“DESIGN OF A POSITION ENCODER USING INFRARED SENSORS”

Master Thesis
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RESUM

La creixent popularitat de la robòtica y el desig de fer la robòtica a l’abast de tothom, fan que noves formes de desenvolupament siguin promocionades. Una de les parts més complexes de la robòtica són les unions, on diversos components es fan servir, com per exemple, els sensors, motors o unitats de control. Aquest projecte està centrat en la part de sensat, en el que es desenvolupa y comprova/testeja un nou prototip de sensor de posició angular i lineal. El nou sensor és escalable en disseny entre les configuracions angulars i lineals, facilitant la feina de realitzar mesures en diverses unions. També es dissenya i implementa el sistema de mesura per comprovar els resultats obtinguts.

El desenvolupament d’aquest nou sensor de posició es divideix en dues parts al estar basat en components optoelectrònics. La primera part consisteix en el mateix sensor òptic. Els components que interactuen amb les propietats òptiques segons la posició formen la segona part. El projecte presentat estableix una base per futurs treballs en nous sistemes de mesura de posició angular i lineal.

RESUMEN

La creciente popularidad de la robótica y el deseo de hacer la robótica disponible para todo el mundo, hacen que nuevas formas de desarrollo sean promocionadas. Una de las partes más complejas de la robótica son las uniones, donde diversos componentes son utilizados, como sensores, motores o unidades de control. Este proyecto está centrado en la parte de sensado, en el cual se desarrolla y comprueba/testea un nuevo prototipo de sensor de posición angular y lineal. El nuevo dispositivo sensor es escalable en diseño entre las configuraciones angulares o lineales, facilitando la tarea de medir en diversas uniones. También se diseña e implementa el sistema de medida para comprobar los resultados obtenidos.

El desarrollo de este nuevo sensor de posición se divide en dos partes al estar basado en componentes optoelectrónicos. El sensor óptico mismo forma una de las partes, y los componentes que interactúan con las propiedades ópticas según la posición forman la segunda parte. El presente proyecto establece una base para futuros desarrollos en nuevos sistemas de medida de posición angular y lineal.
ABSTRACT

The increasing popularity of robotics and the desire to make robotics available to everyone, makes that new ways of development are being promoted. One of the most complex parts of robotics are the joints, where different components are used, like sensing devices, motors and controllers. The focus of this thesis is in the sensing devices, as a new prototype of angular and linear position sensor is designed and tested. The new sensing device is scalable in design between angular and linear configurations, helping the measurement in different joints. The prototype of the measurement system is also designed and implemented to check the obtained results.

The development of this new position sensor is divided in two parts, as it is based on optoelectronics components. The optical sensing device itself forms the first part, whereas the components that interact with the optical properties according to the position form the second part. The work presented establishes a base for further development in new sensing systems for angular and linear position.

ZUSAMMENFASSUNG


COLLABORATIONS

BLUE DANUBE ROBOTICS.

This thesis was carried out in the Technische Universität Wien under the ERASMUS programme from Universitat Politècnica de Catalunya – Barcelona Tech (Barcelona, Spain). And it has been a collaboration work with Blue Danube Robotics, which is designing an assistive robot to support physically handicapped people in their daily lives.

I would like to thank Blue Danube Robotics Company and all the people working there for offering me help and all materials I needed to research and design.
CHAPTER 1: INTRODUCTION

The reproduction of the human functionality and appearance is one of the main reasons for the development of robotics. Anthropomorphism is a desirable goal for a number of reasons where it is expected to provide high flexibility and adaptability, ideally replicating the overall functionality of the human being, other than just a human-like aspect.

Anthropomorphic robotic design imposes particular requirements, such as the presence of the main morphological elements, continuous and smooth contact surfaces, an intrinsic compliant actuation and a size comparable to the average size of a human body.

1.1. Purpose

The purpose of this thesis is to help the development of a robot that Blue Danube Robotics Company is designing. The aim is to develop an assistive robotic companion to support physically handicapped people in their daily lives. The design is made in order to obtain an affordable robot for everyday use. This thesis focusses on all of the position sensors in the robot. The robot uses a water-hydraulic system to achieve movement and requires a new design for the position sensor. The position sensor should able to know the concrete position of a robotic joint. The system has to be implemented using commercial components to minimize the cost. For this purpose, different components were tested and a final choice is made based on the performance results and implementation cost.

1.2. Motivation

The motivation of this study is to find new ways to improve the overall performance in robotic joints. Almost all robotic joints developed so far resort to indirect measurement of the joint through motor angular displacement, which can be easily measured via standard rotary sensors (usually integrated into the motor by the
Several research activities have been carried out to directly integrate the sensors into the mechanical structures of robotic joints. The robotic joints include any place of the robot where there are two parts moving, i.e. the elbow or finger joints. In these cases, the movement could be linear or rotational; thus the position sensor could be angular or linear. The aim of the design is to achieve a system with good performance, low cost and which is easy-to-implement in both linear and angular cases.

1.3. Structure

The structure of the dissertation is as follows:

- Research of sensing devices
- Design of a testing System
- Realization of the measurements
- Processing and analysis of the results
- Final design ready for implementation
In order to design a proper position sensor system for a robotic joint, the different options used nowadays as linear or angular sensors in the field of robotics are analysed. Position sensors can detect the movement of an object in a straight line using linear sensors, or by its angular movement using rotational sensors.

### 2.1. Potentiometers

A potentiometer is a three-terminal resistor with a sliding or rotating contact that forms an adjustable resistance. If only two terminals are used – one end and the wiper – it acts as a variable resistor or rheostat. The measurement of the potentiometer value is using a voltage divider, providing a linear responsiveness. That makes them the simplest tool to make measurements.

![Figure 1.- Linear and angular potentiometers.](image)

However, the potentiometer is usually a source of errors due to its low accuracy, repeatability, wear due to moving parts, and limited frequency response. However, they also offer some great advantages such as low cost, low tech and an output range as big as the range of movement of its slider (though this could be seen as a disadvantage). Another important characteristic is the physical size, usually big, making them hard to integrate in the system when the space is limited.
Potentiometers are available in different shapes and characteristics, allowing both linear and angular measurements.

2.2. Inductive sensors

The most commonly used inductive sensor is the Linear Variable Differential Transformer (LVDT). This is an inductive type position sensor, which operates based on the same principle as the AC transformer used to measure movement. This is a very accurate device for measuring linear displacement and its output voltage is proportional to the position of its moveable core.

It basically consists of three coils wound on a hollow tube former, one forming the primary coil and the other two coils forming identical secondaries. They are serially connected with 180 degrees phase difference at either side of the primary coil.

A moveable soft iron ferromagnetic core (sometimes called an “armature”) which is connected to the object being measured, slides or moves up and down inside the tubular body of the LVDT.

![Figure 2.- Structure of an LVDT.](image)

A small AC reference voltage, called the "excitation signal", is applied to the primary coil, which induces a voltage into the two adjacent secondary coils (transformer principles).

If the soft iron magnetic core armature is exactly in the centre of the tube in the coil’s “null position”, the two induced voltages in the two secondary coils cancel each other out so the resulting output voltage is zero. As the core is displaced slightly to one side or the other from this position, the induced voltage in one of the secondaries will become greater than the one on the other secondary and a non-zero output voltage will be produced.

The polarity of the output signal depends upon the direction and displacement of the moving core. The greater the movement of the soft iron core from its central null position the greater will be the resulting output voltage. The result is a differential voltage output which varies linearly with the core’s position. Therefore, the output signal has both an amplitude that is a linear function of the core’s displacement and a polarity that indicates direction of movement.
Design of a position encoder using infrared sensors

When the armature is moved from one end to the other through the central position the output voltages changes from maximum to zero and back to maximum again, but in the process changes its phase angle by 180 degrees. This enables the LVDT to produce an output AC signal whose magnitude represents the amount of movement from the central position and whose phase angle represents the direction of movement of the core.

Advantages of the linear variable differential transformer (LVDT) compared to a resistive potentiometer are its excellent linearity, very good accuracy, good resolution, high sensitivity and frictionless operation. They are also sealed for use in hostile environments. The main problem is the need to excite the LVDT with an AC signal and read also an AC output. This makes the system really complicated in portable and small robots.

2.3. Capacitive sensors

Capacitive sensors make use of the electrical property of capacitance to provide measurements. Capacitance describes how two conductive objects with a space between them respond to a voltage difference applied to them. When a voltage is applied to the conductors, an electric field is created between them. If the polarity of the voltage is reversed, the electric field is also reversed. The capacitance is directly proportional to the surface area of the objects and the dielectric constant of the material between them, and inversely proportional to the distance between them.

Changes in the distance between the surfaces of the conductors changes the capacitance. In typical capacitive sensing applications, the probe or sensor is one of the conductive objects; the target object is the other. The sizes of the sensor and the target are assumed to be constant as well as the material between them. Therefore, any change in capacitance is a result of a change in the distance between the probe and the target. The sensor output indicates the size of the gap between the sensor's sensing surface and the target.
Figure 4.- Operation of a capacitance position sensor.

Capacitive displacement sensors for use in precision displacement measurement and metrology applications make use of electronic designs to execute complex mathematical functions. These high-performance sensors have output values which are linear, stable with temperature, and able to resolve very small changes in capacitance resulting in high resolution linear measurements of less than one nanometre.

Capacitive sensors have some distinct advantages, i.e. high resolution and not being sensitive to changes in the material (capacitive sensors respond equally to all conductors). Nevertheless, capacitive sensors are not a good choice in dirty or wet environments, or when a large gap between sensor and target is required (optical and laser are better).

2.4. Rotary encoders

A rotary encoder is a rotary transducer that converts an angular movement in a series of digital pulses. A common way to encode the position is to use a disk with slots, allowing the communication between the sensors in these slots. Therefore, when the disk is rotated, a signal is obtained dependant on direction, position and speed. Depending on the electronics used, the rotary encoder could be optical, magnetic, mechanical and even conductive, but the latter is rarely used.

Rotary encoders are usually integrated in the motors. Such a convenient solution can severely limit the performance of the whole robotic system in case of tendon transmission due to friction and elasticity effects.
Two variations of encoders exist depending on when the information is available: the incremental and the absolute encoder. In the incremental encoder it is possible to measure position only when there is a variation; on the other hand, the absolute encoder allows to know the absolute position at any time.

1. **Incremental encoder**: This kind of encoder produces periodic signals when the encoder detects movement. The absolute position can be obtained indirectly by using incremental measurements. To achieve better measurements, the encoder produces two signals with a 90 degree difference. The two signals are interpreted as a coded binary signal that allows the direction of movement to be recognized.

