were used during the project for testing and comparing are the sensor Hokuyo URG-04LX, the sensor VL53L0X, the Arduino UNO board and the servos.

Product	**Amount**	**Price**
Hokuyo URG-04LX	1	1100€
VL53L0X	1	14€
Arduino UNO	1	20€
180º servo	1	9€
360ª servo	1	11€
Total	5	1154€

Table 5.1: Hardware budget

Staff budget

The expenses for the human resources are computed considering that I work as a junior engineer and that both co-supervisors have the salary of a senior engineer. The time spent on this thesis it has been 16 weeks, as it can be seen in the Gantt diagram, and the dedication and the wages can be found in table 5.2.

Position	**Amount**	**Weeks**	**Wage/hour**	**Dedication**	**Total**
Junior engineer	1	16	12€/h	20h/week	3840€
Senior engineer	2	16	24€/h	2h/week	1536€
Total					5376€

Table 5.2: Staff budget

Chapter 6

Conclusions and future development

The main goal of the project was to explore different technologies used for ranging measurements in robotics and build a low-cost omnidirectional scanner that provides accurate results and uses the time-of-flight technology. Although it does not detect targets farther than 1500mm, this one is cheaper than some sensors available in the market.

There are more applications than what we think that need ranging sensors and not just in factories. Autonomous vehicles, for example, are starting to develop and they will need good quality sensors. As it was seen in this thesis, TOF has advantages in front of other technologies: accuracy, simplicity, speed and efficiency.

Despite this, the results obtained in the practical part show that even the TOF sensor uses a robust technology, the ones that are more expensive are better and offer wider ranges for measuring.

After the work done for this project it is easy to see that is hard to find a cheap sensor suitable for all ranging applications. Most of them can't measure both short and long distances and that's why it is important to know the needs of the applications and the possibilities that offers each sensor and each technology.

I think that it would be interesting for viable future research in this project to reduce its size and also attach it to a robot hand and study its possibilities. Researches are more interested everyday in this technology and this will provide new sensors and devices with more capabilities.

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Appendices

Test results

The following tables show the maximum and minimum values that each sensor obtained and which is the accuracy. Every table corresponds to a different target reflectance, light condition and sensor.

Real	**Maximum**	**Minimum**	**Accuracy**
100mm	100mm	97mm	±3%
500mm	509mm	504mm	±1.8%
800mm	806mm	796mm	±0.8%
1000mm	979mm	969mm	±2.2%
1200mm	1185mm	1159mm	±3.4%
1400mm	1416mm	1356mm	±3.1%
1500mm	1525mm	1438mm	±4.1%

Table 6.1: White target with artificial light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	**Maximum**	**Minimum**	**Accuracy**
100mm	101mm	97mm	±3%
500mm	515mm	501mm	±3%
800mm	803mm	795mm	±0.6%
1000mm	987mm	974mm	±2.6%
1200mm	1186mm	1166mm	±2.8%
1400mm	1417mm	1337mm	±4.5%
1500mm	1557mm	1470mm	±3.8%

Table 6.2: Pink target with artificial light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	102mm	97mm	±3%
500mm	518mm	512mm	±3.6%
800mm	798mm	790mm	±1.25%
1000mm	980mm	963mm	±3.7%
1200mm	1268mm	1233mm	±5.6%
1400mm	1570mm	1426mm	±12.1%
1500mm	1672mm	1595mm	±11.5%

Table 6.3: Black target with artificial light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	102mm	98mm	±2%
500mm	510mm	504mm	±2%
800mm	812mm	802mm	±1.5%
1000mm	1015mm	1001mm	±1.5%
1200mm	1248mm	1223mm	±4%
1400mm	1534mm	1448mm	±9.6%
1500mm	1641mm	1561mm	±9.4%

Table 6.4: White target without light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	101mm	98mm	±2%
500mm	507mm	502mm	±1.4%
800mm	809mm	801mm	±1.1%
1000mm	1002mm	986mm	±1.4%
1200mm	1227mm	1169mm	±2.6%
1400mm	1478mm	1430mm	±5.6%
1500mm	1633mm	1532mm	±8.9%

Table 6.5: Pink target without light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	103mm	99mm	±3%
500mm	511mm	505mm	±2.2%
800mm	812mm	803mm	±1.5%
1000mm	1014mm	1002mm	±1.4%
1200mm	1256mm	1228mm	±4.6%
1400mm	1549mm	1438mm	±10.6%
1500mm	1652mm	1585mm	±10.1%