2. **Absolute encoder**: This kind of encoder produces a unique digital code corresponding to the absolute position at any time. The digital code is obtained by reading the detectors values. There are two different options to use for digital coding: Standard binary or Gray encoding. Usually Gray encoding is better since it avoids the problem associated with the transition between two consecutive values. Gray encoding ensures that only one part changes state at each transition, avoiding false lectures and undesired behaviors.
2.4.1. Magnetic encoders

Magnetic encoders are usually built using Hall sensors, which are based on the Hall Effect theory, that is, a voltage differential produced by an external magnetic field. That effect is due to the nature of the current flowing through a conductor device and placed within a magnetic field. The current is affected by the magnetic field, accumulating on the sides of the sensor. As the current is concentrating on the sides of the conductor, a voltage is produced between the two sides of the semiconductor material.

![Figure 6.- Explanation of the Hall Effect in semiconductors.](image)

To generate a voltage across the device, the magnetic field must be perpendicular (90 degrees) to the flow of current and have the correct polarity, generally a south pole. The Hall Effect is sensitive to the magnetic pole and magnitude of the magnetic field. That is very useful when designing a Hall sensor as a switch, therefore a magnetic rotary encoder based on that technique is possible.

a) Incremental encoder

It is possible to design an incremental magnetic encoder in two different configurations. The first configuration would use one hall sensor and multiple magnets, thus obtaining pulses for each magnet (Figure 7, left). The magnets could be the gear itself, with multiple teeth. This configuration is often used as a tachometer, using only one magnet to know when a revolution is made. Then the difference between pulses is processed and the speed is obtained.
The other configuration would use the gear teeth as an obstacle for a single magnet (Figure 7, right). This configuration is very similar to the previous one, but using only one magnet. When the shaft is spinning, the magnetic field is able to go through some openings in the gear.

\[ b) \text{ Absolute encoder} \]

Normally, the absolute magnetic encoder is not used in the common rotary encoder configuration. Instead of using multiple Hall sensors and magnets, a configuration of different Hall sensors with only one magnet is used to obtain the absolute angular position. Hall sensors generate a proportional voltage output when placed near a diametrically magnetized magnet. This output generated is a sinusoidal waveform, one cycle per full revolution. One Hall sensor can be configured only for a limited angular range due to the ambiguity in both directions when crossing the zero point. In practice, the useful linear range is up to ±45 degrees. In order to measure a full revolution, four Hall sensors are spaced equally in the rotating magnet to generate four sinusoidal waveforms shifted 90 degrees from the next sensor.

**Figure 7.-** Typical configurations for magnetic encoders.

By reading the differential output of two opposite Hall sensors, two 90 degrees phase-shifted signals with double amplitude are generated. These two analogue signals are digitized by ADCs and processed further in the digital domain. Using a Coordinate Rotation Digital Computer (CORDIC) algorithm transforms these signals into a linearly increasing output over a full revolution. The output becomes...
independent of the signal amplitude and magnetic offsets caused by external fields are cancelled.

This implementation requires a big number of sensors, hardware and software to acquire and process the position information. Although the obtained data has high accuracy and resolution, the size and cost of the material is significant.

2.4.2. Optical encoders

Optical encoders are based on optocouplers. These devices emit and receive light, operating as a switch activated by light. The light is emitted by a LED, usually Infrared, which saturates a photodetector. The connection between the electronic components is only optical, hence an optical interference should be placed to activate or deactivate the device in order to achieve the desired response. The coded disk allows the light to go through the holes or transparent slits, and is received by the photodetector on the other side of the disk. The optical encoder could also work with both encoding configurations, incremental or absolute.

![Figure 9.- Basic optical encoder.](image)

2.5. Optical Sensors

Research into an optical joint position sensor [1] carried out by Gianluca Palli and Salvatore Pirozzi, from the University of Bologna, exploits the modulation of an infrared LED to a photodetector by means of a variable-thickness canal integrated into the joint itself. The LED and the photodetector are fixed on one of the two links that compose the robotic joint, while the canal is integrated into the other link.

This solution was chosen by G. Palli and S. Pirozzi because of the interesting properties of optoelectronic components such as very small dimensions, immunity to electromagnetic fields, lightness and low power consumption. In order to achieve this goal, the system is based in Infrared devices, as they are cheap and technologically-developed. It also provides the sensor with immunity to electromagnetic fields, lightness and low power consumption.
The operating principle of the proposed solution is based on a suitable occlusion of the light emitted by a LED that illuminates a photodetector. In the initial conditions, i.e. without any occlusion as illustrated in Figure 10(a), the photodetector measures an optical power $P_1$. If a mechanical component is partially positioned between the two optical devices, for instance in Figure 10(b), a certain amount of the light emitted by the LED is occluded and, as a consequence, the photodetector measures an optical power $P_2$ smaller than $P_1$.

The occlusion is defined as a variable that can assume values corresponding to the cases where total occlusion or no occlusion happens. Also, the occlusion is assumed to be symmetric in order to maintain the symmetry of the system. The LED emits light in all directions but, due the occlusion, the photodetector receives only the amount of light with an emitting angle smaller than in the no occlusion case. A proper mechanical design allows one to obtain an occlusion of the light power flow proportional to the physical variable to be measured. From the functional point of view, a change in the joint angle produces a variation of the optical power measured by the photodetector since the amount of light power emitted by the LED and occluded by the mechanical component changes.

The miniaturized robotic joint has been designed so that the amount of light power that illuminates the photodetector changes with the angular position of the joint itself. Since the current that flows through the photodetector (also called photocurrent) is proportional to the amount of light that reaches the photodetector by means of a suitable constant that depends on the device, it is possible to convert the information about the received light and, as a consequence, the percentage of occlusion into an electric signal by using a very simple circuit. This circuit consists of a resistor to limit the current flowing through the LED or the photodetector.
From the figure below, it is worth noticing that the optoelectronic components are mounted face to face into suitable sockets directly built on the fixed link, and the light path is entirely enclosed inside the joint. This is an important design feature that allows the sensor to be insensitive to external disturbances such as sunlight, IR sources or spurious reflection caused by objects in the joint neighbourhood.

![Sockets for the Optoelectronic Components](Image)

**Figure 11.** Detailed view of the designed variable thickness canal by G. Palli and S. Pirozzi [1].

The joint angle range is limited by mechanical stroke limiters in the interval $0$ to $110$ degrees. To avoid undesired border-effects at both ends of the joint excursion that cause abrupt changes in the sensor response, the canal that modulates the light power flux has been designed with maximum (total) occlusion at $-20$ degrees and to present zero occlusion (i.e. the canal is as large as the lens of the optoelectronic components) at $130$ degrees, with the canal thickness that varies linearly with the angle in between these two limits.

Other than compactness and its lightweight-nature, the advantages of this type of implementation consist of a very high sensitivity and the simplicity of the conditioning electronics, together with a high immunity to electromagnetic disturbances and to environmental light, the absence of cross-talking between adjacent sensors and low power consumption. Since the output voltage of the sensor is of the same magnitude of the power supply, it can be directly digitalized by a 12-bit ADC and transmitted to a microcontroller by means of a digital bus. This allows to obtain a joint angular position resolution of about 0.04 degrees over the whole motion range.

The drawbacks of this solution may be the variations in the power of light emitted by the LED due to thermal drift of the junction. This phenomenon can be limited driving the LED with a current as constant as possible, e.g. using high-accuracy and/or controlled current sources.
In the previous figure, the sensor output voltage corresponding to the angular position reconstructed from the motors' information is reported together with the sensor calibration curve obtained by linear interpolation of the experimental data. The calibration of the sensor shows good linearity over the whole motion range. As a demonstration test bench, the sensor has been tested by means of a robotic joint position control loop, showing satisfactory performance over a wide frequency range. The experimental results show that the sensor is suitable for the measurement of joint angles.

2.6. Image processing

This technology is based on the position encoders used in the optical mice for computers. It is a system developed by Agilent Technologies in the 1999. It uses a tiny CMOS camera able to take 1500 pictures every second of a surface enlightened by a LED. The light bounces off the surface and, as it captures the image of the light, it is almost independent of the surface used. Then the image is sent to a Digital Signal Processor (DSP) for analysis. The DSP, operating at 18 MIPS (million instructions per second), is able to detect patterns in the images and see how those patterns have moved since the previous image. Based on the change in patterns over a sequence of images, the DSP determines how far the mouse has moved and sends the corresponding coordinates to the computer.
The main drawbacks of this system are that a lot of digital processing is needed and the space required to install the image sensing and processing electronics may not fit in the space available. But this system allows one to measure any kind of movement, linear or angular, without changing any configuration.

2.7. Selection of sensor

After analysing all the different options as a linear or angular position measurement device, a decision will be made regarding their suitability in the robot that Blue Danube Robotics is developing. According to the objectives to design a position sensor with low cost and good resolution, one of the options will be chosen in order to try to improve the performance. Some of the sensors seen previously are limited, in that they only measure linearly or angularly. Those are excluded as feasible options since the aim is to obtain an easily scalable sensor for linear and/or angular measurements. That excludes the rotary encoders.

Image processing seems to work perfectly in devices like the mouse of the computer, but the complex processing makes it an expensive option. It would probably have more precision than needed, which is not bad, but the cost to obtain that is high.

The most feasible options would be potentiometers, magnetic sensors and optical sensors. Capacitive and inductive sensors are discarded as they are hard and expensive to work with. Magnetic sensors are discarded as the optical sensors seem to be the perfect fit for robotics. According to the research carried out by Gianluca Palli and Salvatore Pirozzi, the design of an optical joint using optical devices, such as an infrared LED and a photodetector, reports good results in a simple electronic design. Therefore, the following work will be focused on improving the performance and minimizing the cost of the design. In order to achieve that, the design will consider using optocouplers to use the emitter and the receiver on the same side of the joint. Different options will be analysed to modulate the light power flux, as the main focus will be on different reflective surfaces.
2.7.1. General principle

If an optical sensor is guided over a reflecting surface with a reflection surge, the radiation reflected back to the detector changes gradually, not abruptly. The surface seen by the transmitter and detector determines the radiation received by the sensor. During the movement, this surface is gradually covered by the dark reflection range. In accordance with the curve of the radiation detected, the change in collector current is not abrupt, but undergoes a wide, gradual transition from the higher to the lower value.

As the following figure depicts, the surface seen by the sensor is named $g$, and the collector current reaches the lower value, not at the intersection ($x_0$), but displaced by a small displacement ($x_d/2$). The whole displacement ($x_d$) of the signal corresponds to an uncertainty when recording the position of the reflection change, and it determines the resolution and the trip point of the sensor. The trip point is the position at which the sensor has completely recorded the light-dark transition, that is, the range around the intersection with half of the displacement on both sides. In practice, this corresponds to the section within the 10% and 90% of the difference between the two values for the collector current. The displacement is also called as switching distance, analogous to switching time.

![Figure 14.- Response to an abrupt reflection change with associated Collector current curve.](image)

The switching distance, $X_d$, is predominantly dependent on the mechanical/optical design of the sensor and the distance to the reflecting surface ($A$). It is also influenced by the relative position of the transmitter/detector axis.

In a possible sensor (TCRT1000 from Vishay Semiconductors) case, the following figure shows the dependence of the switching distance, $X_d$, on the distance $A$ with the sensors placed in two different positions with respect to the separation line of the light/dark transition. In the first position configuration, the transmitter/detector axis of the sensor was perpendicular to the separation line of
the transition. In the second position (curve 2), the transmitter/detector axis was parallel to the transition.

In the first position, the optical sensors have a better resolution (smaller switching distances) than in position 2. The case of maximum light coupling distance, does not correspond to the maximum resolution. The switching distance at 1 mm distance to the reflecting surface ($A_{\text{optimal}}$) corresponds to a 2 mm value. It can recognize lines smaller than half a millimetre at a distance below 0.5 mm.

**Figure 15.**- Switching distance as function of the Distance to the surface of the TCRT1000 sensor.
CHAPTER 3:
DESIGN OF THE TEST SETUP

In order to perform proper testing with a variety of different prototypes, a test setup is considered to facilitate all the measurements. Blue Danube Robotics is considering the control of the robot based on 8-bit microcontrollers. Consequently, the Arduino platform is used in order to control the test setup platform and communicate with the computer. As angular and linear sensors are needed, there will be two different test setups for each case.

3.1. Arduino Platform

The Arduino platform is an open-source physical computing platform based on a simple microcontroller board and a development environment for writing software for the board. Arduino can be used to develop interactive objects, taking inputs from a variety of switches or sensors, and controlling a variety of lights, motors, and other physical outputs. Arduino projects can be stand-alone, or they can communicate with software running on a computer. It simplifies the process of working with microcontrollers and offers low cost, cross-platform (as it works with all the Operative Systems) and all the advantages that an open-source and extensible software and hardware offer.

The Arduino platform has a number of facilities for communicating with a computer, another Arduino platform, or other microcontrollers. The main microcontroller provides serial communication. Another microcontroller on the board, programmed as a USB-to-Serial converter, channels this serial communication over USB and appears as a virtual communication port to the computer.
The Arduino software includes a serial monitor that allows simple textual data to be sent to and from the Arduino board. There is a limitation with that serial monitor, as it only shows the data received in the port. In order to save all the data received, another software is used to interface the serial communication into a spreadsheet.

The software chosen for this duty is Gobetwino, a free software that can interpret commands received in the serial port and execute them on a Windows computer. Gobetwino defines a set of command types that can be used as templates to create actual commands. Arduino can send commands to Gobetwino through the serial communication.

The interesting feature of Gobetwino for the test setup is the ability to work with files, thereby allowing Arduino to create, open, read and write in files. In this case, it will work with CSV (Comma Separated Values) spreadsheet files, as they are simple to use. The way to proceed is to create a file from a designed template, and then start writing the values received in the serial port.

3.2. Linear

In order to develop a test setup platform for the linear measurements, the measurement specifications are needed. The maximum values to measure and desired characteristics in the robot are the following:

- Length: 50 mm
- Resolution: 0.02 mm
- Width available: 10 mm
3.2.1. Optical Sensor

For the linear test setup, the reflective optical sensor with transistor output TCRT1000 from Vishay will be used. In order to make it operate in the nominal values, the characteristics of the datasheet have to be considered in the electronic, and also the physical, design. The most interesting values are the forward voltage for the emitter, which is typically 1.25 V for a forward intensity of 50 mA; and also the optimum distance of operation, which is 1 mm. For the detector, the interesting value is the collector-emitter saturation voltage (0.3 V) in order to keep the transistor working in the saturation mode.

Table 1. Basic characteristics of TCRT1000 sensor.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST CONDITION</th>
<th>SYMBOL</th>
<th>MIN</th>
<th>TYP.</th>
<th>MAX.</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSOR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collector emitter saturation voltage</td>
<td>IF = 20 mA,</td>
<td>VCEsat</td>
<td></td>
<td>0.3</td>
<td>0.3</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>IC = 0.1 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INPUT (EMITTER)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward voltage</td>
<td>IF = 50 mA</td>
<td>Vf</td>
<td>1.25</td>
<td>1.6</td>
<td>1.6</td>
<td>V</td>
</tr>
<tr>
<td>Peak wavelength</td>
<td>IF = 100 mA</td>
<td>λp</td>
<td>940</td>
<td></td>
<td></td>
<td>nm</td>
</tr>
<tr>
<td>OUTPUT (DETECTOR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collector emitter</td>
<td>IC = 1 mA</td>
<td>VCEO</td>
<td>32</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Emitter collector</td>
<td>IE = 100 μA</td>
<td>VECO</td>
<td>5</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Collector dark current</td>
<td>VCE = 20 V, IF = 0 A</td>
<td>ICEO</td>
<td>200</td>
<td></td>
<td></td>
<td>nA</td>
</tr>
</tbody>
</table>

The datasheet provides some graphics for the basic characteristics, and one graphic is interesting for the purpose of the design of the sensor. The following Figure shows the relationship between the collector current and the displacement of a sensing object. Instead of the displacement of the sensing object, a different reflectivity of the material will be used in the final design. According to the graphic, a linear change of collector current happens in a range of 2 mm.

Figure 17.- Relative collector current vs. Displacement for TCRT1000.
A very simple electronic circuit is designed to supply the necessary current to the device. In order to achieve the nominal values in the datasheet, a value for the resistor to limit the current in the emitter is calculated with the following equation. The value for the current is taken as an arbitrary value, and it is related directly to the forward voltage. According to the graphics in the datasheet, the forward voltage has a value of approximately 1.1 V. This value for the detector will be tested later to check the performance with more or less current.

\[ R_{\text{emitter}} = \frac{V_{cc} - V_F}{I_F} = \frac{5 - 1.1}{0.02} = 190 \, \Omega \]  

To limit the current in the detector, another arbitrary value will be used, since it will be used as a pull-down resistor. That way, the transistor will limit the current flowing through the branch, thus the voltage in the resistor.

![Electronic schematic for the TCRT1000 sensor.](image)

**Figure 18.** Electronic schematic for the TCRT1000 sensor.

The output signal will be transformed in the digital domain by the integrated Analog-to-Digital Converter in the Arduino platform. This ADC has a 10-bit resolution, which is not enough for the desired resolution, but will be enough for the linear testing. In the final design, a higher resolution ADC will be implemented.

### 3.2.2. Ground truth reference

A measuring reference is needed in order to know the real value of the measurement. For that purpose, a digital caliper will be used interfaced with Arduino. In order to know how calipers send the read values through the digital bus, reverse engineering is needed. Calipers have four pins available and testing with a voltmeter, is easy to find the ground and supply terminals. To know the functionality of the other two remaining pins, is necessary to check their output with an oscilloscope. The following Figures show the images obtained of different readings in order to know the information coded in the bits send.
All the measurements are done with a time scale of 0.5 ms/DIV and voltage scale of 0.5 V/DIV. The upper signal is the data sent, and the signal below in the graphic is the clock. The data sent consists of 24 bits, being the first bit sent the Least Significant Bit (LSB). The bit time is 140 µs, however it comes with an extra gap, a little longer than one bit time, every 4 bits. The results indicate that when the clock line goes low, then the data line changes; finally the clock rises and the data is assumed to be clocked in. This is known as "SPI Mode Three". A peculiarity in the data is that the data line always returns high on each bit which may draw less current.

Interpreting the data when the caliper is at 0 mm, the bits sent are "0000 0000 0000 0000 0000", which is a totally zero value. When the caliper is at 9.99 mm, the bits sent are "1110 0111 1100 0000 0000", which in decimal value is 999,
Martín Castaño Sánchez

considering that the first bit sent (the one written on the left side) is the LSB. The resolution of the data is then 0.01 mm. Some further testing shows that the last 4 bits sent, are codified as follows: \( \bar{P}/N \times X \times U \). The first bit codifies if the value is positive (0) or negative (1). No utility has been found for the following two bits. The last bit (U) codifies the units that represent the value. If its value is ‘0’, the units are mm; and if its value is ‘1’, the units are inches.

To read these values, the software must communicate with the caliper using the two data and clock signals. As the caliper acts as a Master in the SPI protocol, Arduino is not capable to work as slave. To solve this problem, it is possible to implement the lecture of the protocol polling the data sent by the caliper. The data is accepted as valid when the clock signal goes from low to high, therefore the software will wait for a rising edge in the clock signal. Then reading the bit and setting the appropriate bit, being aware that the first bit sent is the LSB, in a variable to store the data received.

Electrically, the only problem that seems to be in the system, is the voltage level difference between the caliper and Arduino. The caliper operates with a 1.5 V button cell and Arduino operates with the 5 V supplied by the USB connection. To ensure that Arduino interprets the values as high or low correctly, a level converter device is used. This device ensures that it transmits the same signal but changing the maximum voltage of the signal, allowing the two communicating devices to understand.

3.2.3. Test platform

A platform is designed to enclose the prototypes under test and give physical support to the aforementioned sensor and caliper. The platform is created with a 3D printer as it facilitates the creation. The shape of the platform is a simple box with a hole and a slide in the upper side to place a sliding cover with the optical sensor. The sliding cover has also the shape of one of the moving parts of the calliper, thus the sliding cover moves at the same time. In order to maintain the calliper in a static position, the box has also some pads used as a standing points.

![Figure 21.- Assembly of the designed platform for linear testing.](image)

- 30 -
In the Figure 21 above, it is possible to see the platform base in blue, the sliding cover in white and the window in transparent. A generic testing prototype is inserted in the base (the brown piece). The caliper is placed in the upper surface of the base and the moving part of the caliper is held in the socket at one end of the sliding cover. A little plain surface is left in top of the platform base to place the electronic components. The window is used to filter or block completely the external light.

The sensor is placed in the middle of the sliding cover covering the testing prototype from ambient light. The sliding cover protects from the ambient light in the whole displacement of the caliper. As the sensor has the best performance at 1 mm distance, it is inserted in the sliding cover in a manner that its sensing surface remains at precisely that distance from the testing prototype. The surface change in the testing prototype is from top to bottom, and the sensor goes from right to left of the testing prototype, the optimal position is to place the sensor perpendicular to the displacement direction.

![Image of a linear test setup.](image)

**Figure 22.- Picture of the linear test setup.**

The socket to insert the prototype has to be bigger than the measurement range. That is because the prototype will be designed to have safe margins avoiding undesired border-effects at both ends of the measurement.

### 3.3. Angular

In order to develop a test setup platform for the angular measurements, the measurement specifications are needed. The maximum values to measure and desired characteristics in the robot are the following:

- Angular range: 0° – 200°
- Resolution: 0.1°
• Radius space available: 20 – 25 mm

3.3.1. Optical Sensor

For the angular test setup, the reflective optical sensor will be different than the sensor used in the linear test setup. In order to test smaller devices, the sensor for the angular position test setup will be in SMT (Surface Mount Technology). This will require the design of smaller prototypes. The sensor GP2S60 manufactured by Sharp is selected.