Table 6.6: Black target without light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	101mm	95mm	±5%
500mm	509mm	498mm	±1.8%
800mm	821mm	797mm	±2.6%
1000mm	1022mm	967mm	±3.3%
1200mm	1204mm	1107mm	±7.8%
1400mm	1344mm	1215mm	±13.2%
1500mm	-	-	-

Table 6.7: White target with ambient light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	103mm	100mm	±3%
500mm	509mm	504mm	±1.8%
800mm	827mm	796mm	±3.3%
1000mm	1010mm	965mm	±3.5%
1200mm	1208mm	1114mm	±7.2%
1400mm	1373mm	1210mm	±13.6%
1500mm	-	-	-

Table 6.8: Pink target with ambient light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	101mm	96mm	±4%
500mm	509mm	501mm	±1.8%
800mm	821mm	800mm	±2.6%
1000mm	1021mm	971mm	±2.9%
1200mm	1199mm	1104mm	±8%
1400mm	1354mm	1156mm	±17.4%
1500mm	-	-	-

Table 6.9: Black target with ambient light. Accuracy, maximum and minimum values obtained with VL53L0X.

Real	Maximum	Minimum	Accuracy
100mm	138mm	129mm	±38%
500mm	541mm	519mm	±8.2%
800mm	835mm	824mm	±4.4%
1000mm	1029mm	1011mm	±2.9%
1200mm	1230mm	1216mm	±2.5%
1400mm	1423mm	1394mm	±1.6%
1500mm	1533mm	1507mm	±2.2%

Table 6.10: White target with artificial light. Accuracy, maximum and minimum values obtained with Hokuyo.

Real	Maximum	Minimum	Accuracy
100mm	143mm	137mm	±43%
500mm	535mm	527mm	±7%
800mm	835mm	823mm	±4.4%
1000mm	1037mm	1014mm	±3.7%
1200mm	1223mm	1181mm	±1.9%
1400mm	1427mm	1402mm	±1.9%
1500mm	1530mm	1511mm	±2%

Table 6.11: Pink target with artificial light. Accuracy, maximum and minimum values obtained with Hokuyo.

Real	Maximum	Minimum	Accuracy
100mm	135mm	124mm	±35%
500mm	531mm	522mm	±6.2%
800mm	831mm	823mm	±3.9%
1000mm	1031mm	1015mm	±3.1%
1200mm	1223mm	1208mm	±1.9%
1400mm	1424mm	1409mm	±1.7%
1500mm	1527mm	1513mm	±1.8%

Table 6.12: Black target with artificial light. Accuracy, maximum and minimum values obtained with Hokuyo.

Real	Maximum	Minimum	Accuracy
100mm	138mm	127mm	±38%
500mm	533mm	518mm	±6.6%
800mm	831mm	815mm	±3.9%
1000mm	1029mm	1011mm	±2.9%
1200mm	1222mm	1182mm	±1.8%
1400mm	1418mm	1395mm	±1.3%
1500mm	1516mm	1503mm	±1.1%

Table 6.13: White target without light. Accuracy, maximum and minimum values obtained with Hokuyo.

Real	Maximum	Minimum	Accuracy
100mm	143mm	133mm	±43%
500mm	535mm	523mm	±7%
800mm	837mm	816mm	±4.6%
1000mm	1036mm	1017mm	±3.6%
1200mm	1223mm	1167mm	±2.8%
1400mm	1423mm	1399mm	±1.6%
1500mm	1519mm	1501mm	±1.3%

Table 6.14: Pink target without light. Accuracy, maximum and minimum values obtained with Hokuyo.

Real	**Maximum**	**Minimum**	**Accuracy**
100mm	136mm	126mm	±36%
500mm	533mm	521mm	±6.6%
800mm	829mm	813mm	±3.6%
1000mm	1023mm	1012mm	±2.3%
1200mm	1224mm	1183mm	±2%
1400mm	1421mm	1406mm	±1.5%
1500mm	1529mm	1498mm	±1.9%

Table 6.15: Black target without light. Accuracy, maximum and minimum values obtained with Hokuyo.

Glossary

API Application programming interface
CCD Charge-coupled device
IDE Integrated development environment
LIDAR Laser imaging detection and ranging
PSD Position sensitive device
ROS Robot operating system
SPAD Single-photon avalanche diode
TOF Time of flight
VCSEL Vertical-cavity surface-emitting laser