Table 2. Basic characteristics of GP2S60 sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Typical</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Forward voltage</td>
<td>$V_F$</td>
<td>$I_F=20mA$</td>
<td>1.2</td>
</tr>
<tr>
<td>Output</td>
<td>Collector current</td>
<td>$I_C$</td>
<td>$I_F=4mA$, $V_{CE}=2V$</td>
<td>85</td>
</tr>
<tr>
<td>Transfer</td>
<td>Optimal distance</td>
<td>$d$</td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>

The datasheet provides also graphics for the basic characteristics. One of the graphics is interesting for the purpose of the design of the sensor, which is shown in the following Figure. This shows the relationship between the collector current and the displacement of a sensing object. According to the graphic, a linear change of collector current happens in a range of 2 mm, the same switching distance as the linear sensor used.

![Figure 23.- Relative collector current vs. Displacement for GP2S60.](image)

The same electronic circuitry as in the linear test setup is used to supply the necessary current to the device. The same values apply in this case, as the sensor characteristics are very similar, although some further testing in the collector current will be made.
3.3.2. Signal processing

Between the sensor and the Arduino platform, the signal obtained requires to be processed differently than in the linear case. The ADC must have higher resolution than the one integrated in the Arduino platform (10-bit resolution), as the desired resolution is 0.1º/bit. To achieve this resolution, a minimum of 11-bit ADC is needed, but to be switchable with the linear setup, a 12-bit ADC is used. The ADC selected is MCP3202 from Microchip. This offers a dual channel converter with SPI serial interface. The dual channel can be used as independent channels or as differential conversion in the ADC. To read the data converted, the SPI protocol facilitates the communication with the Arduino platform.

The SPI protocol works with 4 signals: chip select ($CS$), clock ($CLK$), data in ($DIN$) and out ($DOUT$). The chip select signal works inverted, which means that it is active when the signal is low. When $CS$ goes from high to low, the ADC is active and ready to transmit information. The clock signal is sent to the ADC, timing the input and output bits on the falling edges of the clock signal. Then the protocol works as follows: the first bit is the starting signal to begin the sample and conversion. The following two bits received in the ADC are the configuration bits. The first is to set whether the ADC should work in single ended or pseudo-differential mode. The second bit depends on the previous bit, being the channel selector in case the ADC works in single ended mode. If the ADC is working in pseudo-differential mode, this bit determines the polarity.

<table>
<thead>
<tr>
<th>Configuration Bits</th>
<th>Channel Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGL/DIFF</td>
<td>ODD/SIGN</td>
</tr>
<tr>
<td>Single Ended Mode</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Pseudo-Differential Mode</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3. Configuration bits for the ADC.

After the channel selection/polarity bit is send, another bit to select the format in which the converted data is sent. If it has a high value, the data is sent with the most significant bit first (MSB). Otherwise, the converter sends first the data with the MSB first and after sends it with the least significant bit (LSB). In any case, the converter sends first a null low bit that should not be read. After the 12 bits are sent in every falling edge of the clock signal, in case that the chip select signal is not set to a high value, the converter transmits zeros.
The manufacturer recommends the signal to be buffered, in order to avoid inaccurate conversion results \[2\]. This is thanks to the ability of active filters using Operational Amplifiers that provide isolation between stages. It is also recommended to implement an anti-aliasing low-pass filter to eliminate any signals that may be aliased into the conversion results. One filter that can provide a low impedance output and a low pass is the Sallen-Key topology. Designing a 2\(^{nd}\) order low-pass filter is convenient to eliminate unwanted high frequency noise.

In this filter configuration, the \(R_3\) and \(R_4\) resistors configure a feedback loop with gain. The gain is positive, meaning that the output signal maintains the same polarity as the input signal. It is possible to not have gain in the negative feedback loop ignoring the mentioned resistors, but maintaining the feedback loop in the negative input of the operational amplifier. To calculate the values of the other resistors and capacitors, there are some key parameters on the design that are needed to be considered.

Any low pass filter can be specified with four parameters. The cut-off frequency \((f_{\text{cut-off}})\) is defined as the frequency which the filter has a gain of -3 dB. The frequencies between DC and the cut-off frequency are defined as the frequencies
that can pass. Higher frequencies are considered rejected by the filter. In the rejection band, there is a transition bandwidth where the signal is not fully rejected. This is determined by the order of the filter (M). The filter order is equal to the number of poles in the system. Usually, when more poles are used to implement the filter, the transition bandwidth becomes smaller and approximating more to the ideal filter.

The low-pass filter rejects ideally all the frequencies above the cut-off frequency. Practically there is a gain value in the above frequencies. The important parameter is the filter system gain (AMAX), which is defined as the difference between the gain in the pass band region and the gain in the stop band region. To define the value of the gain in the stop band region, another parameter tells at which frequency the minimum attenuation is reached. This is the stop band frequency (fSTOP).

The first parameter applies to the sample rate of the ADC, which in this case is 100 kSamples per second. According to the Nyquist theory, the sample rate must be, at minimum value, double the cut-off frequency to be considered reliably digitalized. In this case, the cut-off frequency of the filter cannot be higher than 50 kHz.

In the anti-aliasing filters, there is the Signal-to-Noise Ratio (SNR) which determines the minimum gain of the filter at the Nyquist frequency, half value of the sample rate (fsample/2). This is to ensure a minimum rejection at the Nyquist frequency. In a 12-bit A/D Converter, the ideal SNR is 74 dB. The filter should be designed so that its gain at fSTOP is at least 74 dB less than the pass band gain.

To determine a cut-off frequency, it should be based on the highest frequency at which the sensor contains any relevant information. That frequency is often related to the response time of the sensor, but in this case is related to the rotational or linear speed of movement. This is caused by a much faster response of the sensor than the movement.

$$f_{\text{cut-off}} = \frac{1}{2\pi} \cdot \sqrt{\frac{1}{R_1 \cdot R_2 \cdot C_1 \cdot C_2}}$$ \hspace{1cm} (2)

One parameter that must be considered when designing is the quality factor, or Q factor. This parameter determines the behavior of the filter as a result of a step function in the input. That is to determine the oscillation of the frequency response, characterized by the overshoot and the settling time of the damped waveform. A low value is said to be overdamped, which has a very slow rising signal; and on the opposite, a high value is said to be underdamped, which results in a much faster response but with more overshoot and oscillation. A quality factor too high can result in a pure oscillatory system. Usually, to obtain good performance in anti-aliasing filters a value of Q between 0.5 and $\frac{1}{\sqrt{2}}$ is enough. In order to achieve this, the component values have to be chosen considering the quality factor also, according to the following equation.

$$Q = \frac{\sqrt{R_1 \cdot R_2 \cdot C_1 \cdot C_2}}{(R_1 + R_2) \cdot C_2}$$ \hspace{1cm} (3)

Considering all the aforementioned parameters and restrictions, the values are estimated and approximated to commercial values, being the capacitors the most restrictive. The cut-off frequency is selected to be 100 Hz to start filtering. Only
selected to filter signals of ambient light affecting the system. The quality factor is selected to be 0.7 as it is the highest of the recommended values.

Table 4. Component values for the Sallen-Key filter at 100 Hz.

<table>
<thead>
<tr>
<th>Component</th>
<th>Resistors (kΩ)</th>
<th>Capacitors (µF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component 1</td>
<td>7.87</td>
<td>0.22</td>
</tr>
<tr>
<td>Component 2</td>
<td>14.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Conditions**  
\( Q=0.7 \)  
\( f_{\text{cut-off}}=100 \text{ Hz} \)

To ensure the desired performance of the filter, the designed circuit is simulated with a software. Therefore obtaining the frequency response of the filter.

![Frequency response for Sallen-Key filter at 100 Hz.](image)

The frequency response is the desired, as the previous graphic shows. At 100 Hz, the gain is around -3 dB and the phase stabilizes at -74 dB. This are the desired characteristics for this filter, ensuring a good response for the anti-aliasing filter in the measurements.

3.3.3. **Ground truth reference**

To ensure that the measure is made for a determined angle, an angle reference is needed. For that purpose, a magnetic encoder is integrated in the test setup. The magnetic encoder will be the commercial AEAT-6012 model, which has a digital output of 12-bit resolution using the SPI protocol. This is an absolute position encoder, fitting perfectly as a reference position measure.
The most important characteristic of this sensor is the size and the shape, as it will limit the physical testing platform. It consists of a circular ‘housing’ into which a magnetic shaft is inserted. The physical testing platform will have to ensure that this magnetic shaft spins equally as the testing prototype or the sensor.

3.3.4. **Physical support**

The magnet encoder is built with a housing, and a magnet to insert in the shaft. A platform base is needed to connect the shaft with the testing prototype. In addition, it has to ensure that the optical sensor stays static in the same position. In order to ensure these two conditions, a bearing that will be subjected to the shaft is enclosed inside a static base platform where the optical sensor is placed. At the end of the bearing, the testing prototype is placed and it stays at the optimal distance from the sensor recommended by the manufacturer.
For the angular prototype, two testing cases are designed using a circular shape, thus two versions of the testing prototype. The first version of testing prototype is designed thinking about that it would be inserted inside a rotating mechanism, then the reflective surfaces use a small area from the center of the circle. The second version is thought to be inserted in a shaft, so it has a small hole in the center that allows the shaft to be inserted. The reflective surfaces would be in the outer ring of the circular shape.

Figure 29.- First (left) and second (right) versions of the angular prototype.

The housing available to use with the magnetic encoder is star-shaped, as the Figures above show. In order to fix it to the platform, some screws are used. There is a hole in the testing platform base to put the bearing in, so it can rotate freely inside the fixed platform base. The sensor is held by a cover that is fixed itself to a couple of slots on the sides of the platform base. To determine the best sensor position, two different covers with both positions slots are implemented. Theoretically, the sensor should be placed parallel to the radius of the prototype.

Figure 30.- Picture of the angular test platform.
CHAPTER 4:  
DESIGN OF THE TESTING PROTOTYPE  

This section will explain the different testing prototypes designed as a possible solution to create the reflective changing surface. The testing prototypes are divided in the different shapes and materials of the surface. They will be adapted in shape to each linear or angular case. The testing prototypes have the dimensions where the reflective surface can change, limited by the given range of the optical sensor. As both optical sensors used have the same range, it does not require the design of different testing prototypes for each case.

To implement the design, the software Inventor from Autodesk is used. This software allows one to design pieces in 3D and programme the CNC milling machine to obtain pieces with precise shape and size. Also, it allows one to export the piece into a readable file for the 3D printers. Thus, this software is appropriate for the design of tough materials. To design graphics, the graphic software GIMP is used.

4.1. Materials

In order to select the best fit materials for the prototypes, three characteristics are the most important. Reflective coefficient, availability and easiness to manipulate the piece and achieve the desired shape. For the reflective coefficient of a variety of possible materials, Vishay manufacturer offers a table with some tested materials on their devices [3]. This table is useful to have an idea of the possible materials to use.

According to the following table and the materials available, a list of materials that can be used in the prototype design is made. The most interesting materials are those whose reflectivity is close to the highest or lowest value. In this case, a value
close to the reference is considered high (100 %) and lowest is null. Also some other materials, that are not in the table but available, might be considered.

**Table 5. Relative collector current of the reflex sensors for reflection on various materials.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Collector Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kodak neutral card</strong></td>
<td></td>
</tr>
<tr>
<td>White side (reference medium)</td>
<td>100%</td>
</tr>
<tr>
<td>Gray side</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Paper</strong></td>
<td></td>
</tr>
<tr>
<td>Typewriting paper</td>
<td>94%</td>
</tr>
<tr>
<td>Drawing card, white (Schoeller)</td>
<td>100%</td>
</tr>
<tr>
<td>Card, light gray</td>
<td>67%</td>
</tr>
<tr>
<td>Envelope (beige)</td>
<td>100%</td>
</tr>
<tr>
<td>Packing card (light brown)</td>
<td>84%</td>
</tr>
<tr>
<td>Newspaper paper</td>
<td>97%</td>
</tr>
<tr>
<td>Pergament paper</td>
<td>30-42%</td>
</tr>
<tr>
<td><strong>Black on white typewriting paper</strong></td>
<td></td>
</tr>
<tr>
<td>Drawing ink (Higgins, Pelikan)</td>
<td>4-6%</td>
</tr>
<tr>
<td>Foil ink (Rotring)</td>
<td>50%</td>
</tr>
<tr>
<td>Fiber-tip pen (Edding 400)</td>
<td>10%</td>
</tr>
<tr>
<td>Fiber-tip pen, black (Stabilo)</td>
<td>76%</td>
</tr>
<tr>
<td>Photocopy</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Plotter pen</strong></td>
<td></td>
</tr>
<tr>
<td>HP fiber-tip pen (0.3 mm)</td>
<td>84%</td>
</tr>
<tr>
<td>Black 24 needle printer (EPSON LQ-500)</td>
<td>28%</td>
</tr>
<tr>
<td>Ink (Pelikan)</td>
<td>100%</td>
</tr>
<tr>
<td>Pencil, HB</td>
<td>26%</td>
</tr>
<tr>
<td><strong>Plastics, glass</strong></td>
<td></td>
</tr>
<tr>
<td>White PVC</td>
<td>90%</td>
</tr>
<tr>
<td>Gray PVC</td>
<td>11%</td>
</tr>
<tr>
<td>Blue, green, yellow, red PVC</td>
<td>40-80%</td>
</tr>
<tr>
<td>White polyethylene</td>
<td>90%</td>
</tr>
<tr>
<td>White polystyrene</td>
<td>120%</td>
</tr>
<tr>
<td>Gray partinax</td>
<td>9%</td>
</tr>
<tr>
<td><strong>Fiber glass board material</strong></td>
<td></td>
</tr>
<tr>
<td>Without copper coating</td>
<td>12-19%</td>
</tr>
<tr>
<td>With copper coating on the reverse side</td>
<td>30%</td>
</tr>
<tr>
<td>Glass, 1 mm thick</td>
<td>9%</td>
</tr>
<tr>
<td>Plexiglass, 1 mm thick</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td></td>
</tr>
<tr>
<td>Aluminum, bright</td>
<td>110%</td>
</tr>
<tr>
<td>Aluminum, black anodized</td>
<td>60%</td>
</tr>
<tr>
<td>Cast aluminum, matt</td>
<td>45%</td>
</tr>
<tr>
<td>Copper, matt (not oxidized)</td>
<td>110%</td>
</tr>
<tr>
<td>Brass, bright</td>
<td>160%</td>
</tr>
<tr>
<td>Gold plating, matt</td>
<td>150%</td>
</tr>
<tr>
<td><strong>Textiles</strong></td>
<td></td>
</tr>
<tr>
<td>White cotton</td>
<td>110%</td>
</tr>
<tr>
<td>Black velvet</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

4.1.1. **Paper**

Paper is a very cheap material and it is very easy to manipulate by printing something over the paper. As the table shows, the different inks have different reflection coefficients, so white paper can be used as a reflective surface and the ink on the paper as a non-reflective surface. For this material, the gradient and dot patterns fit perfectly. The designs will be tested in ink or laser prints to see which achieves a better result.

4.1.2. **Plastic**

According to table 5, plastics show a good difference of reflectivity. The problem lies in the unavailability of PVC to test on. But other plastics are tested to see if they show good responsiveness to the light. The plastics available to work are polyethylene (PE) and polylactic acid (PLA), which is the material used in the 3D printers.

4) PE

Polyethylene plastic has a good reflectivity index, as the table from the manufacturer shows. In order to manipulate this material into the desired shape, a CNC milling machine is used. The main problem of this plastic shaped with a
milling machine, is that the edges have some plastic left. Trying to clean the edges afterwards can change the shape and then cause some bad readings from the sensor.

\[b)\] **PLA**

This is the default kind of plastic used on the 3D printers available. This is very useful as all shapes can be designed and created with the 3D printer with great accuracy. There are different colour options, but white is the available colour. The white PLA plastic shows a good reflectivity value, therefore it has to be used with a non-reflective material.

**4.1.3. Aluminum**

Aluminum appears to be the perfect reflective surface. But on the opposite side, it is hard to work with as the surface and edges must be perfectly plain. Otherwise, the light is reflected in all directions and the sensor might not be able to collect it all on the next millimeter. To shape the aluminum, the CNC milling machine is used as with the plastics.

**4.1.4. Tape**

The black tape shows a low reflectivity value. The low cost and easy to use makes it a good material to work with. The problem lies that a perfect positioning of the tape in the testing prototype is required. This can be solved using the normal shapes with a small step, allowing the tape to have the desired shape in the prototype.

**4.1.5. Wood**

Wood is not in the list, but is also a tractable material. It shows a medium reflective surface. But it needs to be perfectly edged, as when cutting the wood, some wood chips might appear. This translates into wrong reflection of the light and bad readings from the sensor. To shape the wood, the CNC milling machine is also used.

**4.1.6. Foam**

Black foam has a low reflectivity value. That makes it perfect for filling the testing prototypes with this material, as it can be cut and shaped easily thanks to its own physical characteristics. It can be cut using the CNC milling machine as with other materials, but with more caution as it is a softer material.

**4.2. Shape**

To have different reflective surfaces changing as the position is changing, implies a shape change. That way, the two surfaces make a shape that encodes the position.
4.2.1. Slopes

That is the most obvious and easy shape, a line that crosses the prototype increasing linearly. That makes the reflective surface and the non-reflective surface increase and decrease respectively at the same proportion.

a) Triangle

This shape consists of a rectangle build with two triangles inside. This shape achieves to split the prototype in two different zones but keeping the ratio between them. That way, the two zones have a linear difference.

![Prototype with triangle shape.](image)

**Figure 31.** Prototype with triangle shape.

To keep the separation inside the sensor range, the triangles have to go through determined points in a range of 2 mm. The following figure shows how the basic triangle prototype for linear measurements is.

![Prototype with triangle shape within 2 mm range.](image)

**Figure 32.** Prototype with triangle shape within 2 mm range.

In this case, the extrapolation into an angular testing prototype results into the following figure. The first version of angular testing prototype consists in a full 360 degrees shape changing linearly in 2 mm radius. The second prototype changes from 10 to 350 degrees in a 3 mm range, providing a margin of 1 mm. Thus the useful 2 mm range covers 226 degrees approximately.

![Angular Prototypes with triangle shape within 2 mm range.](image)

**Figure 33.** Angular Prototypes with triangle shape within 2 mm range.

b) V-shape

This shape consists of a double triangle shape, from the upper and bottom side to the center of the piece. Achieving a similar shape as the previous shape but instead of one surface change, there is two changing surfaces. The outer surfaces are the same and the surface in the middle has a different reflective surface.
The angular testing prototype is also designed with this shape, but working with such small pieces, the 3D printer loses precision when joining the two sides. The prototype is designed only in the second version, as the first one is too small.

**Figure 34.** Prototype with V-shape.

**c) Step-Void**
This shape consists of the same previous two shapes but instead of two different surfaces, the non-reflective surface consists of no surface.

**d) Fading surface**
Instead of using two reflective surfaces, only one surface is used. To make some linear changes in the reflection, the relationship between the amount of light received and the distance of the object is taken in mind. As the datasheet shows, this relation seems linear with a linear increasing distance.

**Figure 36.** Prototype with fading surface. As seen from the side.

**e) Circle**
This shape applies only to the angular prototypes. It consists of a constant circle from the maximum radius, 2mm, to the minimum in the 200 degrees to measure. It is implemented in the first version of the prototype only, as in the second is hard to design while there is a shaft going through the center of the prototype.

**Figure 37.** Angular prototype with the circle shape.
4.2.2. Gradients

If the ink is able to change the reflective coefficient of a paper surface, an interesting method is the gradient. A gradient is a directional change in the intensity of a value, in this case the quantity of ink, hence the reflection. Technically it is possible to change this intensity linearly in a way that the optical sensor can perceive. In the case of colouring, it means a gradual blend from one colour to another, i.e. blending from black to white.

![Linear gradient prototype](image)

**Figure 38.** Linear gradient prototype.

For the angular prototype, the gradient can be shaped in two different ways: conical or spiral. The graphic software allows to design the gradients with two characteristics in each shape. For the conical, it can be symmetrical or asymmetrical. For the spiral shape, it can be directed clockwise or counterclockwise.

![Conical gradient prototype](image)

**Figure 39.** Conical gradient prototype.

![Spiral gradient prototype](image)

**Figure 40.** Spiral gradient prototype.

4.2.3. Dot patterns

This technique is based on the previous gradient method, but the main difference is that the intensity is modified by the percentage of a dot cloud. A higher percentage of dots implies a higher average intensity value. The advantage of this method could be that the dots can take different shapes and may have different results.

![Halftone round dots pattern prototype](image)

**Figure 41.** Halftone round dots pattern prototype.

![Halftone diamond dots pattern prototype](image)

**Figure 42.** Halftone diamond dots pattern prototype.
All these patterns, except the lines pattern, have a small cell size containing a form that changes its size as the position increases. All the forms are black with a white background and they share the cell space differently. The lines pattern is based on the V-shape, but with a bigger number of lines. All the patterns are made using the newspaper graphic filters in a software for image manipulation, thus the figures are the dot functions available in the program.

4.3. Interferences

The most probable source of external interferences is the ambient light. The effect of ambient light falling directly on the detector is always very troublesome. Weak steady light reduces the sensitivity of the sensor. Strong steady light can saturate the photoelectric transistor. The sensor cannot recognize any reflection change. Chopped ambient light gives rise to incorrect signals and feigns non-existent reflection changes. Indirect ambient light, which is ambient light falling onto the reflecting objects, mainly reduces the contrast between the object and background or the feature and surroundings. The interference caused by ambient light is predominantly determined by the various reflection properties of the material.

In practical applications, it is generally rather difficult to determine the ambient light and its effects precisely. Therefore, an attempt to keep its influence to a minimum is made from the outset by using a suitable mechanical design and optical filters. The detectors of the sensors are equipped with optical filters to block such visible light. Furthermore, the mechanical design of these components is such that it is not possible for ambient light to fall directly or sideways onto the detector for object distances of up to 2 mm. Nevertheless, in the robot, the whole sensing system is assumed to be encapsulated and kept away of the ambient light influence, as it is built inside the mechanical joint.

The possible interference caused by the ambient light is tested through the linear test setup, as a window to let the light in is considered in the design. The worst case scenario would be with no window to filter the ambient light compared to a window blocking the light.
In this chapter, all the measurements made with the previous testing prototypes are shown and analysed. To minimize the human errors in the measurements, a certain amount of measurements in the same conditions are made. Then obtaining averaged values to help reduce all the possible errors of the human-test setup interaction, and other sources not considered and unexpected.

For the reference measurements, meaning the readings from the magnetic encoder or the calliper, it is physically impossible to obtain a sensor reading for every minimum value (resolution). The reference measurement skips some values, thus not obtaining all the possible values in the whole motion range. This case is worse with the caliper readings, due to the human interaction and to the slower reading rate when interfacing with the SPI communication. In order to simulate the lost readings, the values in between are filled with the latest reading. That gives a better approximation of the overall performance.

The position values units, for the linear case, are $10^{-5}$ m, which correspond to the calliper resolution. This resolution is the LSB send, so the range of linear position is 0 to 5000. In the angular range, the range is 0 to 360 degrees, as the magnetic encoder used as reference can read in any angle. The magnetic encoder resolution is determined by the ADC used, which has 12 bits of resolution: $360^\circ / 2^{12\text{bits}} = 0.088^\circ / \text{bit}$.

Contrasting the measurements with a linear regression approximation of the results tendency, the coefficient of determination ($R^2$) provides a numerical expression to measure up the linearity. In statistics, this value quantifies how well the regression line fit into the real data points. A value of 1 indicates that the line approximates perfectly to the data. A value higher than 0.99 is accepted as a feasible approximation.
5.1. Potentiometer

To have a reference of measurements and compare the results obtained with the designed sensors, some measurements have been made with a linear potentiometer. The testing consists of a simple voltage divider with the potentiometer.

5.1.1. Voltage divider

The voltage divider is designed to have an output range from 0 V to 5 V. That translates the movement of the sliding contact into a voltage inside the limits of the power supply of the global system. This power supply is used as a reference voltage for the analog-to-digital converter, thus the voltage divider works in the full range of the converter. Although an external power supply has been used for the voltage divider in order to achieve the desired output range. The external source supplies 9 V and is connected to a 10 kΩ potentiometer in series with an 8.2 kΩ.

Measuring the values read by the sensor an amount of 8 measurements and averaging them, the following figure is obtained. The potentiometer range of movement is more than the necessary (50 mm). Nevertheless, the curve obtained is compared only in the range of voltage change. There are two linear approximations in the graphic, the dots line is a linear approximation of the response curve, trying to minimize the error. The orange curve is a linear function going from the minimum to the maximum voltage achieved in the position range. Both of them have the same value of $R^2$.

![Figure 44.- Averaged potentiometer Measurements.](image)

The potentiometer shows a slight bended curve over the theoretical linear response. The measurements obtained from the potentiometer are good but not lineal enough, as the $R^2$ value is low. Thus another electrical configuration is needed in order to linearize the response curve.
5.1.2. Voltage divider with Op-Amps

Exist different electronic configurations to improve the accuracy of the potentiometers. Normally, they include an operational amplifier in buffer configuration to provide an impedance transformation. That impedance transformation helps preventing interferences between input and output signals, thus isolating both signals. Another interesting characteristic of the buffer is that it has a unity gain, keeping the same voltage on both sides.

![Figure 45. - Configuration used to increase accuracy in voltage divider mode.](image)

One configuration to improve the accuracy of potentiometers is the configuration in the figure above. The voltage is divided by three fixed resistors and the potentiometer is placed in parallel with the resistor in the middle. This configuration preserves the flexibility of the variable output with higher accuracy. On the opposite side, it reduces the output range.

![Figure 46. - Averaged potentiometer measurements configured with Op-Amps.](image)
In the previous figure, the averaged measurements of the potentiometer in this new configuration is shown. The linearity response improved considerably, but the accuracy seems to get worse, as there is a lot of noise in the signal. Furthermore, the repeatability of the measurements worsened, showing considerable deviations in consecutive measurements.

5.2. Electronic configuration

The light emitted and received in the sensor is dependent on the intensity flowing through the optical components. This intensity allows obtaining different results in the measurements when modified. In the receiver components, the value of the resistor is not as critical as in the emitter. That is because the resistor is used only to ensure the appropriate voltage in the phototransistor and also a variable voltage in the output. Therefore, only the intensity in the emitter is tested.

5.2.1. Intensity in the emitter

Increasing or decreasing the value of the resistor modifies the intensity in the emitter. As mentioned previously, this resistor limits the intensity flowing in the emitter branch and thus the light intensity.

- Linear

To obtain better results, three different values of intensity are chosen. As the maximum intensity through the emitter is 50 mA, and recommended is 20 mA; the values chosen are 45, 20 and 10 mA. According to the equation 1, these values are approximated to 82, 220 and 390 Ω respectively.

![Figure 47.- Graphic of different intensities through the emitter in linear test setup.](image)

The figure above shows that a high current value implies a big slope, and also a lot of energy in the resistor that heats up. A value between 20 and 10 mA seems
to be the perfect fit, as the response does not cover the full position range with 20 mA, and has a smaller slope with less current. Using a value of 270 Ω, an intensity of 14.5 mA is obtained and seems to perform perfectly.

- Angular

Although another sensor is used in the angular test setup, the same testing with different intensities through the emitter are tested. In the angular test setup, it seems that the sensor selected needs a higher value of the forward intensity to obtain good readings. For the same prototype, a total different response is obtained, as the figure below shows. With small currents, the sensor barely changes its value. With big currents, the sensor has better response and bigger range of values.

![Graphic comparison of different intensities flowing through the emitter in the angular test setup.](image)

The signal has more noise as the current decreases, but on the other hand, the signal has smaller response with higher currents. An intensity value of 25 mA seems to be the best fit. This intensity has a better range response and the curve obtained has also enough range to obtain the desired resolution. A resistor of 150 Ω is used to obtain approximately this current.

5.2.2. Anti-aliasing filter

To see the effects of the anti-aliasing filter, which theoretically do not affect the normal behavior, the measurements are compared with the same testing prototype. In the first case, it is measured only with a buffer and in the second case, the anti-aliasing filter is added. As the following graphic shows, the curves are almost the same, as expected. That is that the filter works properly and it does not affect the proper performance of the system.
5.2.3. Physical configuration

According to the physical explanations commented on the last section of the 2\textsuperscript{nd} chapter, the sensor could be positioned perpendicular or parallel to the surface transition of the testing prototype. This affects the switching distance of the sensor, achieving higher values with the former position. For the linear prototype, the position is obvious. In the angular case, that decision is not that obvious, thus some measurements are made.

- Angular

For the angular test setup, the sensor can be placed parallel or perpendicular to the direction of the circular movement. As the Figure below shows, the parallel position seems to detect better the surface transitions. This difference can be seen as the sensor has wider values in the voltage range when measuring. Therefore, the position in the final design will be placed parallel to the rotary direction. The curve obtained is different from the previous results, due to the fact of using another testing prototype.
5.3. Linear Prototypes

Different measurements of the designed shapes are made with different materials combined in the linear test setup. The only material that is used alone is the paper with printed ink. The other potential materials are combined in different manners to check the performance.

5.3.1. Paper

1. Slope

Testing the triangle slope in the whole range of the testing prototype gives a curve as the graphic in the following figure. The curve makes a smooth transition from low values to high values, though this transition is only in a small section. Zooming a little bit, the transition is done around 21 mm and 31 mm approximately. This translates into 42% and 62% of the whole motion range (50 mm), making a range of 20% linear response. The conversion to the surface transition direction would be 20% of the width. That is to say 2 mm out of 10 mm width, which is the aforementioned switching distance of the sensor.
Designing a new testing prototype with the surface transition only within the 2 mm range, a new linear response is obtained. The slope direction is in the opposite direction due to switching the position of the materials. The figure below shows that the linearity of the curve is good, as the $R^2$ value shows, but still not good enough, as in the end the curve has a slight slope difference.

2. Gradient

The gradient shape has a curve with two different slopes. When it reaches the middle point of the whole motion range, it starts to flatten. As done previously, the gradient is redesigned to cover the whole motion with variation only until the half of the gradient.
3. Dot patterns

The dot patterns are similar to the gradient design, therefore the expected behaviour is similar to the gradient. However, there is a slightly difference as with the printed prototype it is harder to achieve the desired quality. This is due to the small size of the testing prototypes for the printer. Therefore the printed result is not the same as the designed, obtaining a curve not as expected.
a) Round

In the figure below, the curve obtained from the round shaped prototype is linear even with a lot of deviations. This makes the curve not suitable as the errors of measurement will be big.

![Figure 55. - Graphic of the halftone round pattern on paper measurement.](image)

Figure 55.- Graphic of the halftone round pattern on paper measurement.

b) Diamonds

With the diamond shaped prototype, the curve obtained is similar to the curve obtained with the rounded shape. The curve has a linear tendency with error deviations as the round shape does.

![Figure 56.- Graphic of the halftone diamonds pattern on paper measurement.](image)

Figure 56.- Graphic of the halftone diamonds pattern on paper measurement.
c) Lines

With the lines shape, the same result as the previous two cases is obtained. The printing quality is not good enough and the curve shows big errors to the ideal linear curve.

![Graph of the halftone lines pattern on paper measurements.](image)

**Figure 57.** Graphic of the halftone lines pattern on paper measurements.

5.3.2. Plastic-Tape

A black tape is used as a dark part combined with the plastic. This results in a quite useful and cheap way to implement a different reflective surface.

a) PLA

All the following measurements consist of the plastic printed with the 3D printer and black tape inserted in the step designed in the testing prototypes.

- Triangular shape

To see the sensor response, the basic prototype with the triangle shape through the whole range is tested. As the Figure below shows, there is a linear range between 17 mm and 26 mm. This range is 34% and 52% respectively, which translated in the other axis, knowing that the width is 10 mm, is between 3.4 and 5.3 mm. That space is almost the 2 mm switching distance that the manufacturer specifies in the datasheet. The next prototypes tested will have the slope on that 2 mm of the sensor range.

\[ R^2 = 0.97 \]
When the triangular shape is limited to the switching distance, and widened a little bit to ensure good measurements, the following curve is obtained.

The curve obtained is linear satisfactorily, with an $R^2$ value higher than 0.99. On the contrary, the sensor did not read the full position range linearly. The value stayed constant when it was above 38 mm approximately.

- **V-Shape**

The curve obtained for a V-shaped testing prototype is not linear, consequently discarding this prototype for future measurements. Although a possibility to modify the V-shape testing prototype exists. Hence obtaining probably more linear results, as seen in the study carried by Palli and Pirozzi. However this effort is focused in the triangular shape.
b) PE

The modified testing prototype reshaped to work on the 2mm range is used with PE plastic. Nevertheless, to obtain perfect edges in this plastic is difficult, as aforementioned. The following graphic shows this noise, probably as a result of not well polished edges, and a non-linear response.

![Figure 60.- Graphic with V-shape measurements.](image)

**Figure 60.-** Graphic with V-shape measurements.

5.3.3. Plastic-Ink

Continuing with the same shape as a prototype testing, but using a different non-reflective surface. The next measurement consists of painting the lower step of the prototype with black ink.

a) PLA

Testing first with the 3D printer plastic, the results are not satisfactory. The curve has only a small linear slope at the end.

![Figure 61.- Graphic with the plastic PE-tape measurement.](image)

**Figure 61.-** Graphic with the plastic PE-tape measurement.
b) PE

Testing with the other plastic, results are also not satisfactory. The results show a linear tendency, but with a lot of noise in the measurements. This instability makes this option not usable.

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5.3.4. Wood-Plastic

Even though these two materials have good reflective coefficients to infrared light, wood shows a lower value than plastic. This difference is tested to check this response difference. Thus the wood is used as the non-reflective surface, and the plastic as the reflective surface in the same prototype shape as previously.
a) PLA

The combination of wood with 3D printer plastic is tested. The curve seems to have a linear tendency, although the slope is not big enough. That is to say, that the responsiveness difference between this two materials is small. In addition, the curve has some noise.

![Figure 64.- Graphic of the PLA plastic combined with wood measurement.]

b) PE

Testing with the other plastic available, the results are worse than with the PLA plastic. In this case, the curve shows only a small slope at the final part. Moreover, the signal has a lot of noise and stays around the same level.

![Figure 65.- Graphic of the PE plastic combined with wood measurement.]

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5.3.5. Plastic-Foam

This case is only tested with PLA plastic, due to the previous unsatisfactory results with the PE plastic. In addition, the prototype has an expanded range to check if the range used previously is the optimal. The new used range in this case is 3 mm instead of the previous 2mm used. According to the graphic below, the 2 mm range seems to be optimal.

![Figure 66.- Graphic with PLA plastic combined with black foam measurements.](image_url)

Zooming in in that linear area, it is possible to identify the area limits. The linear area starts at 15 mm and finishes at 47 mm, that is 30% and 94% respectively of the position range. The prototype is designed in this case with 3 mm changing surface range, thus the interval that is linear is 2 mm (64% out of 3 mm).

![Figure 67.- Graphic of the selected range of PLA plastic combined with black foam measurements.](image_url)
The linear regression approximation fits well with the obtained curved, looking smooth enough. The R² value is higher than 0.99, thus the curve is considered linear. Reading with a 12-bit resolution ADC, some characteristics can be obtained. The useful position range is 33 mm and the readings of the sensor vary 2881 bits. According to these values, the estimated resolution of the sensor would be approximately of 0.0115 mm/bit. Extrapolating this case to 50 mm, assuming the bit range is maintained the same, the resolution would be 0.017 mm/bit.

5.3.6. Fading surface

Building the prototype with a fading surface is complicated. To obtain a plain slope depends on the CNC milling machine process. To mill the material, it is usually divided in layers. Thus there is always a small step between the layers. Even though the results are good, the range does not cover the full position range (50 mm). However, the range could be improved by redesigning the testing prototype shape. The linearity of the curve obtained is not linear enough, although the R² value is high. The figure below shows that the curve has some bends.

![Graph](image)

**Figure 68.** - Graphic with selected range of fading surface measurement.

5.3.7. Aluminum

Aluminium prototypes show a high value of infrared light reflectance. A completely flat surface is needed in order to obtain a clear measurement. Otherwise, the measurements obtained are not stable and difficult to obtain a linear output. That makes aluminium a not useful material for the final design, as a result of its difficulty and cost to have plain aluminium surface.
In the Figure above, a couple of measurements with aluminium are shown. This measurements are made with a PE plastic base and Aluminium. It is easy to see that the measurements obtained are random and unpredictable, due to the cut edges and not perfectly plain surface.

5.4. Angular prototypes

According to the linear results, some of the material combinations are discarded and no further tests in the angular test setup are done with these materials.

5.4.1. Paper

The results obtained with the angular paper prototypes are really smooth, but the curves have three different sections. Firstly, a section consists of the direct transition between the two surfaces at the end of the reflective change area. This first section is the steep slope due to the abrupt transition between the highest and lowest values. The other two sections split the remaining range in two linear curves but with different slopes. Therefore both sections have smaller ranges than the desired. In order to use both, a system to linearize the two sections separately could be implemented. This double linearization could be implemented by hardware or software. Using hardware implies more components, thus increasing the total cost. Using software implies more workload to the processor. Normally when linearizing by software, it also reduces the resolution.

   a) Conical

The conical shape is printed in paper and tested. The sensor range is big and presents very small amount of noise. However, the curve has not the same linearity in the whole curve. The biggest range obtainable in one of the sections would be between 90 and 220 degrees, making it an angular range of 130 degrees. But in this big range, the variation of the sensor value is small, while the slope of
the curve in this section is low. Using the two different sections, the range would increase to a value of 300 degrees approximately, although some precision would be lost in the intersection.

**Figure 70.** Graphic with the conical gradient on paper measurement.

*b*) Spiral

Similar results are obtained with the spiral prototype as with the conical shape. Three different sections are given, but none of them has enough range close to the desired. The biggest range in any of the sections would be between 220 and 360 degrees, resulting in a range of 140 degrees. However, the variation in this range of the sensor value is small, as is the slope of the curve. Using the two different sections, the range would increase to a value of 270 degrees approximately. As mentioned in the previous case, some precision would be lost in the section change.

**Figure 71.** Graphic with the spiral pattern on paper measurement.
5.4.2. First version prototype

a) Triangle shape

- PLA plastic - Foam

The first version of the testing prototype tests firstly the triangle shape. There are two variations of this testing prototype. Basically, the main difference between these two variations is that the two different reflective surfaces switch places. The first variation has the plastic on the inside surface and the black foam on the outside part. The second variation has the plastic surface on the outside area, and the foam inside.

![Figure 72.- Graphic comparison of the angular prototype with plastic.](image)

The comparison between the two different variations, showed in the previous figure, results in the same curve but with opposite values. This is expected, since the sensor receives the reflection of the IR light. The light changes at an inversed proportion in each variation as they use the same materials.

The useful linear range would go from around 110 to 290 degrees, which is a range of 180 degrees. That would be the range for the prototype with the plastic in the outside area. On the other variation, the same angular range is obtained, as it would go from 130 to 310 degrees. The slope obtained is big, therefore the resolution obtained would cover the desired resolution.

- PLA plastic – Ink

Painting one of the surfaces with black ink, the slope of the curve is not as expected, since it only changes a few bits. Even though the curve seems to be linear, the curve has a lot of spurious interferences and noise.
The results with PE plastic and ink are similar to the results obtained with PLA plastic. The curve has a lot of noise and spurious interferences. The slope of the curve is also small, as it only varies a few bits.

**Figure 73.- Graphic of the PLA plastic with ink measurement.**

- PE plastic – Ink

The other prototype shape is the circle used in the first version of the testing prototype. The curve obtained has enough slope to achieve the desired resolution. However, the curve obtained is not much linear. The curve resembles to a cosine waveform, hence only approximately 90 degrees are linear. Testing with other collector currents, the shape is even more similar to the cosine waveform.

**Figure 74.- Graphic of the PE plastic with ink measurement.**

b) Circle
Figure 75.- Graphic of the circle shape measurement compared with a cosine waveform.

5.4.3. Second version prototype

With the second version of the testing prototype, the measurements are not as expected, even though the curves obtained seem to have a linear tendency. Nevertheless, the curves have a lot of deviations that make them useless.

a) PLA Plastic – Void

In this simple case, where only one surface is useful, the results obtained are not satisfactory. The curve has some linearity but the difference to the ideal linear line is important. In addition, the slope is small due to a small range of the sensor values measured.

Figure 76.- Graphic with the PLA plastic and void measurement.
b) PLA plastic – Ink

Combining the plastic with ink, the curve has bigger range in the sensor values read. Although, the curve is divided in three sections. These sections are also not useful, as they have a small angular range, small slope or non linearity.

![Figure 77.- Graphic with the PLA plastic and ink measurement.](image)

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c) PLA plastic – Foam

The plastic combined with black foam reports the best results using the first version of the testing prototype. However, in this prototype version, the results obtained are not as expected. The curve shows a linearity but has a step in the middle of the slope, which makes it useless. Moreover, it seems to have bigger deviations from the ideal linear curve.

![Figure 78.- Graphic with the PLA plastic and black foam measurement.](image)
5.5. Interferences

The possible interference caused by the ambient light is tested through the linear test setup platform. A window to let the light in is implemented in the design. The worst case scenario would be without window to filter or block the ambient light.

As it is possible to see in the Figure above, the comparison of the sensor values obtained are similar. The testing uses the same prototype but the light is allowed to go through or not depending on the window. The differences are really small and barely noticeable. A slight difference in the slopes appears. The measurement without cover has slightly a bigger slope and reaches the highest value before than with cover.

With further testing, the effect of the ambient light is noticeable. The values measured by the sensor are always a little bit higher than with a blocking light window. Nevertheless, the ambient light effect will be considered negligible in the final design. It is assumed that the sensor will be enclosed inside the joint. Theoretically, ambient light will be almost imperceptible for the sensor, allowing the sensor to be immune to external light disturbances, such as ambient light, spurious reflections and other possible Infrared sources.

Figure 79.- Graphic comparing the effect of ambient light.
CHAPTER 6:
FINAL DESIGN

According to the results obtained in the measurements of the different tested prototypes, a final solution is designed and implemented.

6.1. Materials

Firstly, the materials to be implemented in the final design are selected. Although the paper showed an overall better performance, the PLA plastic and black foam seem to fit better for an automated construction of the robot. It would be possible to implement the paper surface, since the curve obtained with the paper has good linearity response. Likewise, different shapes with PLA plastic could be used even though they are not linear in the whole position range. This could be solved dividing the curve in two sections and then linearizing the two sections by hardware or software.

The option decided to implement is, for both linear and angular measurements, constructed with PLA plastic and black foam. They should have the triangle shape within the 2 mm switching distance of the sensor. The first version of the angular testing prototype reported better results, hence it is the selected final version. This version is designed to be as an extension of the shaft or angular device to measure.

6.2. Electronic configuration

The electronic components values are selected according to the different electronic configurations tested previously. Therefore, the final values for the electronic components are shown in the table 6. The reference numbers for the components are the same reference numbers used in the electronic schematic.

The different blocks of the electronic configuration consist of, first of all, the optoelectronic sensor and the current limiter resistors; second, the anti-aliasing filter processes the voltage at the sensor to isolate and filter interferences. The
final block consists of the analog-to-digital converter, which will communicate with the external components. The full electronic schematic is as follows:

![Electronic schematic of the final design.](image)

Two bypass capacitors have been included to stabilize the supply voltage. The connector is a simple 6 pin connector as there are needed 6 signals to use. Two are the supply and ground to supply power to all the circuitry. The other 4 signals are the SPI protocol signals to communicate with the ADC.

**Table 6. List of the electronic components values.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>150 Ω</td>
</tr>
<tr>
<td>R2</td>
<td>10k Ω</td>
</tr>
<tr>
<td>R3</td>
<td>7k8 Ω</td>
</tr>
<tr>
<td>R4</td>
<td>14k7 Ω</td>
</tr>
<tr>
<td>C1</td>
<td>10 µF</td>
</tr>
<tr>
<td>C2, C4</td>
<td>0.1 µF</td>
</tr>
<tr>
<td>C3</td>
<td>0.22 µF</td>
</tr>
</tbody>
</table>

### 6.3. Specifications

As a final implementation, it requires some product specifications to estimate its functionality. The specifications estimated are the resolution, position range, error and output type. The position range is already specified in the design requirements.

#### 6.3.1. Resolution

The resolution is estimated by the relationship between the position range and the variation of the values read within that range. The estimation can be obtained simply dividing the position range by the variation of the values read. The position range corresponds to the starting until the final position measured, thus the units are millimetres or degrees. The variation of the values read is the difference between the maximal and minimum point of the linear approximation, that is to say the bits margin where the ADC reads.
6.3.2. Estimated error

In order to estimate an average error, the standard deviation tells the dispersion of a set of data values. The standard deviation is dependant of the variance, which indicates the distance between the measured values and the expected. Applying that variance to all the measured values with a quadratic sum, the standard deviation can be estimated. Its value tells the margin where 68% of the values will be. That is estimated according to statistical procedures (equation 4). In addition, the maximum and minimum variance of the data measured are also estimated.

\[ \sigma = \frac{1}{N} \cdot \sum_{i=1}^{N} (x_i - \mu)^2 \]  

Where \( N \) is the number of data values, \( i \) is the iterated position, \( x_i \) is the value measured and \( \mu \) is the expected value (mean). The expected values are the linear regression approximation values.

6.3.3. Output signal

The output type of signal is determined by the ADC. The data is transfered in digital format, using the SPI protocol incorporated in the ADC. Therefore, the data will be available to the microcontroller with 4 signals. These signals consist of chip selector, clock, data in and out, determined by the SPI protocol.

6.3.4. Final specifications

The resolution obtained in the sensors is better than the desired, but the error margin is much bigger than the error obtained with the potentiometer. Other specifications, like the distance to the surface, are determined by the electronic component that performs the specific action. Naturally, ground and source need to be supplied externally to all the components of the sensor. The voltage supplied should be of 5 Volts. In the following table, there is a characteristics comparison of the sensors designed and the linearized potentiometer. The printed gradient on the paper is also included to compare with the other designs, whereas it is also a viable option.

<table>
<thead>
<tr>
<th>Table 7. Resolution and error values comparison.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Potentiometer</td>
</tr>
<tr>
<td>Paper Gradient</td>
</tr>
<tr>
<td>Linear</td>
</tr>
<tr>
<td>Angular</td>
</tr>
</tbody>
</table>

Note: The potentiometer values have been scaled to a 12-bit ADC to be at the same scale as the other measurements.
CHAPTER 7:
COST OF COMPONENTS

This section explains the economic cost of the materials used in the final design. First, a cost estimation of the materials used to build the reflective and non-reflective surface. Finally, a cost estimation of the electronic components used in the final design. This is only an estimation of the cost of the components, therefore the estimated cost for the design is not included.

7.1. Reflective materials

The reflective materials cost is considered by the approximate dimensions used to build the reflective linear surface. The angular materials, as they are smaller pieces than the linear pieces, are not included in the estimation. The PLA material is sold in spools of 1 kg, which approximately equals to 335 m of PLA filament. The black foam is sold in boards with normalized sizes, in the selected case, an A2 with 5 mm width board. One board costs 6.09 €, thus the cost per area can be calculated.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Description</th>
<th>Quantity</th>
<th>Cost per unit</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PLA</td>
<td>3D factories</td>
<td>White colour</td>
<td>553 mm</td>
<td>35.90 €/kg</td>
</tr>
<tr>
<td>2 Foam</td>
<td>Black colour</td>
<td>762.5 mm³</td>
<td>4.88 €/cm³</td>
<td>0.037</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td>0.095</td>
</tr>
</tbody>
</table>

7.2. Electronic components

All the electronic components used in the final design are included in the cost estimation. Some generic prices are taken for the resistors and capacitors. The actual cost may vary into lower values, due to the fact that when a major quantity for each component is bought, less expensive it becomes.
Table 9. Electronic components list.

<table>
<thead>
<tr>
<th>Ref. Number</th>
<th>Manufacturer</th>
<th>Description</th>
<th>Quantity</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Optocoupler</td>
<td>GP2S60 SHARP Photointerrupter; SMD</td>
<td>1</td>
<td>0.737</td>
</tr>
<tr>
<td>2</td>
<td>Analog-to-Digital Converter</td>
<td>MCP3202 MICROCHIP 12-bit ADC; SMD</td>
<td>1</td>
<td>2.45</td>
</tr>
<tr>
<td>3</td>
<td>Operational Amplifier</td>
<td>MCP6042 MICROCHIP Dual OA single supply; SMD</td>
<td>1</td>
<td>0.79</td>
</tr>
<tr>
<td>4</td>
<td>150Ω Resistor</td>
<td>R1 - ¼ W, 1%</td>
<td>1</td>
<td>0.039</td>
</tr>
<tr>
<td>5</td>
<td>10kΩ Resistor</td>
<td>R2 - 0.1 W, 1%</td>
<td>1</td>
<td>0.026</td>
</tr>
<tr>
<td>6</td>
<td>7k8Ω Resistor</td>
<td>R3 - 0.17 W, 0.1%</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>14k7Ω Resistor</td>
<td>R4 - ¼ W, 0.1%</td>
<td>1</td>
<td>0.191</td>
</tr>
<tr>
<td>8</td>
<td>10µF Capacitor</td>
<td>C1 - 10 V</td>
<td>1</td>
<td>0.049</td>
</tr>
<tr>
<td>9</td>
<td>0.1µF Capacitor</td>
<td>C2, C4 - 10 V</td>
<td>2</td>
<td>0.005</td>
</tr>
<tr>
<td>10</td>
<td>0.22µF Capacitor</td>
<td>C3 - 16 V</td>
<td>1</td>
<td>0.11</td>
</tr>
<tr>
<td>11</td>
<td>Connector</td>
<td>J1 - Header</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

TOTAL  5.05

7.3. Total cost

Adding the two separated estimations, the final cost of the system is **FIVE EUROS AND FIFTEEN CENTS**.

Table 10. Total cost.

<table>
<thead>
<tr>
<th></th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflective materials</td>
<td>0.095</td>
</tr>
<tr>
<td>Electronic components</td>
<td>5.05</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5.15</td>
</tr>
</tbody>
</table>
CHAPTER 8: CONCLUSIONS

This thesis has been carried out researching a new way of sensing the joint position in robotics. This new sensing system was a challenge to implement while it is still in development in the robotics industry. The thesis is based on the optical joint developed by Palli and Pirozzi, who are also researching actively in robotics. Their work inspired this thesis to research and try new ways to improve it. A new optical characteristic is researched, using the reflected infrared light instead of blocking the quantity of light. On one hand, the improvement achieved is that the electronic components can be placed in one surface, hence using less space. On the other hand, the materials interacting with the infrared light must be specific materials with specific light reflectance values.

Another big challenge was to design a scalable sensing system for linear and angular position. Since the optical sensors have such a small switching distance to detect reflectance change on surfaces, it was challenging to work with small components. However, it could be managed due to the equipment and tools available in Blue Danube Robotics Company.

The system has been designed according to the requirements and materials available at Blue Danube Robotics Company. The materials selected are becoming more and more available to everyone. In particular, 3D printers are becoming more popular and receiving more technical support, thus making them increasingly affordable and easy to work with. These were the goals set by Blue Danube Robotics to design and implement the robot, which have been the main focus during the whole process of elaborating this thesis.

The experimental results show that the sensing system is suitable for the measurement of angular and linear joints. The sensor response has good linearity in the whole motion range, although the sensor has some error deviations that should be considered. The sensing system has an angular range smaller than the desired, although it is still a big range compared to other sensing systems available. On the other hand, the linear range covers the whole position range.
desired. Furthermore, a big improvement is the resolution acquired for such big ranges, which shows better values than expected. In addition, the very limited requirements in terms of conditioning electronics make this solution more feasible to implement. The implementation with few components reduces the physical space needed in the robot and eventually, the cost. The estimated cost is within the expectations, while it is an affordable price and really improved compared to the sensors available.

The sensing system designed in this thesis is just one step into new easier and cheaper sensing devices in robotics to make the robotics accessible to more people.

8.1. Future work

The following natural step would be to design the PCB layout and create the physical sensing system according to the mechanical restrictions of the robot. The PCB layout would be restricted by the position of the sensor, whereas it has to be placed in a concrete position respect the reflecting surfaces in the joint. The other components are not as critical as the sensor, thus them can be placed in the remaining space of the electronic board.

The connector to communicate with the sensing system will be a 6-pin connector. Therefore, the connector can be any standard design with the required number of pins, fitting in the space available in the joint.

8.1.1. Different configuration

Another option would be to decide to use other materials in the angular joint for the printed ink on a paper. They show better accuracy although it requires more signal processing to achieve the required specifications. As commented in the results, the curve is divided in different sections though that could be solved by hardware or software. On the contrary, the implementation of the paper in the robot is difficult; therefore, new ways to insert the paper in the joint and that it endures all the mechanical movement without losing its characteristics.

The hardware solution requires to use an operational amplifier to modify the two different sections in order that the output signal is equivalent to one single linear section. The operational amplifier would be configured as a non-inverter amplifier. To select the different gain for the output signal, consequently the slope, diverse resistors are added in the circuitry. While these added resistors should work only when the voltage reaches the starting point of the section, an operational amplifier working as an ideal diode performs that selection. To activate the resistors, the operational amplifier should know the voltage where it has to start to work.

The software solution would be the same but processed in the microcontroller. Two different implementations are possible: store the linearized data in a table where the software looks up; read the initial and end values of the sensor and simulate the linear approximation. The look-up table has the problem that not all the possible values are stored, thus the action to do in those cases should be considered.
The bibliography is divided in three parts. First the references that are cited in the text are listed. The second part consist in the books consulted listed but not cited in the text. The last part are all the websites visited to recollect information for the thesis.

9.1. References


http://www.vishay.com/

9.2. Consulted bibliography


9.3. Websites

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